FREE ELECTRON LASER TRIGGERED PHOTO-CATHODE

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Abstract

The possibility of realizing a FEL triggered photocathode has been proposed long time ago and the advantages have been pointed out. In these devices the FEL can be exploited to extract electrons from a photocathode to provide a high quality e-beam. The device becomes even more appealing if photo-thermoioinic cathodes can be exploited in two different phases. In the first the electrons are extracted from the cathode working as thermoionic and are used to drive a FEL oscillator, the FEL light is then used to flash the cathode which operates as a photo thermal assisted device. We comment on the possibility of using FEL triggered photocathodes to produce high quality e-beams for SASE or oscillator FEL devices. The use of the same e-beam driving the photocathode and the FEL makes the system naturally free of any synchronization problem arising when an external laser is used. Examples of interplay between the generation of electron and optical bursts are also investigated.

INTRODUCTION

In previous investigations it has been shown that FEL radiation can be exploited to trigger a photocathode gun [1], [2]. In this paper an extension to an "hybrid device" has been considered: in such a device, sketched in Fig. 1,2 a thermoionic gun produces an e-beam driving a FEL oscillator, the FEL radiation can be backward sent to illuminate the thermoionic cathode in order to exploit a different operating regime, i.e., a thermally assisted photoemission. Such a feedback mechanism, with a proper choice of the parameters, can enhance the e-beam brightness despite a modest increase of the transverse emittance.

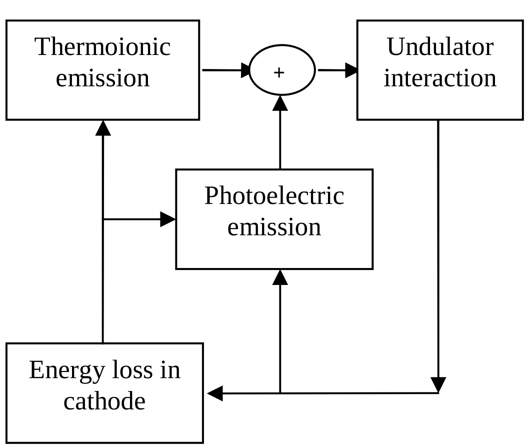

Fig. 1: Block diagram of "hybrid FEL oscillator".

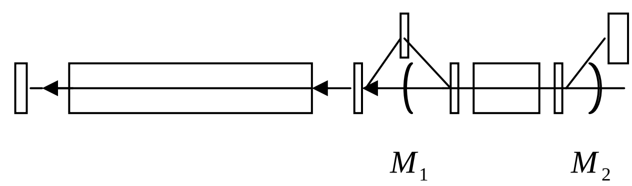

Fig.2: Layout of the "hybrid FEL oscillator".

In this paper we will consider a thermal dispenser cathode [3], with good photoelectric quantum efficiency, initially operating in the thermoionic mode and heated at a sufficient temperature in order to have enough e-beam current to allow FEL operation, radiation is then feed back to the cathode to switch it on the photo-assisted mode.

THEORETICAL MODEL

Under a number of assumptions and proper approximations that will be explained in the following, a semi-analytical model has been developed to take into account the interplay among the oscillator intra-cavity radiation growth, the temperature rise due the photonic incident energy loss in the cathode material and the electron current extracted. It has already been shown that the round-trip evolution of a FEL oscillator can be written as [4]:

$$I_n = I_0 \frac{[(1-\eta_{cl})(1+G)]^n}{1+\frac{I_0}{I_E}[[(1-\eta_{cl})(1+G)]^n - 1]} \qquad (1)$$

where n is the round trip number, G the maximum small signal gain, η_{cl} the total cavity losses, I_0 the initial seed and I_E the intra-cavity equilibrium intensity given by

$$I_E = \left(\sqrt{2}+1\right)\left(\sqrt{\frac{1-\eta_{cl}}{\eta_{cl}}G} - 1\right)\frac{1}{2Ng_0}P_e \qquad (2)$$

with N being the number of undulator periods, g_0 the small gain coefficient and P_e the e-beam power.

In the previous relations (1) and (2), the quantities I_0, g_0, G, P_e are no longer constant but, due to the feed-back mechanism, they are updated at each round trip.

The temperature rise due to the photonic incident energy loss in the cathode can be evaluated using the Anisimov heat equations [5], [6] which relate the electron to the lattice temperature. As suggested in [3], for time scale characteristic of laser pulse in the range 1ps-1ns, a steady state approximation of the Anisimov equation can be considered, which implies that the electron and lattice temperature are equal. Moreover, under the assumption of a laser pulse with a uniform spatial profile and a constant power of duration τ (microbunch duration) [7], at a power level such that neither melting nor vaporization occure, and by considering the heat to be generated at the surface of the cathode, we get:

$$\Delta T = \frac{(1-\eta-R)I_\lambda \tau}{\sqrt{2\kappa\rho c_v \tau}} \quad (3)$$

where η is the photoelectric quantum efficiency, κ, ρ, c_v are the thermal conductivity, the density and the specific heat of the cathode material respectively, R the cathode reflectance, τ the laser micro-pulse duration, I_λ the power laser density to the cathode.

The electron current density extracted from the cathode, using the Richardson approximation, can be obtained as a sum of 2 contributions: one proportional to the laser intensity, the other to the Richardson-Laue-Dushmann current density for thermoionic emission [3]:

$$J = (1-R)\left(\frac{e}{h\nu}\right)I_\lambda\left(\frac{U((h\nu-\phi)/kT)}{U(\mu/kT)}\right) + J_{RLD} \quad (4)$$

$$J_{RLD} = AT^2 e^{-\phi/kT} \quad (5)$$

where A is the Richardson constant, R the cathode reflectance, $h\nu$ the incident photon energy, k the Boltzmann constant, T the electrons temperature, μ the chemical potential, $\phi = \Phi - \sqrt{4QF}$ the barrier height, Φ the cathode work function, $\sqrt{4QF}$ the Schottky barrier lowering due to the image charge Q , F the product of the electric field gradient between cathode and anode and the electron charge and finally U is the Fowler-DuBridge function [8], [9].

It may be argued that since the cathode is operated as thermoionic and photocathode there is a detrimental effect due to the increase of beam emittance (both transverse and longitudinal). The emittance increase can be estimated following the recent analysis by Bazarov and Sinclair [10]. In their scaling law the transverse emittance is related to the extracted charge and bunch length :

$$\varepsilon\,[\text{mm mrad}] = q\,[\text{nC}]\cdot\left(0.73 + \frac{0.15}{\sigma_z^{2.3}[mm]}\right) \quad (6)$$

where q is the photoelectric extracted charge and σ_z is the length of the bunch.

We can estimate the amount of emittance increase by relating it to the illuminating power. An example of the relevant behaviour is given in Fig. 3.

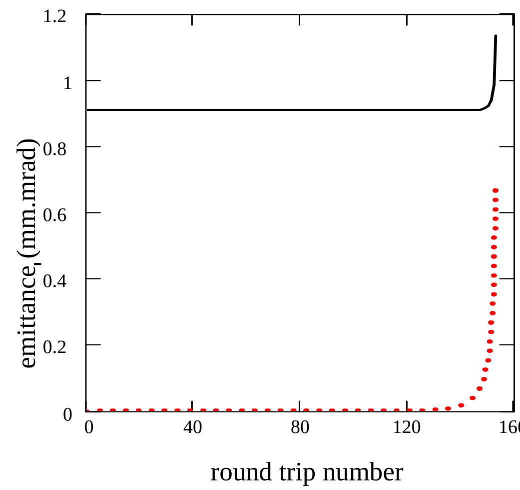

Fig.3: Emittance increase vs. round trip number (in red the photoelectric contribution, see Eq. 6, in black the total emittance) [mm mrad].

It is evident that with increasing number of reflections the emittance grows (we have assumed quadratic composition for the different emittance contributions) but the increase of current is larger and the net effect is an increase of the e-beam brightness. We must however not exceed the reflections to avoid effects of power overloading which may create a too large emittance degradation as shown in Fig. 4. It may also be argued that the Bazarov-Sinclair scaling holds for an optimized system and therefore the previous estimation may be optimistic.

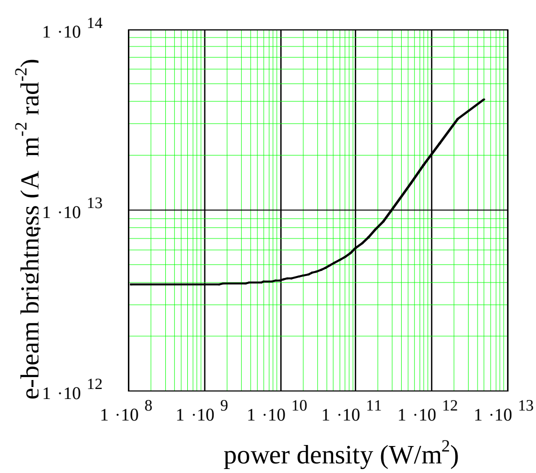

Fig. 4: e-beam brightness [A m^{-2} rad^{-2}] vs. power density [W m^{-2}]

RESULTS AND DISCUSSION

A preliminary analysis of the device has been developed using the parameters listed in Table 1 and 2

Table 1: FEL oscillator

λ	laser wavelength	500 nm
λ_u	undulator wavelength	2.8 cm
N	number of undulator periods	100
γ	e-beam energy	305.8
σ_ε	relative energy spread	10^{-3}
r	e-beam radius	$8.9\ 10^{-3}$ m
I_0	Input seed	1 W/cm ^{2}
τ	e-beam micropulse duration	3 ps
τ_M	e-beam macropulse duration	10 μs
n	round trip number	153
δ	distance between RF gun and mirror M_1 (see Fig. 2)	20 m
L_c	resonator cavity length	10 m
η_{cl}	total cavity losses	4%
T_1	mirror M_1 transmissivity	2%

Table 2: Dispenser cathode characteristics

Sc_2O_3 in matrix of W		
Φ_w	work function	1.8 eV
ϕ	effective barrier height	1.68 eV
d	inter-electrode distance	1 cm
κ	thermal conductivity	1.78 W/cm°K
ρ	density	19.3 g/cm ^{3}
c_v	specific heat	0.13 J/g°K
T_{in}	temperature operation before first illumination	1300 °K

The example we have considered is a FEL oscillator in which the distance between the cathode and the first semitransparent mirror M_1 (see Fig. 2) is 2 times the length L_c of the resonator cavity. The system is designed in such a way that for the first 3 round trips the intra-cavity radiation grows according to the Eq. 1 with constant parameters (I_0 , g_0, G , P_e), then Eqs. 1, 2, 3, 4 and 5 are fully coupled.

In our example we have considered 153 round trips which ensure, as already remarked

- Increase of the bunch current.
- Increase of the e-beam brightness despite a modest increase of the transverse emittance (this last point deserves however a dedicate analysis including the contributions from the longitudinal and transverse shapes of the optical bunch).

In Fig. 5, 6 and 7 the time evolution of cathode temperature, e-beam current density and laser intensity are shown respectively.

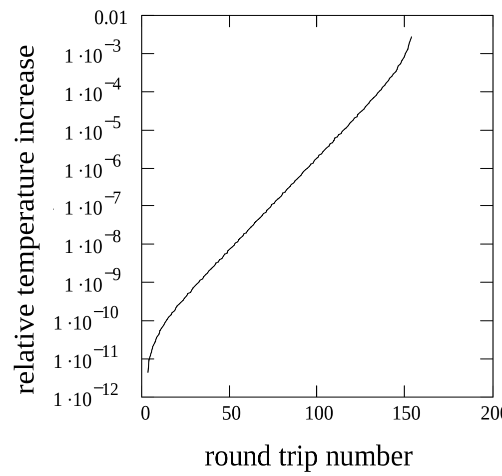

Fig. 5: Relative temperature increase vs. round trip number.

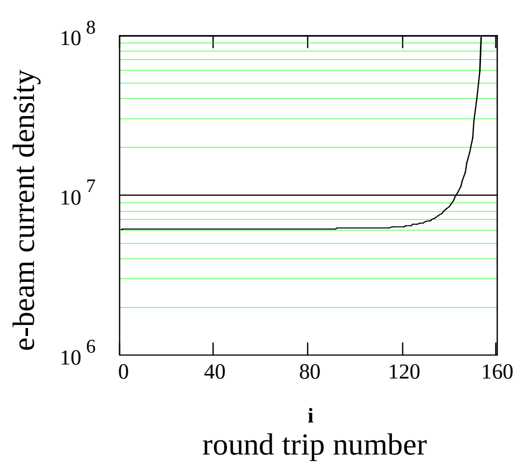

Fig. 6: E-beam current density [A m $^{-2}$] vs. round trip number.

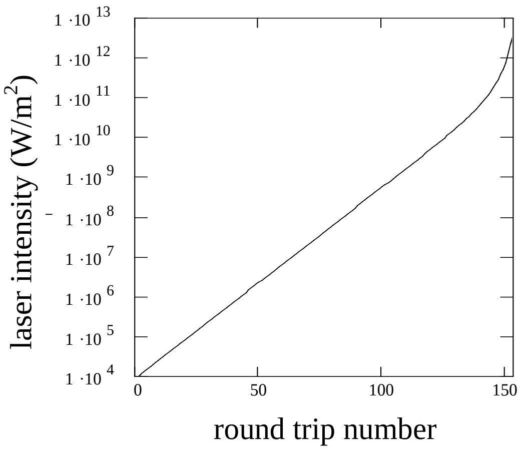

Fig. 7: Laser intensity [W m^{-2}] vs. round trip number.

CONCLUSIONS

A different possibility has been discussed in a previous paper [11] in which a hybrid SASE FEL has been considered: the radiation inside the undulator may be collected with a mirror (if we consider radiation in the visible) and sent back to the cathode. This has not a feed back on the radiation and it is just an external passive device. We must underline that for this device the radiation grows from the noise and the optical spectrum may be dominated by spikes and energy fluctuations, thus inducing dangerous effects which may strongly affect the quality of the e-beam itself. On the contrary, the use of the resonator cavity, acting as an active feed back on the optical field, may eliminate all the problems due to the shot noise, and the length of the optical pulse can also be easily controlled as well as other problems due to the transverse distribution.

It is worth noting that the technique we have considered can be exploited for higher harmonics of the radiation. It is indeed well known that along with the fundamental higher order harmonics are generated in the optical cavity. The harmonic power is not stored in the cavity but it is emitted shot after shot. The harmonic radiation too can be exploited to irradiate the cathode. This different operation will be more deeply examined in a forthcoming investigation.

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