# Investigation on Relaxations in Electron Beams

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*Abstract*

The achievement of high density very-low energy spread electron beams requires a deep knowledge of this topic. For this purpose longitudinal and transverse beam relaxations are studied for two different sources, a thermo- and a photo-cathode. As a result a plasma parameter greater than 1 has been measured, that may potentially increase the efficiency of the electron cooling technique.

## I. INTRODUCTION

Since very-low energy spread provides a higher measurement accuracy and a substantially beam performance improvement, it is the main goal in several research areas.

If the energy broadening at the source is equal to $\Delta E_{\parallel 0}$, neglecting the interactions between electrons, the relation between $\Delta E_{\parallel}$ in the beam rest frame and the kinetic energy $W$ results in:

$$\Delta E_{\parallel} = \Delta E_{\parallel 0}^{2} / 4W \qquad (1)$$

The charged particle interactions contribute to two effects [1, 2]: the energy transfer from transverse to longitudinal components (Boersch effect), and the relaxation in the longitudinal component. Both could be adequately compensated.

The transverse-longitudinal relaxation can be damped using an axial magnetic field. The magnetic field intensity depends on the condition that the Larmor radius $\rho$, experienced by the electrons in the magnetic field, has to be less than the minimum inter-particle distance $r_{min}$. Two regime have to be distinguished: low densities $n_e$ with energy spread $\Delta E$, in which the inter-particle distance is $r_{min} \sim e^2/\Delta E$, and high densities, in which $r_{min} \sim (4\pi n_e/3)^{-1/3}$. When the applied magnetic field satisfies both the conditions, the energy transfer from transverse component to the longitudinal one is suppressed.

On the other hand due to the longitudinal relaxation, neglecting the interaction between transverse and longitudinal degrees of freedom , the equation (1) becomes:

$$\Delta E_{\parallel} = \Delta E_{\parallel 0}^{2}/4W + C\, e^2/n^{1/3} \qquad (2)$$

where the parameter $C$ depends on the accelerating structure.

In such a case with adequate slow acceleration the longitudinal energy spread $\Delta E_{\parallel}$ is maintained by plasma oscillations.

If $\lambda$ is the ratio between the plasma oscillation period and the relaxation time in the beam; then

$$\lambda = (1/\omega_0\, \Delta E_{\parallel})(d\Delta E_{\parallel}/dt) \qquad (3)$$

For value of $\lambda \ll 1$, the acceleration is called adiabatic respect to the oscillations and as a result the $C$ value in (2) decreases.

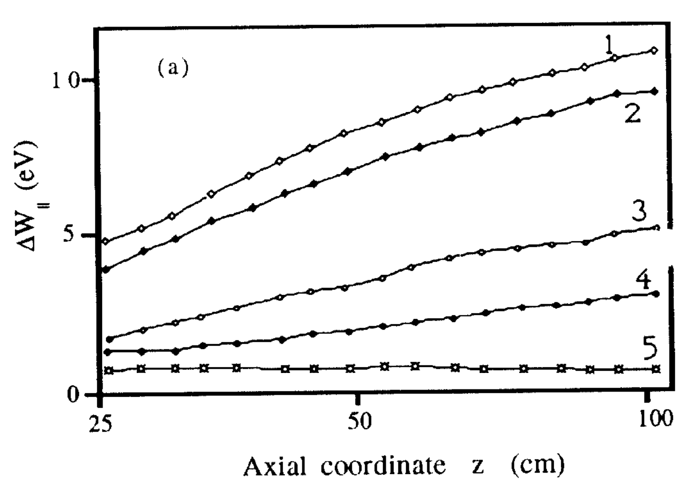
## II. APPARATUS AND RESULTS

*a) the apparatus*

The electron sources, a BaO thermocathode and a GaAs photocathode, the latter activated in NEA condition [3] and illuminated by a 450 mW maximum power single-mode [4] Ti:$Al_2O_3$ tunable within 750-900 nm, are placed in a Pierce diode at high extraction potential (2 mm of gap between anode and cathode). The continuous electron beams out of the gun enter the adiabatic acceleration section of five 10 mm radius pipes, then they travel along a drift section 1.8 m long [2]. A movable retarding potential analyzer [5] measures the beam energy spread with a 8 meV resolution.

*b) transverse-longitudinal relaxation*

The energy analyzer allows accurate measurements along the longitudinal direction. The relationship between the energy spread $\Delta W_{\parallel}$, measured by the analyzer, and the longitudinal distance $z$ is illustrated in fig.1 (a) and (b). The electrons, extracted from the thermocathode and rapidly accelerated to 470 eV, generate a beam current ranging from 0.1 to 9.0 mA. The comparison is carried out at 1 and 3 kG magnetic fields.

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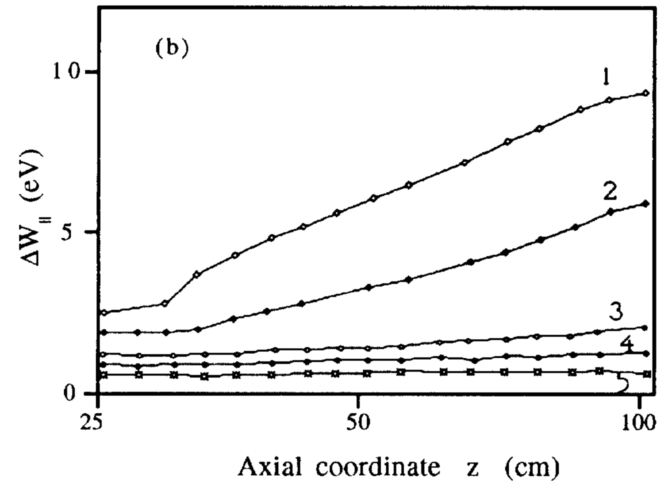


*Fig. 1*

Energy spread $\Delta W_{\|}$ for the oxide thermocathode, versus the longitudinal coordinate $z$ at various beam currents: *1*- 9.0 mA, *2*- 6.4 mA, *3*- 3.2 mA, *4*- 1.6 mA, *5*- 100 μA and for different values of magnetic field: *a)* $B$=1 kG, *b)* $B$=3 kG. In all cases is $W$=470 eV.

It is evident that the stronger the magnetic field the higher the damping of the transverse-longitudinal relaxation. Actually at 1 kG $\Delta W_{\|}$ remains unchanged only for the 100 μA current level, instead at 3 kG it does not change for current levels up to 3.2 mA.

In fig.2 the energy spreads are compared for the two different sources versus the current density $J$. For $J$->0, when any contribution due to relaxation is negligible, the energy spread recorded for the photocathode is lower.

While increasing current the transverse-longitudinal relaxation occurs and the benefit provided by photocathode is fully lost.

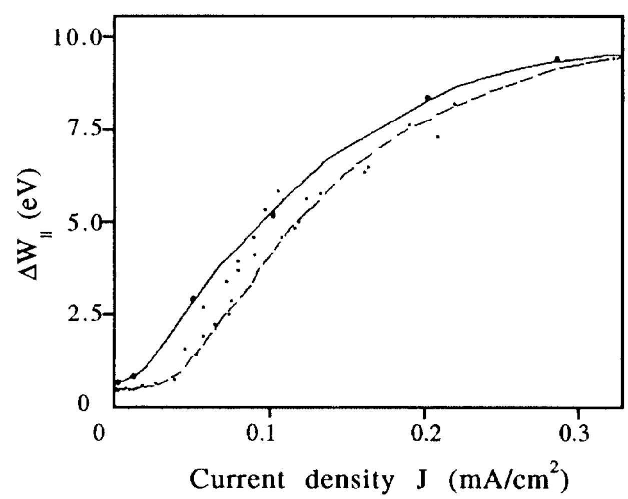


*Fig. 2*

Energy spread $\Delta W$ versus beam current density for (+) thermo- and (•) photo-cathode at 1 kG magnetic field for fast acceleration.

*c) longitudinal-longitudinal relaxation and adiabatic acceleration*

In fig.3 the measurement of the time taken by the electron beams to develop the relaxation is reported. Herewith it is shown the energy spread $\Delta E_{\|}$ versus the flight time, both value are normalized to the average electrostatic energy and the plasma period respectively.

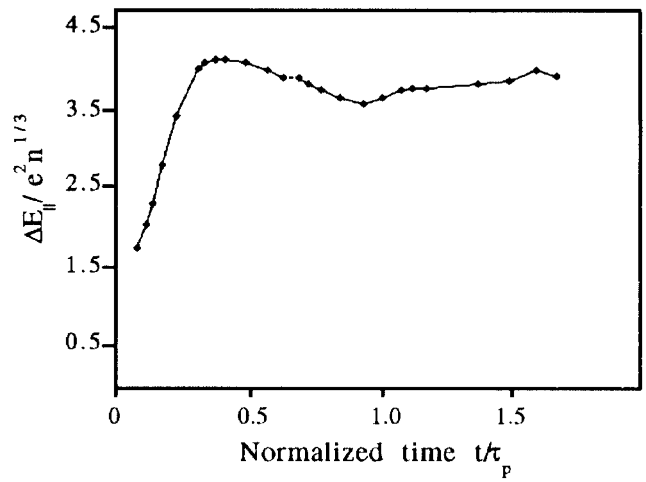


*Fig. 3*

Experimental trend of normalized longitudinal electron energy spread $\Delta E_{\|}$versus time after a fast acceleration for the oxide thermocathode; $I$=300 μA, $W$=800 eV, $n$=3.73·10$^7$ cm$^{-3}$, $B$=3 kG.

This measurement confirms the assumption of the plasma period like relaxation time. The differences on the energy spread between fast and adiabatic acceleration is demonstrated in fig.4. The initial difference at the adiabatic section end is due to the longitudinal-longitudinal relaxation. Then along the $z$ axis the beam experiences the transverse-longitudinal one,

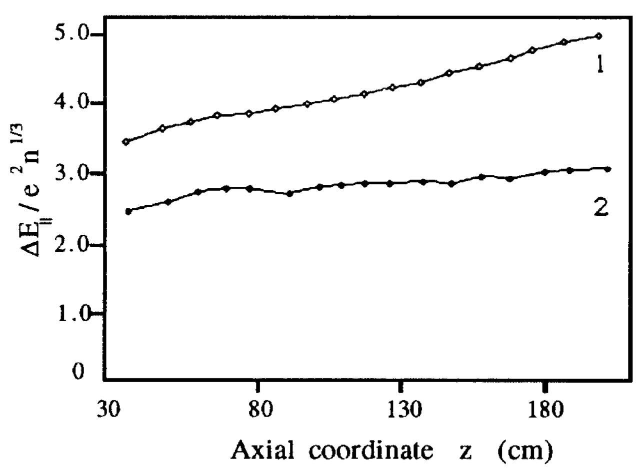


*Fig. 4*

Normalized energy spread $\Delta E_{\|}/e^2n^{1/3}$ for the thermocathode versus axial $z$ coordinate after (1) fast and (2) adiabatic acceleration; $W$=470 eV, $I$=200 μA.

resulting in a further increase of the spread. This latter can be only compensated by a stronger magnetic field.

Assembling a photocathode and an adiabatic acceleration better performances should be obtained.

### *d) Plasma parameter*

Considering the electron beam as a one-component plasma confined by the focusing forces of the accelerator device, its macroscopic behavior may be described by the plasma parameter $\Gamma$ (ratio between interparticle Coulomb energy and average kinetic energy). To measure $\Gamma_{\parallel}$ we need to know the particle density $n$, computable by the current measured in the collector, and $\Delta E_{\parallel}$ in the rest frame of the beam computable by the equation (1). In fig.5 is reported the $\Gamma_{\parallel}$ parameter for fast and adiabatic acceleration [6].

Only with a photocathode in an adiabatic acceleration structure is possible to reach a $\Gamma_{\parallel}$ values greater than 1, that is the first experimental evidence for an electron beam.

Superimposing this cold electron beam on an ion beams, it should be possible to obtain much colder ion beams.

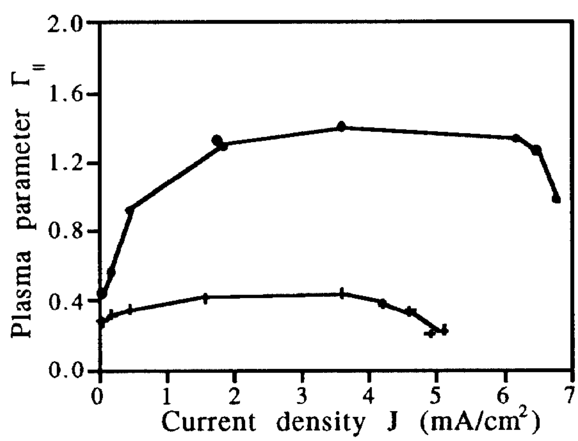


*Fig. 5*
Plasma parameter as a function of current densities for (+) fast and (•) adiabatic acceleration with $B$=3 kG and $W$=900 eV.

Fig.6 shows the behavior for fast and adiabatic acceleration of beams from the activated GaAs. At low densities the $\Delta W_{\parallel}$ is lower for the adiabatic case, while increasing the current the Boersch effect is dominating. Then the adiabatic acceleration seems disadvantageous for high current beams, unless the magnetic field is adequately strong.

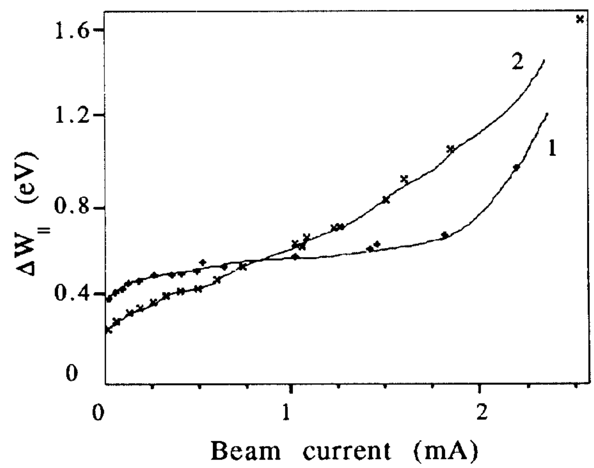


*Fig. 6*
Longitudinal energy spread $\Delta W_{\parallel}$ for the photocathode versus collector current $I$ at $W$=900 eV and $B$=4 kG: *1*- Fast acceleration 2- Adiabatic acceleration.

## III. CONCLUSIONS

This paper has examined the differences between a thermo- and a photo-cathode in fast and adiabatic acceleration cases. The best performance of a continuous electron beams is allowed by a photoemission source, which provides a 'cold' beam, an adequately magnetic field, which counteracts the transverse-longitudinal energy transfer, and an adiabatic acceleration structure, which damps the longitudinal-longitudinal relaxation. The maximum value of $\Gamma_{\parallel}$ reached is an important step towards the improvement of electron cooling technique and perhaps some hopes for ion beam crystallization.

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