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. 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.

Figure 1: Layout of a self sustained FEL device.

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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]

\[ P_r = P_0 \left[ \frac{1}{1 + P_0 \left[ \frac{N}{P_e} \right]^r} \right] \]

where \( r \) is the round trip number, \( G \) is the maximum small signal gain, \( \eta_d \) is the total cavity loss, \( P_0 \) is the input seed and \( P_e \) is the intra-cavity equilibrium intensity given by

\[ P_e = \left( \sqrt{2} + 1 \right) \frac{1}{2N \eta_d} P_0 \]

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]

\[ P_n(r) = P_{n,0} \frac{\left[ \frac{1}{1 - \eta_d} \frac{1}{(1 + G)^n} \right]}{1 + \left[ \frac{1}{1 - \eta_d} \frac{1}{(1 + G)^n} \right]} \]

\[ \Pi_{n,0} = (n - 1)!(n - 2) \left( \frac{n - 1}{2} \right)^2 g_{0,n} \frac{P_e}{2N} \left( \frac{P_0}{I_s} \right)^n \]

where \( I_s = \frac{n}{4} \frac{n - 1}{2} \frac{2N}{g_{0,n}} P_e \) 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 \( \tau \) (microbunch duration), and by considering the heat to be generated at the surface of the cathode, we get

\[ \Delta T = \frac{(1 - Q_e - R) \nu \kappa \rho c_v \tau}{\sqrt{2 \pi \kappa \rho c_v \tau}} \]

where \( Q_e \) is the photoelectric quantum efficiency, \( \kappa, \rho, c_v \) are the thermal conductivity, the density and the specific heat of the cathode material respectively, \( R \) the cathode
reflectance, \( \tau \) and \( I_\lambda \) 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 n-th harmonic power density to the cathode and to the Richardson-Laue-Dushman current density for thermoionic emission [8], namely,

\[
J = (1 - R) \left( \frac{e}{h \nu} \right) I_A \left( \frac{U(h \nu - \phi)/kT}{U(\mu/kT)} \right) + J_{RLD}
\]

(5)

\[
J_{RLD} = AT^2 e^{-\phi/kT}
\]

(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, \( \Phi \) 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, \( \mu \) 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 \( \eta_3 \) 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 \( \eta_3 = 6\% \), are shown.

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**Table 1: Dispenser Cathode Characteristics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Phi )</td>
<td>Work function</td>
</tr>
<tr>
<td>( \varphi )</td>
<td>Effective barrier height</td>
</tr>
<tr>
<td>( d )</td>
<td>Inter electrode distance</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Density</td>
</tr>
<tr>
<td>( c_v )</td>
<td>Specific heat</td>
</tr>
<tr>
<td>( T_{in} )</td>
<td>Temperature operation before first illumination</td>
</tr>
</tbody>
</table>

**Table 2: FEL Oscillator**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda )</td>
<td>Wavelength at fundamental</td>
</tr>
<tr>
<td>( \lambda_3 )</td>
<td>3rd harmonic wavelength</td>
</tr>
<tr>
<td>( \lambda_u )</td>
<td>Undulator wavelength</td>
</tr>
<tr>
<td>( N' )</td>
<td>Number of undulator periods</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>e-beam energy</td>
</tr>
<tr>
<td>( \sigma_c )</td>
<td>Relative energy spread</td>
</tr>
<tr>
<td>( r )</td>
<td>e-beam radius</td>
</tr>
<tr>
<td>( P_0 )</td>
<td>Input seed</td>
</tr>
<tr>
<td>( \tau )</td>
<td>e-beam micropulse duration</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Distance between RF gun and mirror ( M_1 ) (see Fig. 2)</td>
</tr>
<tr>
<td>( L_c )</td>
<td>Resonator cavity length</td>
</tr>
<tr>
<td>( \eta_{cl} )</td>
<td>Total cavity losses</td>
</tr>
<tr>
<td>( \eta_3 )</td>
<td>Coupling coefficient of the 3rd harmonic on the cathode</td>
</tr>
</tbody>
</table>

Fig. 3 shows the behaviour of the same quantities with no feedback operation \( (\eta_3=0, \text{standard FEL oscillator}) \).

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/m²) of the fundamental (red) and the 3rd harmonic (bleu) at \( \eta_3=0 \).

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 \( \eta_3 \) values. Finally in Fig. 6 the radiation intensity vs. \( \eta_3 \) 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. \( \eta_3 \).

Figure 6: Power density (W/m²) of the fundamental (I₁ solid line in red) and the 3rd harmonic (I₃ dotted line in bleu) vs. \( \eta_3 \).

REFERENCES