ON EMITTANCE EVOLUTION IN THE EXTRACTION SYSTEM OF HIGH-CURRENT ELECTRON AND ION SOURCES

J-M. Lagniel, P. Balleyguier, D. Guilhem, J-L. Lemaire, N. Pichoff, M. Promé
CEA/DAM, DIF/DPTA/SP2A, Bruyères-le-Châtel, France

Abstract

A simple model has been built to study the evolution of high-current electron or ion beams in axially symmetric extraction systems (electron guns or ion sources). Both electric and magnetic field components induced by a HV diode and a focusing solenoid respectively are computed using analytical formulas. The space-charge forces are computed using a ring method. In a first step, the individual effects of the 3 nonlinear forces (electric, magnetic and space charge) on the emittance evolution are presented. We then discuss how the knowledge acquired in the first step can be used to understand and optimize the emittance evolution in systems combining these effects.

INTRODUCTION

A simple model has been built to understand the behavior of high-current beams in extraction systems of electron guns or ion sources with azimuth symmetries. In a first step, the emittance evolution has been analyzed for each kind of nonlinear force present in such systems:

- nonlinear forces induced by the electric field of the diode,
- nonlinear forces induced by the magnetic field of a focusing solenoid,
- nonlinear space-charge forces.

The understanding of the individual effects has been used in a second step to optimize the emittance evolution in the case of combined effects of these forces.

DIODE

The model uses the simplest diode geometry: a flat disc as emissive area (cathode) and a thin plane with a cylindrical hole as anode. An analytical formula giving the potential distribution at any location in the (r,z) plane [1] is used to calculate the longitudinal (E_z) and radial (E_r) components of the electric field. This technique allows very fast computations of the particle trajectories. Fig. 1 gives an example for the following parameters :

Cathode : $z = 0$, $R_K = 4.5$ cm, $V = -100$ kV

Anode : $z = 10$ cm, $R_A = 5$ cm, $V = 0$

Fig. 2 shows that the rms emittance evolution in this simple system (zero current, no focusing solenoid) is already pretty complicated. In a first zone (D1), the rms emittance starting from zero at the cathode (no divergence) increases up to a maximum at z ~ 9 cm. In the anode area (D2, ~ 9 cm < z < ~ 11 cm), the emittance decreases rapidly before reaching a second maximum. After the anode area (D3), the emittance reaches another minimum before raising to a final plateau at z ~ 30 cm (anode position + ~ 4 R_A).

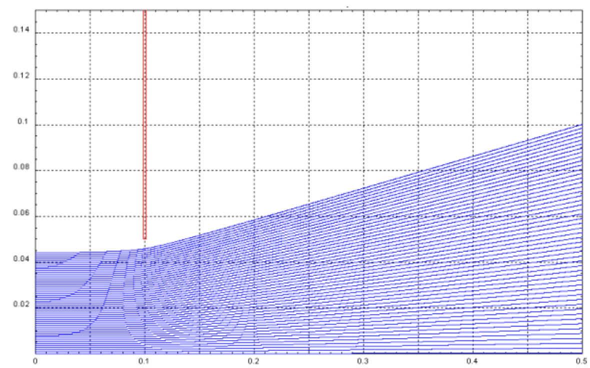

Figure 1: Particle trajectories in the diode : R = f(z) (m).

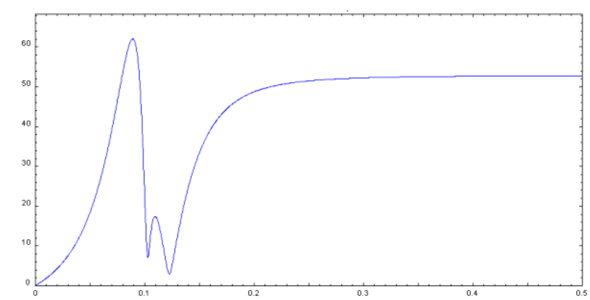

Figure 2: Evolution of the (R,R') unnormalized rms emittance value (mm.mrd) along the diode axis z (m).

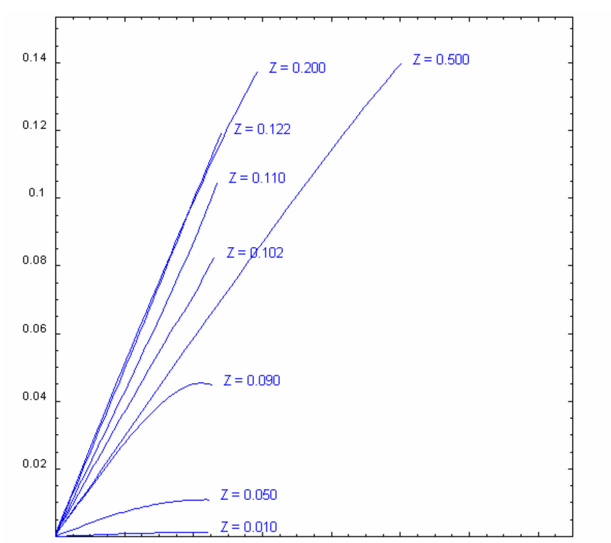

Figure 3: (R,R') emittance plot at different positions z (m) along the propagation axis of the diode.

Fig. 3 explains the rms emittance evolution. The electric field nonlinearities bend the (R,R') emittance curve - towards the R axis in zone D1, - towards the R' axis in D2 (the distribution is straighten up and the emittance reaches a minimum), - and finally again towards the R axis in D3. The nonlinear effects become negligible at z ~ 30 cm where the final emittance plateau starts. In this example the final rms unnormalized emittance is ~ 50 mm.mrd; this value depends upon the ratio R_A/R_K but the emittance behavior shown on fig. 2 remains unchanged for different R_A/R_K values.

SOLENOID

Analytical formulas giving the longitudinal (B_z) and radial (B_r) components of the magnetic field generated by a coil of current at any position in the (r,z) plane can be found in [2]. They are used to compute the effect of solenoids formed by an addition of several of these coils. In a first step the particle trajectories have been analysed in such solenoids without electric field or space charge. For the results presented here a 8 cm radius 100 keV electron beam starts at z = 0 without divergence, a 5 coils 2 cm long 10 cm radius solenoid powered with 200 A is located at z = 40 cm.

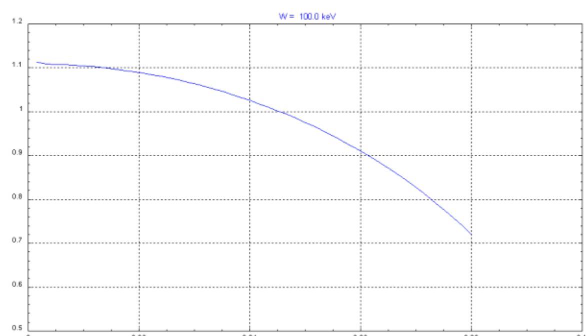

Figure 4: Solenoid focal length (m) function of r (m).

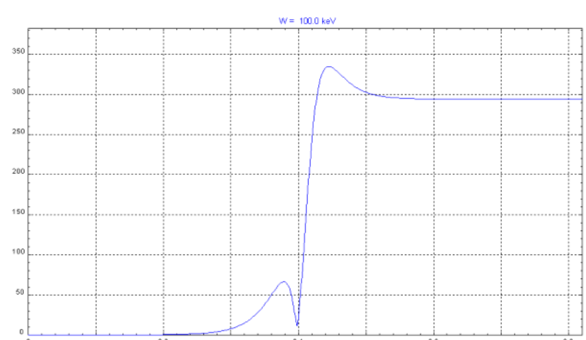

Figure 5: Evolution of the (R,R') unnormalized rms emittance value (mm.mrd) along the solenoid axis z (m).

The plot of the solenoid focal length as a function of the particle input radius (fig. 4) demonstrates the nonlinear character of this focusing element. The rms emittance evolution (Fig. 5) shows a first zone (S1) where the emittance starting from zero increases up to a maximum at z ~ 38 cm. After this point (S2 zone), the emittance decreases down to 0 before a big jump up to a final value of 250 mm.mrd. Fig. 6 explains this behaviour, the magnetic field nonlinearities bend the emittance curve - towards the R axis in S1, - towards the R' axis in S2 (the distribution is straighten up and the emittance reaches 0 when this effect perfectly compensates the first one).

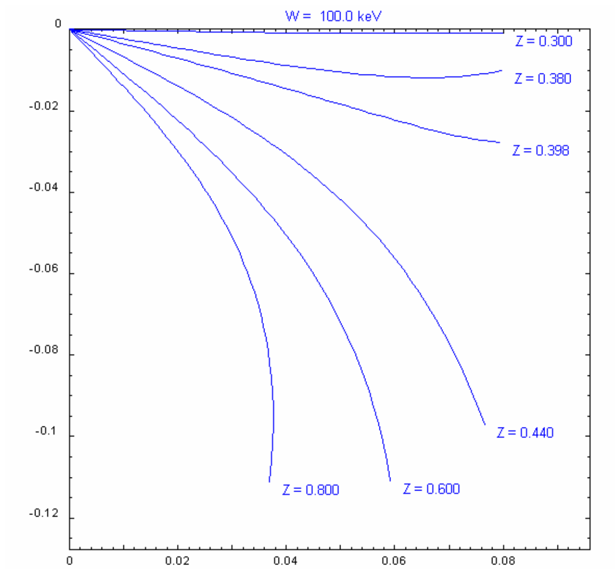

Figure 6: (R,R') emittance plot (m, rd) at different positions along the propagation axis (z) of the solenoid.

SPACE CHARGE

Since the beam is axially symmetric, each beam cross section at a particular point along the z-axis can be described by a large number of equally-charged adjacent rings. This beam description allows very fast calculations of the radial space-charge forces [3].

The examples presented here deal with the evolution in free space of 100 A - 100 keV electron beams starting with two types of current densities :

$\rho(r) = \rho_0 \{1 - r^2/R^2_{max}\}$: parabolic distribution,

$\rho(r) = \rho'_0 \{1 + r^2/R^2_{max}\}$: hollow distribution,

R_{max} = 5 cm and no initial divergence.

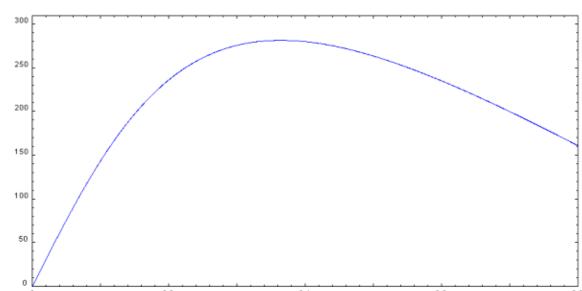

Figure 7: Evolution of the (R,R') unnormalized rms emittance value (mm.mrd) for the parabolic distribution.

Both distributions lead to very similar rms emittance evolutions (see fig. 7 for the parabolic distribution) but fig. 8 and 9 show that the space-charge nonlinearities bend the emittance curve in opposite directions : - towards the R axis for the parabolic distribution, - towards the R' axis for the hollow distribution.

MIXED SYSTEMS

Systems mixing several of these nonlinear forces have been optimized adjusting and combining opposite nonlinear effects to minimize the resulting nonlinearities.

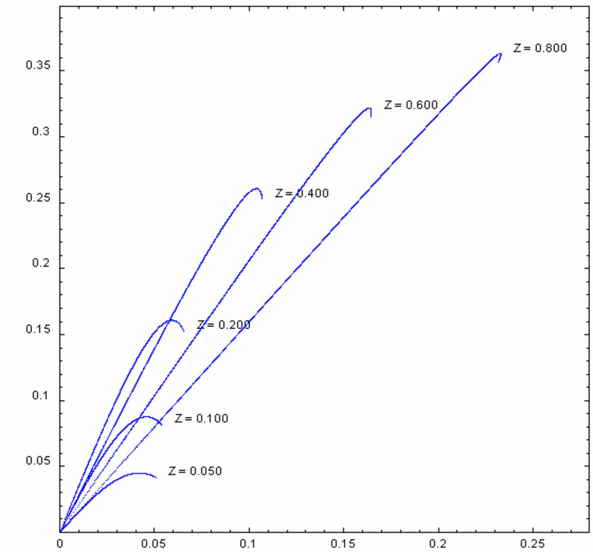

Figure 8: (R,R’) emittance plot at different positions along the propagation axis for the parabolic distribution.

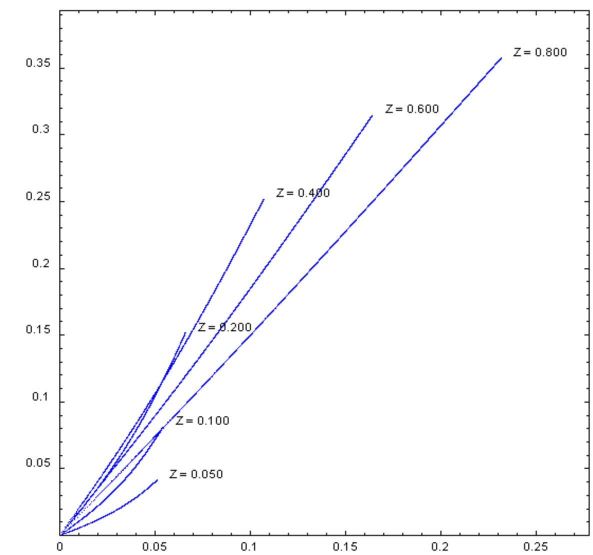

Figure 9: (R,R’) emittance plot at different positions along the propagation axis for the hollow distribution.

Diode with solenoid

High emittance growth such as the one shown on fig. 5 will be also observed when a solenoid located downstream the anode of a diode is used in similar conditions. To minimize the final emittance once the diode parameters are fixed, the solenoid parameters (radius, length and strength) and position with respect to the anode must be optimized to minimize the nonlinear effects resulting from both electric and magnetic fields.

Fig. 10 gives an example for the diode parameters used previously. The optimization process on the solenoid parameters leads to a short solenoid (2 cm long) centred on the anode (z = 9 cm) in order to have a good overlap of the main electric and magnetic fields nonlinear zones. The solenoid radius (14 cm) and excitation current (300 A, 5 turns) have been adjusted to minimize the emittance growth keeping an efficient beam focalisation.

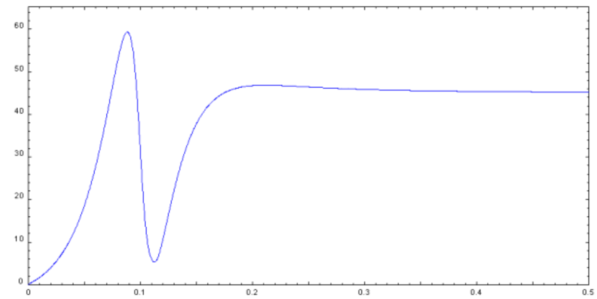

Figure 10: Evolution of the (R,R’) unnormalized rms emittance value (mm.mrd) along the diode and solenoid.

Diode with solenoid and space charge

The space-charge nonlinear effects are important at low energy, i.e. in the cathode-anode area of the diode. Looking to fig. 8 and 9 with respect to fig. 3 shows that the addition of the space-charge and electric fields in this region leads to - strong nonlinear effects in the case of parabolic-type distributions, - reduced effects in the case of hollow distributions. A greater emission density at the cathode edge is then favourable to minimize the emittance growth. This is demonstrated on fig. 11 and 12 plotted for a 1 A electron beam evolving in the diode with solenoid studied previously. Calculations with the same parameters show that the ratio of the emittances with and without current at z = 50 cm are 1.18, 3.18 and 0.35 for uniform, parabolic and hollow density profiles respectively.

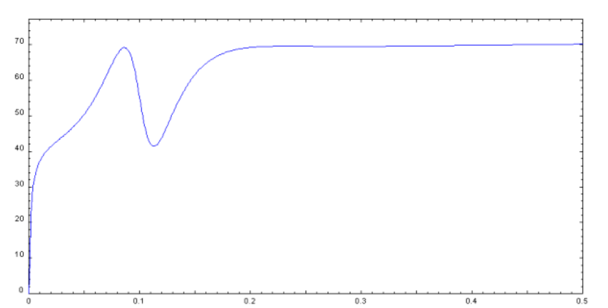

Figure 11: (R,R’) unnormalized rms emittance (mm.mrd) f(z) (m), diode with solenoid, 1 A beam, parabolic profile.

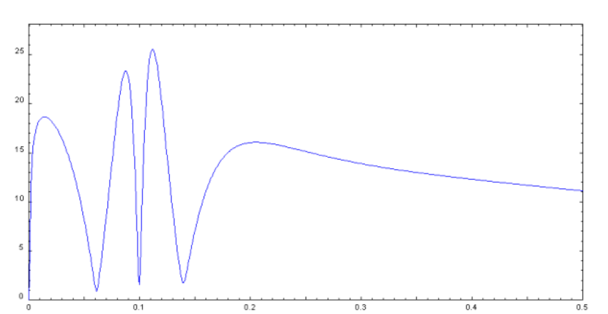

Figure 12: (R,R’) unnormalized rms emittance (mm.mrd) f(z) (m), diode with solenoid, 1 A beam, hollow profile.

REFERENCES

[1] E. Durand, Electrostatique, Masson et Cie, 1966.
[2] E. Durand, Magnétostatique, Masson et Cie, 1968.
[3] K.R. Crandall, “A numerical experiment on space-charge effects”, LINAC’66 proc., 1966, p. 233.