PLASMA GENERATION AND EXPANSION AT THE ANODE SURFACE IN A VIRTUAL CATHODE OSCILLATOR
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Abstract. We have performed two- and three-dimensional, relativistic, electromagnetic particle-in-cell simulations of an axially-extracted Virtual Cathode Oscillator (vircator). The simulations include, for the first time, self-consistent dynamics of the anode foil under the influence of the intense electron beam. This yields the variation of microwave output power as a function of time, including the role of anode ablation and anode-cathode gap closure. These simulations have been done using locally-developed Particle-in-Cell (PIC) codes. The codes have been validated using two vircator designs available from the literature. The simulations reported in the present paper take account of foil ablation due to the intense electron flux, the resulting plasma expansion and shorting of the anode-cathode gap. The variation in anode transparency due to plasma formation is automatically taken into account. We find that damage is generally higher near the axis. Also, at all radial positions, there is little damage in the early stages, followed by a period of rapid erosion, followed in turn by low damage rates. A physical explanation has been given for these trends. As a result of gap closure due to plasma formation from the foil, the output microwave power initially increases, reaches a near-“flat-top” and then decreases steadily, reaching a minimum around 230 ns. This is consistent with a typical plasma expansion velocity of ~2 cm/us reported in the literature. We also find a significant variation in the dominant output frequency, from 6.3 to 7.6 GHz. This variation is small as long as the plasma density is small, up to ~40 ns. As the AK gap starts filling with plasma, there is a steady increase in this frequency.

1. Introduction

VIRTUAL cathode oscillators (vircators) are of great interest as narrow band, high-power microwave (HPM) sources. This is because of their ability to generate high power levels, their tunability over a wide frequency range and their simple design [1-4]. The output power level and frequency of emission are very sensitive to design parameters such as the anode-cathode gap and the transparency of the foil anode to high-energy electrons [1], [2] & [3]. This makes it essential to optimise design through detailed computer modelling before experiments can be started. Considerable experimental and simulation work has been reported on vircators.

We have performed two-dimensional (2-D), relativistic, particle-in-cell (PIC), electromagnetic simulations for an axially-extracted vircator. This has been done using a locally-developed particle-in-cell (PIC), Electromagnetic, Relativistic, two and three dimensional code MWS. Earlier work [1] has shown that the power output and the dominant frequency strongly depends upon the model used for foil transparency. In those simulations, we assumed that the foil transparency remains constant in time [1]. That assumption leads to three errors. Firstly, it eliminates the major closure mechanism in the diode. Secondly, since the foil ablates in time, its transparency should be time-dependent. Thirdly, the plasma created by foil ablation significantly affects vircator dynamics, which is ignored in our earlier model. These issues are of particular importance in determining the microwave output pulse duration in long-pulse vircators and have not, to our knowledge, been addressed in earlier simulation studies.

This paper is a first step towards addressing these issues, and is divided into two parts. The first part involves a study of foil damage with time, and the consequent plasma generation and expansion. On the basis of this model, we attempt to estimate the closure time of the diode and the lifetime of the foil. The second part involves the effect of anode ablation, and plasma formation and expansion, on the performance of the vircator.

2. Computational Model
A schematic of the device is shown in Figure [1]. All simulations have been performed using a locally-developed code MPIC, a two and three dimensional, electromagnetic, PIC code. The PIC code included a variety of features, such as relativistic particle push, field emission, interaction of particles with material surfaces and an advanced graphical interface with multiple diagnostics [1]. In this Section, we report on the model used to simulate foil ablation under intense electron beam irradiation, and the limitations of this model.

Figure 1 : Schematic of Axially Extracted Vircator

As per our earlier simulation the foil transparency model play an important role in computation hence we generated a database for different conducting materials transparency as a function of energy using monte-carlo calculations and this database is used to compute the local and instantaneous transparency of foil. Linear interpolation scheme is used to get transparency for arbitrary energy. For a given electron, incident upon a given part of the foil anode having a specified thickness, a random number is generated and used to decide whether or not the particle is “absorbed” in the foil. If the particle is absorbed, it is assumed that all its kinetic energy is deposited in the foil. Conversely, energy deposition by “escaping” particles is ignored. We plan to refine this simple model in a more detailed study.

The energy so deposited is assumed to be used for converting atoms in the solid state into a singly-ionized plasma. That requires taking account of the following contributions:

1. Sensible heat contributions required for heating the solid to the melting point, and then the liquid from the melting to the boiling point.
2. Latent heats of melting and vaporization.
3. Ionization potential for converting neutral atoms to singly-charged ions.

The sum of these three contributions yields the total energy required for producing an electron-ion pair at rest, $E_{\text{tot}}$. The total number of such pairs created, in a given timestep from a given region of the foil, can be calculated from:

$$N_{\text{pair}} = \frac{E_{\text{dump}}}{(E_{\text{tot}} + E_{i})}$$

where $E_{\text{dump}}$ is the energy dumped on that region in one timestep and $E_{i}$ is the initial kinetic energy of the electron-ion pair. This calculation rests upon two major simplifying assumptions. The first is that all atoms transition from the solid state to a singly-ionized plasma state. In reality, there is likely to be a distribution of charge states, depending upon the energies of the incident electrons. The second assumption is the neglect of high-density plasma effects on the ionisation potentials.

Now, there is strong variation in $E_{\text{dump}}$ at a given timestep, as a function of radial position on the foil. That yields a strong variation in foil erosion rates with radial position. This effect is taken into account by dividing the radial extent of the foil into several intervals, and calculating $N_{\text{pair}}$ for each interval.
The above calculation yields the plasma generation rate from the foil surface as a function of time and radial position. On the one hand, this yields a source of plasma particles, electrons and ions, which are subsequently evolved by the PIC code. On the other, it yields the foil thickness as a function of time and radial position, which must be taken into account in calculating foil transparency for the next timestep.

The model used for electron interactions with surfaces is the same as in [1]. Ions hitting any surface are assumed to be absorbed without backscattering or secondary emission.

3. RESULTS AND DISCUSSION

The following Table lists the parameters used in the simulations, which are taken from Ref.[1].

| PARAMETER          | VALUE                          |
|--------------------|--------------------------------|
| Drift tube length  | 50 cm                          |
| Drift tube radius  | 4.8 cm                         |
| Cathode Radius     | 2.0 cm                         |
| Cathode Length     | 2.0 cm                         |
| Foil material      | Cu                             |
| Foil thickness     | 25 microns                     |
| Foil radius        | 4.8 cm (same as drift tube)    |
| Foil Transparency  | Energy dependent [1]           |
| Anode-cathode Gap  | 0.5 cm                         |
| Applied voltage pulse $V_{in}(t)$ | Flat top at 290 kV, with a 5 ns rise time. |

Figure 2 : Temporal evolution of output microwave power. Curves A and B show results with and without foil ablation.

Figure 2 shows the output microwave power as a function of time. We observe that the output microwave power stabilizes around $t = 50$ ns. The rest of this work is devoted to understanding the physical phenomena underlying this variation.

3.1 Plasma generation and expansion rate:
The simulations, both two- and three-dimensional, show that the electrons beam has a finite current density throughout its cross-section. Hence we can expect foil damage throughout the foil radius, the damage level depending upon the power flux distribution along the radius.

Figure [3] shows the rate of plasma generation as a function of radial location on the anode, at three different time points, viz., early time, midway and after the microwave power output stabilizes. It can be seen that the rate of plasma generation is almost inversely proportional to the radial distance after the power stabilizes [curve C]. At earlier times, the generation rate does not fall off as fast. For example, at early times, the plasma generation rate scales as $1.0/r^{0.54}$, while at the midway mark, it scales as $1/r^{0.93}$. This trend has been confirmed with three-dimensional simulations performed for an axisymmetric geometry.

Figure [4] shows the plasma expansion for electrons & ions. It can be seen that the electrons (light particles) are leading the ions (heavy particles). It is important to quantify these expansion velocities, since that determines the anode-cathode gap closure time. The expansion velocity is recorded separately for these two species, using the following procedure. Firstly, we consider time points after the output microwave power has stabilized, since that is the point after which gap closure becomes relevant. Secondly, since the charged particles occupy, in general, the entire space between the foil and cathode, we consider several axial locations between the foil and cathode. Thirdly, we limit ourselves to only those charged particles that are emitted due to foil ablation. Fourthly, we consider three different radial locations, viz., near the axis of symmetry (close to $r=0$), at $r = r_c/2$ and $r = r_c$, where $r_c$ is the cathode radius. At each specified r-z location, we determine the average axial velocity of particles of each species that pass through a small area element normal to the axial direction. To reduce statistical error, an average is taken over one time period corresponding to the dominant microwave frequency. For each radial position, the results from different axial locations are averaged to yield the average axial velocity. At $t = 90$ to 100 nsec, the average axial expansion velocity for electrons is found to be 2.26 cm/us, 2.22 cm/us and 1.96 cm/us at the radial locations specified above. This means that the electrons emitted from the foil expand almost uniformly towards the cathode.
The Table below shows the average axial expansion velocity of electrons as a function of time, at $r = 0$. Note that the output microwave power stabilizes around $t = 50$ ns to $t=120$ ns, hence this table covers time points both before and after the stabilization.

| Time (ns) | Velocity (cm/us) |
|-----------|------------------|
| 40        | 3.2              |
| 45        | 2.9              |
| 50        | 2.7              |
| 70        | 2.3              |
| 90        | 2.28             |
| 100       | 2.27             |
| 120       | 2.6              |
| 140       | 2.63             |

It can be seen that the axial velocity of electrons is near constant over the interval 70-100 ns. As the electron cloud approaches the cathode, however, the velocity increases again.

Now the generated plasma affects the system in two different ways. Firstly it limits the foil life and secondly limit the temporal width of the microwave pulse. These issues are examined in the following subsections.

3.2 Foil damage study:
Figure 5: Radial variation of foil damage at 80 ns. The thick line shows the initial foil thickness of 25 um, while the thin line shows the thickness as a function of radial position on the foil.

Figure [5] shows the radial variation of foil thickness at 80 ns. The original foil thickness was taken as 25 um. This time point has been chosen as one where there is significant plasma formation in the inter-electrode gap. We see that there is much higher erosion near the axis than near the periphery of the anode. This result support the higher generation rate near the axis, as shown in Figure [3].

Figure [6] shows the temporal evolution of foil damage at three different radial locations. Two points can be noticed. Firstly, damage is generally higher near the axis. Secondly, at all radial positions, there is little damage in the early stages, followed by a period of rapid erosion, followed in turn by low damage rates.

Figure 6: Temporal evolution of foil thickness at three radial positions, [A]: near the axis, [B]: at half the cathode radius and [C]: at the cathode radius.

This can be understood in terms of the radial distribution of electron flux incident on the foil from the left. Figure [7] shows the normalized radial distribution of current density incident on the foil from the left, i.e., the side nearer the cathode. We see that the current density is highest near the axis and falls off towards the periphery. This leads to higher erosion rates near the axis.
3.3 Effect of anode ablation on performance:

We next consider the effect of plasma expansion on vircator performance, in terms of parameters like the output power, frequency and gap closure time.

Power and Gap Closure time: The temporal evolution of output microwave power has been shown in Figure [2], both with and without the inclusion of foil erosion. For purposes of smoothing, we have performed a moving-window average with a window width of ~0.153 ns. This width has been taken as five times the period corresponding to the peak output frequency produced when we ignore foil erosion. We see that the power initially increases, reaches a near-“flat-top” and then decreases steadily, reaching a minimum around 230 ns, which is marked as “gap closure”. Beyond this point, there appear to be rapid variations in the power, which may be an artifice of the limitations of our model.

![Figure 7. Radial variation of current density incident on the foil from the left. The ordinate is normalized to its peak value.](image)

Output frequency: A vircator often emits a range of frequencies, with two major frequency peaks, one of which is dominant [2,4]. Figure [8] shows the temporal evolution of the dominant frequency. This has been obtained by taking the FFT of the time series of the electric field measured near the exit. Intervals of size 5 ns were selected, along with a Hanning window, for determining the evolution of the dominant frequency. This corresponds to an error bar of 0.2 GHz. Two points are noteworthy.

![Figure 8 : Temporal evolution of dominant frequency](image)
Firstly, the total variation in the dominant frequency, from 6.3 to 7.6 GHz, is much larger than the error bar, hence the variation is significant. Secondly, the variation in frequency is small as long as the plasma density is small, up to ~40 ns. As the AK gap starts filling with plasma, there is a steady increase in this frequency.

4. CONCLUSIONS

We have performed 2-D and 3-D, relativistic, electromagnetic, particle-in-cell simulations of the evolution of an axially-extracted vircator. These simulations take account of foil ablation due to the high heat load from incident electrons. We find that damage is generally higher near the axis. Also, at all radial positions, there is little damage in the early stages, followed by a period of rapid erosion, followed in turn by low damage rates. A physical explanation has been given for these trends. As a result of gap closure due to plasma formation from the foil, the output microwave power initially increases, reaches a near-“flat-top” and then decreases steadily, reaching a minimum around 230 ns. This is consistent with a typical plasma expansion velocity of ~2 cm/us reported in the literature. We also find a significant variation in the dominant output frequency, from 6.3 to 7.6 GHz. This variation is small as long as the plasma density is small, up to ~40 ns. As the AK gap starts filling with plasma, there is a steady increase in this frequency.

5. REFERENCES

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