TOWARDS A SELF SUSTAINED FREE ELECTRON LASER DEVICE

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Abstract

We explore the possibility of using free-electron laser (FEL) triggered cathodes to produce high quality e-beams. We propose a scheme which foresees cathodes operating either as thermionic and photo-cathodes, which can be exploited in devices using the same e-beam to drive the laser and the cathode. We discuss different mode of operation, in particular we consider oscillator FELs, in which the light from higher order harmonics, generated in the oscillator cavity, is used to light the cathode. The dynamics of the system is explored along with the technical solutions, necessary for the stability of the system. 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. The device is a kind of regenerative amplifier in which the growth of the optical power can be controlled by using a proper detuning or misalignment of the optical cavity.

INTRODUCTION

In previous investigations it has been shown that the FEL radiation can be exploited to trigger a photocathode gun [1], [2]. In a Self Sustained FEL device [3] a thermionic gun produces an e-beam driving a FEL oscillator, the FEL radiation can be backward sent to illuminate the thermionic cathode in order to exploit a different operation 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. In this paper, as sketched in Fig. 1, an extension of this technique [3] to higher harmonics of the radiation has been considered. It is 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 is backward sent to irradiate the cathode.

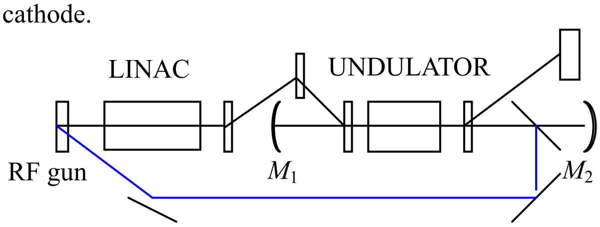

Figure 1: Layout of a self sustained FEL device.

The difficulties in the extraction of the UV radiation can be overcome by using a proper optical system (simply depicted in Fig. 1) which includes beam splitter and grating. Such an optical system will be reported in a forthcoming paper.

SELF-CONSISTENT MODEL

A semi-analytical model has been developed to take into account the interplay among the oscillator intra-cavity radiation growth, the higher harmonics non linear generation, the temperature rise due to the photonic incident energy loss in the cathode material and the electron current extracted. To this aim, we remind that in an oscillator the intra-cavity radiation grows according to the equation [4]

$$P_r = P_0 \frac{[(1-\eta_{cl})(1+G)]^r}{1+\frac{P_0}{P_e}[[(1-\eta_{cl})(1+G)]^r-1]} \tag{1}$$

where r is the round trip number, G is the maximum small signal gain, η_{cl} is the total cavity loss, P_0 is the input seed and P_e is the intra-cavity equilibrium intensity given by

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

with N being the number of undulator periods, g_0 the small gain coefficient, and P_E the e-beam power. The n-th harmonic evolution can be reproduced by an equation analogous to Eq. 1 [5]

$$P_n(r) = \Pi_{n,0} \frac{[(1-\eta_{cl})(1+G)]^{nr}}{1+\frac{\Pi_{n,0}}{P_n^*}[[(1-\eta_{cl})(1+G)]^{nr}-1]}$$

$$\Pi_{n,0} = (n-1)!(n-2)\sqrt{\frac{n-1}{2}}\cdot g_{0,n}\frac{P_E}{2N}\left(\frac{P_0}{I_s}\right)^n \tag{3}$$

$$P_n^* = \frac{1}{4}\frac{\sqrt{n}}{n^3}\sqrt{\frac{n-1}{2}}\cdot g_{0,n}\frac{P_E}{2N}$$

where I_s is the fundamental harmonic saturation intensity, and $g_{0,n}$ is the n-th harmonic small signal gain.

The temperature rise due to the photonic incident energy loss in the cathode can be evaluated using a steady state approximation of the Anisimov heat equations [6], [7], [8]. Moreover, by assuming a n-th harmonic radiation with a uniform spatial profile and a constant power of duration τ (microbunch duration), and by considering the heat to be generated at the surface of the cathode, we get

$$\Delta T = \frac{(1-Q_e-R)I_\lambda \tau}{\sqrt{2\kappa\rho c_v \tau}} \tag{4}$$

where Q_e 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 and I_λ are the FEL micro-pulse duration and the n-th harmonic power density to the cathode.

Under the assumption of the Richardson approximation (i.e., electrons transmitted, with unit probability, if its energy exceeds the surface barrier height), the electron current density can be obtained as a sum of two contributions. These contributions are proportional to the the n-th harmonic power density to the cathode and to the Richardson-Laue-Dushmann current density for thermoionic emission [8], namely,

$$J = (1-R)\left(\frac{e}{h\nu}\right) I_\lambda \left(\frac{U((h\nu-\phi)/kT)}{U(\mu/kT)}\right) + J_{RLD} \quad (5)$$

$$J_{RLD} = AT^2 e^{-\phi/kT} \quad (6)$$

with A being the Richardson constant, R the cathode reflectance, $h\nu$ the incident photon energy, k the Boltzmann constant, T the electron temperature, $\phi = \Phi - \sqrt{4QF}$ 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, μ the chemical potential (Fermi level) and finally the function U appearing in Eq. 5 is the Fowler-DuBridge function [9], [10].

RESULTS AND DISCUSSION

We will consider now a specific example based on the layout of Fig. 1 and on the parameters of Tables 1 and 2. Moreover we will consider a thermal dispenser cathode, initially operated in thermionic mode and heated at a sufficient temperature in order to have enough e-beam current to allow the FEL oscillator operation. Radiation is then fed back to the cathode to switch it on a thermally photo-assisted mode. In the example only the 3rd harmonic is backward sent to the cathode. The harmonic power emitted shot after shot is extracted from the optical cavity by using 3 reflections so that only a small fraction η_3 of the light irradiates the cathode. In Fig. 2 the intra-cavity round trip evolution of the fundamental (600nm) and the 3rd harmonic (200nm), with η3=6%, are shown.

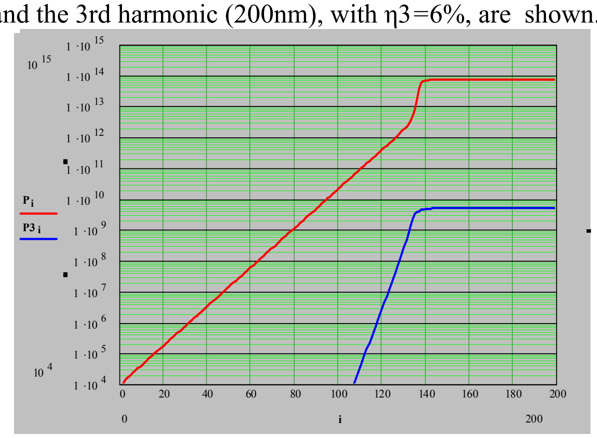

Figure 2: The intra-cavity round trip evolution (W/m^2) of the fundamental (red) and the 3rd harmonic (bleu) at η_3=6%.

Table 1: Dispenser Cathode Characteristics

	Sc_2O_3 in matrix of W	
Φ	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	1500 °K

Table 2: FEL Oscillator

λ	Wavelength at fundamental	600 nm
λ_3	3rd harmonic wavelength	200 nm
λ_u	Undulator wavelength	2.8 cm
N	Number of undulator periods	100
γ	e-beam energy	306
σ_ε	Relative energy spread	10^{-3}
r	e-beam radius	8.9 10^{-3} m
P_0	Input seed	1 W/cm^2
τ	e-beam micropulse duration	3 ps
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%
η_3	Coupling coefficient of the 3rd harmonic on the cathode	0 ÷ 8%

Fig. 3 shows the behaviour of the same quantities with no feedback operation (η_3=0, standard FEL oscillator).

Analysis of Fig, 2 and 3 clearly shows the advantages of this technique:

- A faster growth of the radiation intensity of the fundamental and 3rd harmonic wavelength occurs: it means that the plateau is reached in a smaller number of round trips, so that a shortened e-beam macropulse duration can be used.
- An actual increase of the radiation intensity occurs.

As discussed in ref. [3], the emittance grows (due to the photo thermal assisted cathode regime) notwithstanding the increase of current being large enough to compensate for the negative effects of the increase of the emittance and yield a net increment of the e-beam brightness (see Fig. 4).

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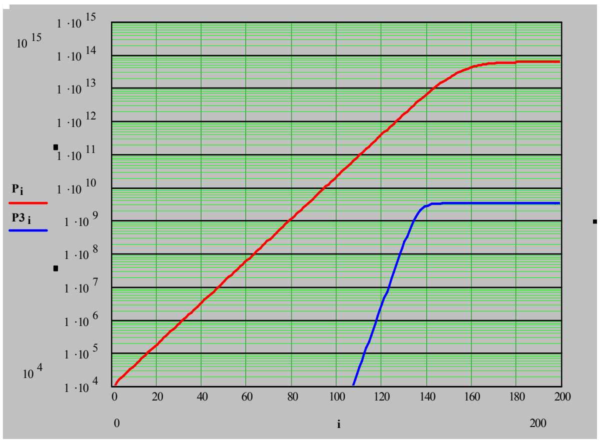

Figure 3: The intra-cavity round trip evolution (W/m^2) of the fundamental (red) and the 3rd harmonic (bleu) at η_3=0.

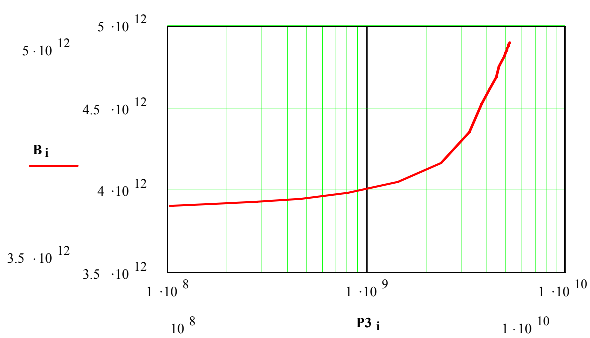

Figure 4: e-beam brightness (A m^{-2} rad^{-2}) vs. the illuminating power (W m^{-2}).

In Fig. 5 we have drawn the behaviour of the round trip number necessary to reach the saturation for different η_3 values. Finally in Fig. 6 the radiation intensity vs, η_3 is shown.

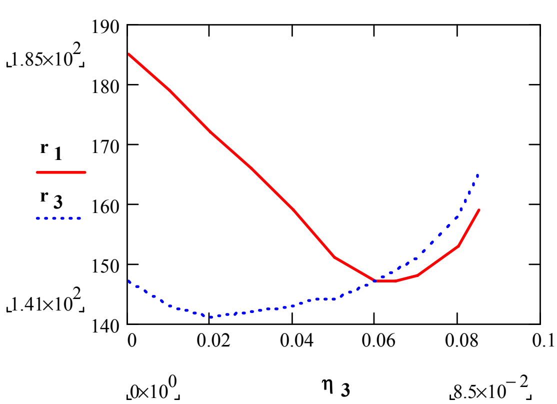

Figure 5: Round trip number needed to reach the saturation for the fundamental (r_1) and for the 3rd harmonic (r_3) vs. η_3.

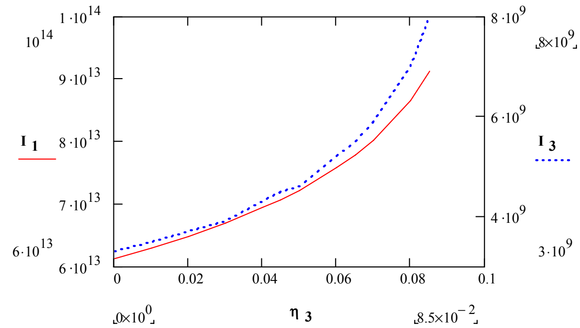

Figure 6: Power density (W/m^2) of the fundamental (I_1 solid line in red) and the 3rd harmonic (I_3 dotted line in bleu) vs. η_3.

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