Invited Paper

The physics of and prospects for THz-Compact FELs

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Abstract: In this paper we review the physics of long wavelength Free Electron Lasers (FELs) driven by low-energy electron accelerators. We show how the waveguide operation can lead to new attracting features, like a wide gain bandwidth, a short resonator length, and the possibility of generating sub-picosecond radiation pulses in compact table-top devices. The short electron pulse duration associated with radio-frequency (RF) accelerators also gives rise to the so-called "coherent spontaneous emission", which greatly enhances the performance of this type of sources.

Keywords: Terahertz sources, Free electron lasers, Coherent synchrotron radiation

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1. Introduction

In the Far-InfraRed (FIR), Terahertz (THz) and mm-wave spectral regions, small size, FELs can be built at moderate cost, achieving at the same time excellent performance like wide range tunability and high peak brightness. In terms of the frequency of the emitted radiation, this region covers approximately the range from 100 *GHz* to 10 *THz*, where there are a variety of interesting effects to be studied in solid state physics and material science, as well as in biology, biomedicine, environmental sciences and art conservation, particularly for imaging and spectro-microscopy applications.

Due to the long wavelength of electromagnetic radiation in this spectral range, to limit the diffraction losses in the active medium, a waveguide operation is generally preferred. Such special boundary conditions are extremely interesting for the generation of terahertz and millimeter wave radiation, since the dispersion properties of the waveguide give rise to new kinematic and dynamic effects [1]. In cylindrical metallic waveguides the higher value of the phase velocity, with respect to the vacuum operation, shifts the FEL resonance to lower frequencies. A second low frequency resonance also appears, which in some cases may become a backward-wave. The group velocity, lower than the speed of light *c*, reduces the slippage length and allows millimeter wave operation even with short electron bunches such as that produced by RF accelerators.

Moreover, it has been shown [2] that a RF modulated electron beam passing through a magnetic undulator emits coherent radiation at harmonics of the RF with a phase which depends on the electron drift velocity. Treating the electron bunches as ensembles of particles, each with its energy and phase, the radiated field is calculated as a sum over the particle distribution in the phase space. At long wavelengths a proper correlation between the energy and phase distributions of the electrons in the bunch can be exploited to lock the radiated field in phase, resulting in a significant enhancement of the coherent emission [3]. In 2004 this led the first observation of enhanced coherent emission of terahertz radiation in a compact free electron laser [4].

The main results of two THz sources built at the ENEA Research Center, the Compact FEL operating in the range 90-150 *GHz* and the Compact Advanced Terahertz Source FEL-CATS operating between 0.4 and 0.7 *THz*, will also be recalled together with a glance into the future perspectives of further reducing the size and cost of these devices.

2. Basics of compact FEL design

The problem of energy transfer between a beam of relativistic electrons and a co-propagating wave can be easily addressed within the framework of classical electrodynamics [5]. It is known that the rate of energy exchange between flowing charges and a wave is given by the integration of the $\vec{J} \cdot \vec{E}$ product over the volume $V = \Sigma \cdot L$ of the region of space where the interaction occurs:

$$\Delta P = -\frac{1}{2}\int_V \Re\left(\vec{J} \cdot \vec{E}\right) dV \tag{1}$$

Here $\vec{J}$ is the electron current density, $\vec{E}$ is the electric field of a wave of the form $\vec{E} = \vec{E}(x, y)\exp[i(\omega t - kz)]$ and the interaction volume V is defined by a mode cross section Σ and an interaction length L along the direction of propagation z. It is clear from (1) that energy exchange can only occur between corresponding components of the electron current density and of the wave electric field. In general, the longitudinal component of the current density due to the drift motion of the electrons will not couple to an electromagnetic wave propagating in the free space, since the latter one has zero longitudinal electric field component. However, in a waveguide or in a suitable loaded structure like the Travelling Wave Tube (TWT), TM modes can be excited, which have a longitudinal component of the electric field. Cerenkov Free Electron Lasers (C-FEL) [6] and Orotrons, or grating FELs (G-FEL) [7], rely on this type of coupling scheme. On the other hand, in an undulator FEL (U-FEL) [4], electrons travel through a magnetic structure, called undulator, which provides a spatially periodic magnetic field along the direction of propagation (Fig.1).

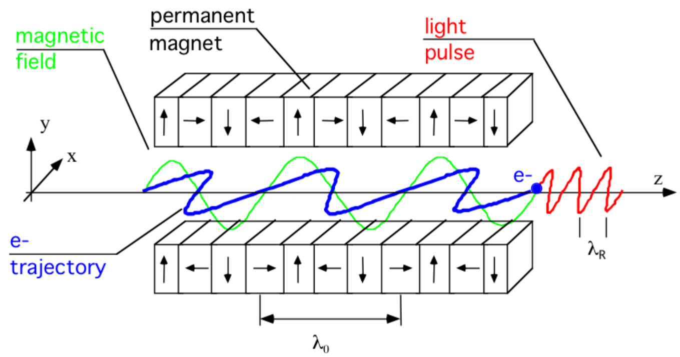

Fig. 1 Geometry of undulator radiation. Source: http://clio.lcp.u-psud.fr/clio_eng/FELrad.html.

Under the action of a purely sinusoidal undulator magnetic field $\vec{B} = B_0 \cos(k_u z)\hat{y}$, electrons undergo oscillations in the plane perpendicular to $\vec{B}$ with transverse velocity:

$$\vec{\beta}_T = \frac{\sqrt{2}K}{\gamma} \sin(k_u z)\hat{x} \tag{2}$$

and average electron drift velocity:

$$\beta_z = \sqrt{1 - \frac{1+K^2}{\gamma^2}} \tag{3}$$

where $k_u = 2\pi/\lambda_u$, λ_u is the undulator period, and $K = eB_0\lambda_u/\left(2\sqrt{2}\pi m_0 c^2\right)$ is the so called undulator parameter that determines the amplitude of the electron oscillations. The transverse motion of the electrons can therefore couple to the corresponding component of the electric field of the wave transferring energy into the radiation field. The amount of transferred energy and the efficiency of the process strongly depend on the relative phase between electron and wave.

By analysing the emission process in the frequency domain [2], in a first approximation, the volume integral (1) can be factorised in two terms, a form factor *F* given by the surface integral of the normalised electron density distribution over the cross section *Σ* of the mode, and a coupling integral over the interaction length *L*, which describes the beating between the electron motion and the wave:

$$C = \int_0^L \left\{ \exp\left[i\left(\frac{\omega}{c\beta_z} - k_e - k \right) z \right] \right\} dz = Le^{i\theta/2} \frac{\sin(\theta/2)}{\theta/2} \tag{4}$$

where ω and k are the frequency and wave vector of the wave respectively and k_e is the wave vector of the electron oscillations. $\theta = \left(\frac{\omega}{c\beta_z} - k_e - k \right) L$ is the so-called phase shift parameter, which is a function of frequency and plays a crucial role in all free electron devices.

In free space, if there is no transverse motion of the electrons, $k_e = 0$ and the velocity of the wave $\omega/\kappa=c$ will always be greater of the electron drift velocity $c\beta_z$. The integrand in (4) will be rapidly oscillating giving rise to a negligible amount of coupling. In a guided structure, synchronism can be achieved in absence of transverse motion if the phase velocity of the wave equals the electron velocity. However, synchronism can also be achieved in free space if the transverse motion provides a wave vector $k_e > 0$.

So far we have discussed the exchange of energy with an external wave. It can be shown that the field coefficients A_λ of the spontaneous emission from radiating charges can be calculated by an expression similar to (1), in which the external field is substituted by the orthonormal modes satisfying the boundary conditions of the medium [2]:

$$A_\lambda = -\frac{Z}{2}\int_V \Re\left(\vec{J}\cdot\vec{E}_\lambda\right)dV \tag{5}$$

where Z is the impedance of the medium.

Synchronism and therefore the resonant frequency of the emission process are defined by the condition $\theta(\omega)=0$, once the dispersion relation of the electromagnetic waves in the medium is known. The radiated power is proportional to the square module of (5) and, its dependence on frequency will show a narrow line-width with a line-shape function $\frac{sin^2(\theta/2)}{(\theta/2)^2}$.

Some insight in the various emission mechanisms of free electron devices can be gained by a graphical representation of the synchronism condition. In the plane $(k,\omega/c)$ the condition $\theta=0$ is represented by a straight line called "beam line"; the resonance of the emission process is given by the intersection of this line with the dispersion relation $\omega=\omega(k)$ of e.m. waves in the medium in which the interaction with electrons occurs. To get a deeper physical insight in this process we can discuss the U-FEL resonance condition in a rectangular waveguide. In this case the dispersion relations of the $TE_{0,1}$ and $TE_{1,1}$ modes in a rectangular waveguide are plotted in Fig. 2 together with the beam line and the light line of unity slope. The dispersion relation intercepts the ω/c axis at the cut-off frequency $\omega/c_{co}=\Gamma_{0,n}$. Due to the transverse oscillations of the electrons the beam line also intercepts the ω/c axis at $c\beta k_u$.

Depending on the value of the parameter k_u and of $\Gamma_{0,n}$, one can distinguish between the following three cases [1]:

$k_u < \Gamma_{0,n}/\beta_z$ - There are two distinct solutions corresponding to the two resonant frequencies

$$\frac{\omega_\pm}{c} = \beta_z\gamma_z^2 k_u\{1\pm\beta_z\Delta\} \qquad \text{with} \qquad \Delta = \left[1-\left(\frac{\Gamma_{0,n}}{\beta_z\gamma_z k_u}\right)^2\right]^{1/2}, \qquad 0\le\Delta\le 1 \tag{6}$$

The parameter Δ characterizes the downshift of the resonant frequencies with respect to the free space resonance $\frac{\omega_v}{c} = (1+\beta_z)\gamma_z^2 k_u$

$k_u = \Gamma_{0,n}/\beta_z$ - There is a degenerate solution (Δ=0) occurring when the beam line is tangent to the dispersion relation curve. This means that the group velocity of a propagating wave is equal to the electron drift velocity :

$$\beta_g \equiv \frac{\partial\omega/c}{\partial k} = \beta_z \qquad (7)$$

This is the so called «zero slippage» condition, which allows a wave packet to travel with optimum overlap with an electron bunch through the whole undulator length. In this case the resonant frequency for relativistic electrons approaches one-half the free space value.

$k_u < \Gamma_{0,n}/\beta_z\gamma_z$ - There are no real solutions of the resonance conditions. Electrons cannot radiate energy. This can be understood considering that the e.m. wave associated with the undulator is below cut-off in the electron rest frame and cannot propagate through the waveguide.

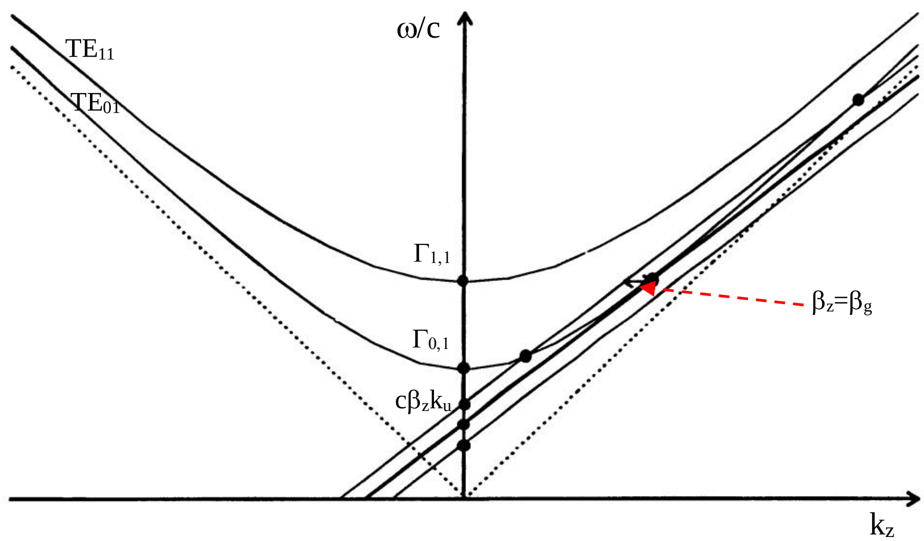

Fig. 2 Graphical representation of the waveguide dispersion relation and the FEL resonance condition (see text for details).

3. The gain mechanism

As discussed in the previous section, the rate of exchanging energy between electrons and a wave depends on the relative phase of the electron motion. For a continuous beam with a uniform distribution in phase of the electrons, the net energy transfer will be zero, and the spontaneous emission can be seen as arising from the statistical fluctuations in the number of particles. However, a wave co-propagating with the electron beam will induce a density modulation on the scale of the wavelength, which eventually results in coherent emission and amplification.

For a weakly perturbed electron motion, the gain can be calculated as the ratio of the electron energy loss $\Delta\gamma mc^2$ to the energy W_L transported by the wave during the interaction time. Following the analysis in [8], without entering the detail of the calculations, the well known expression of the FEL gain is obtained:

$$G = \pi \frac{\left(1+K^2\right)K^2}{\beta_g\left(\beta_z\gamma\right)^5} F \frac{L^3}{\Sigma} \frac{I}{I_0}\left(k+k_u\right) f\left(\theta\right) \tag{8}$$

where I and I_0 are the electron beam current and the Alfven current respectively, and $f(\theta)$ is the so-called gain line-shape function:

$$f(\theta) = \frac{d}{d\theta}\left[\frac{sin\left(\theta/2\right)}{\left(\theta/2\right)}\right]^2 \tag{9}$$

Unlike conventional lasers, the gain is therefore proportional to the derivative of the emission line shape function. This is a quite general feature of free electron generators of coherent radiation that is usually known as Madey theorem [9].

4. Coherent spontaneous emission

Utilising the physical model described in [2] it is possible to calculate the field amplitude of the coherent emission for a beam composed of an infinite train of electron bunches spaced at the RF period T_{RF}. Since the electron current density is periodic in time, it can be expanded in series of harmonics of the fundamental $\omega_{RF} = 2\pi/T_{RF}$. As a consequence radiation will be also emitted only at discrete frequencies which are harmonics of ω_{RF} and fall within the FEL resonance curve. The total radiated power is then calculated as:

$$P_{l,0,n} = \frac{\beta_{gl}}{2Z_0}\left|A_{l,0,n}\right|^2 \quad \text{where} \quad A_{l,0,n} = -\frac{Z_0}{\beta_{gl}} I_p \frac{C_l}{2} \frac{KL}{\sqrt{ab}} F \frac{1}{\beta\gamma} \frac{sin(\theta/2)}{\theta/2} ie^{i\frac{\theta}{2}} \tag{10}$$

where $Z_0=377\ \Omega$ is the free space impedance, β_{gl} is the normalized group velocity of the waveguide mode at the frequency $\omega l = 2\pi l/T_{RF}$ with wave vector $k_{0,n}$, C_l is the Fourier coefficient of the electron current density at the *l-th* harmonic, F is the form factor describing the overlapping between the e-beam transverse distribution and the waveguide mode, and a and b are the transverse waveguide dimensions. The factor $e^{i\theta/2}$ in (10) shows the dependence of the phase of the radiated field on the electron drift velocity, which is implicit in θ.

Expression (10) for the coherent radiated power from a modulated electron beam predicts a quadratic dependence on the electron current. This has been verified on the two sources built at ENEA Frascati, the Compact-FEL and the FEL-CATS, which will be described in greater details in the next sections. Spectral measurements of the coherent spontaneous emission from the Compact-FEL [10] show the striking feature of emission at discrete frequencies that are harmonics of the fundamental RF. A Fabry-Perot interferogram of the coherent spontaneous emission, taken with a resolution of 1 *GHz*, is shown in Fig.7. Two bands, typical of the FEL emission in a waveguide close to the zero-slippage condition, can be observed at the first interferometric order for values of the mirror gap between 1 and 2 *mm*. A line-structure clearly appears within these bands and is well resolved at the second interferometric order, showing a separation of 3 *GHz* between adjacent lines equal to the fundamental frequency driving the accelerator.

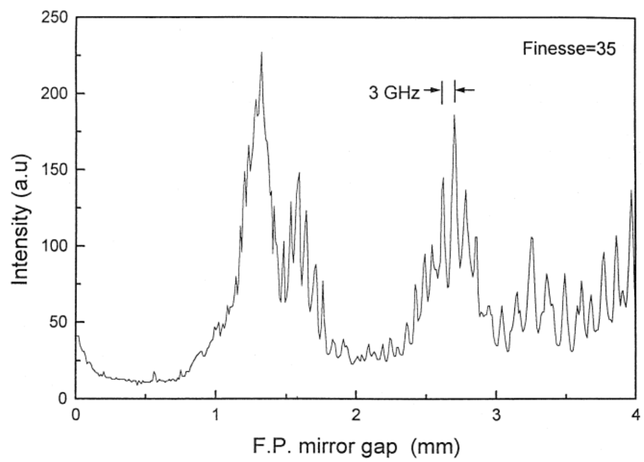

Fig. 3 Fabry-Perot interferogram of the Compact-FEL coherent spontaneous emission.

5. The ENEA THz Compact FEL

One of the critical issues of a long wavelength FEL, when driven by an RF accelerator, is the effect of «slippage», i.e. the lack of overlapping between electron bunches and wave packets as they travel through the undulator with different velocity. In free space the slippage length over the undulator length is $\delta = N\lambda$; at millimeter wavelengths it can be quite large causing a gain reduction and an increase of the threshold for oscillation. In a waveguide the slippage can be strongly reduced by controlling the group velocity of the excited mode, i.e. by varying the waveguide boundary conditions.

At the "zero slippage" condition stated in (7), which can be expressed as $\lambda_u \approx 2\frac{\gamma}{\sqrt{1+K^2}}b$ for the fundamental $TE_{0,1}$ mode in a planar or rectangular waveguide, additional features appear which make the waveguide operation particularly attractive:

- The group velocity of wave-packets gets close to the e-beam velocity allows operation with short electron bunches;

- The merging of the two FEL resonances results in a broad band gain curve with an half-width of the order of $1/\sqrt{N}$;

- The intersection of the $TE_{0,1}$ mode at grazing incidence results in the operation on a single transverse mode even in an overmoded waveguide.

The Compact-FEL built at ENEA-Frascati employs a permanent magnet undulator with 8 periods of 2.5 *cm*. Zero slippage is reached at a wavelength of 2.6 *mm* (120 *GHz*) using 2.3 *MeV* electron energy and a waveguide gap of 4.32 *mm*. The resonator is composed of a 30 *cm* long WR42 rectangular waveguide placed within the undulator gap and terminated at both end by wire grid mirrors used as electron transparent mirrors (ETM). The upstream mirror has 80 μm wire spacing with a reflectivity > 99% at wavelengths longer than 2 *mm*. It can be translated along the resonator axis to allow tuning of the resonator length. The downstream mirror is used as output coupler and has therefore a larger wire spacing. Maximum output power of about 1.5 *kW* in 4 μs pulses was obtained with a 14% output coupler.

The wide gain curve obtained at zero slippage is shown in Fig.4. It can be exploited to tune the emission wavelength. Indeed the round-trip time of a wave packet in the resonator has to be tightly synchronised to the time distance between electron bunches entering the undulator. Since the group velocity in a waveguide is a function of frequency, this allows to tune the frequency by varying the resonator length [11].

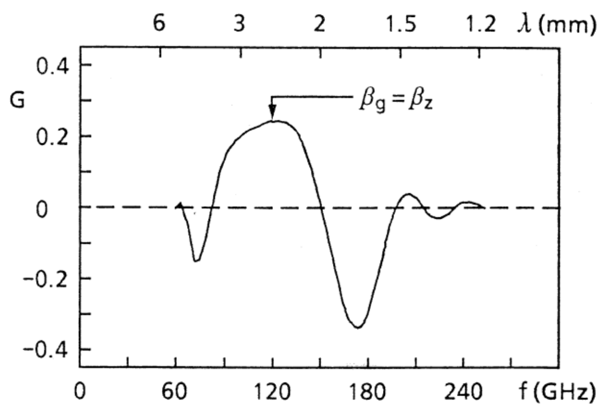

Fig. 4 Calculated gain curve of the Compact-FEL as a function of operation frequency. Source [11]

A measurement of the spectrum of the laser output at maximum power is shown in Fig. 5, where a high finesse (F=200) FP interferogram is reported. The line structure is extremely clear with a measured relative bandwidth of the FEL emission of about 7%.

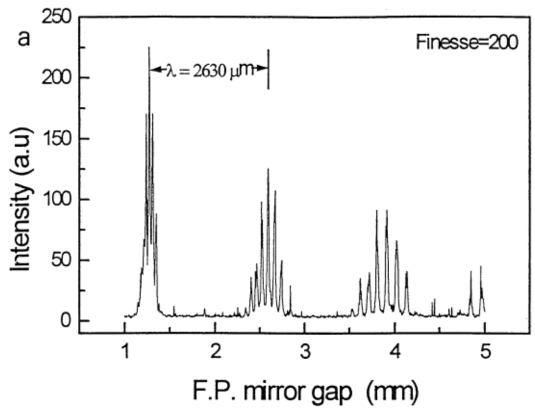

Fig. 5 Fabry-Perot interferogram of the Compact-FEL lasing emission.

6. Energy-phase correlation

Another interesting feature is the possibility of enhancing the coherent spontaneous emission from an RF modulated electron beam by a proper manipulation of the electron distribution in the longitudinal phase space.

Indeed the phase factor present in the expression of the radiated field (10) shows that the electron current and the radiated field are no longer in phase when the electron drift velocity does not match the resonance condition $\theta = 0$. If each electron bunch is treated as a collection of particles each with its energy γ and position or phase ψ along z, the total radiated power is maximum when the single electron contributions in the expansion coefficient $A_{l,0,n}$ interfere constructively with each other. This happens when the electrons are distributed in the longitudinal phase space (ψ,γ) as close as possible to the «phase-matching» curve [3]:

$$\psi = -\pi \frac{L}{cT_{RF}} \left(\frac{1}{\beta_z(\gamma)} - \frac{1}{\beta_{z0}} \right) \tag{11}$$

Calculations show that an increase of about one order of magnitude in the radiated power is expected for a proper correlation between the energy and phase of the electron in the bunch.

7. The FEL-CATS source

The method of enhancing the coherent emission by energy-phase correlation has been successfully tested on the Compact Advanced Terahertz Source (FEL-CATS) at the ENEA laboratories in Frascati. The layout of the experimental setup, which occupies a space of about 0.5 *m* x 1 *m* x 2 *m*, comparable to that of a standard optical table, is shown in Fig. 6.

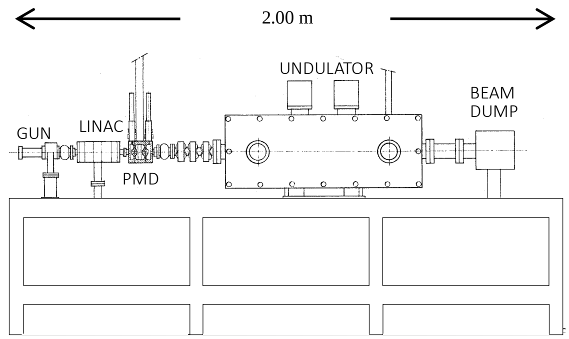

Fig. 6 Lay-out of the FEL-CATS source.

The electron beam source is a 2.998 *GHz* RF linear accelerator (LINAC) capable of generating an electron current of 250 *mA* in 5 to 10 μs macropulses at a kinetic energy of about 2.5 *MeV* [4]. The electron macropulse is composed of a train of 15 *ps* bunches spaced at the RF period of 330 *ps*. The electron beam is generated by a pulsed triode gun, equipped with a 7.7 *mm* diameter osmium treated dispenser thermoionic cathode and is accelerated to the 13 *kV* anode potential before entering the Linac structure through a magnetic lens assembly. The electrons, after having been accelerated in the Linac, enter into a second RF section, called Phase Matching Device (PMD), where the correlation in the longitudinal phase-space takes place. The RF system has been described in detail in [12]. The distribution of the bunched electrons in the phase space at the PMD output can be modified by varying the phase and the amplitude of the RF field driving the PMD with respect to the LINAC. Two sets of steering coils and a triplet of quadrupoles transport the “energy-phase correlated” electron bunch to the undulator entrance. The undulator is a 40 *cm* long permanent magnet linear device. It is realized with NdFeB magnets in the Halbach configuration and it consists of 16 periods of 2.5 *cm* each. The gap is variable and can be remotely controlled to vary the undulator parameter *K* between 0.5 and 1.4.

THz radiation is generated in a rectangular waveguide with cross section dimensions a x b = 24.67 x 6.32 mm^2 placed inside the undulator. Immediately after the undulator, a copper horn and a 45° copper-mesh reflector are used to extract the THz radiation. The spent electron beam passes through the mesh reflector and is sent into a beam dump. At the end of the light-pipe the radiation is analyzed by means of a Fabry-Perot (FP) interferometer equipped with mesh reflectors and a pyroelectric detector (Molecron P4-35). To analyze the coherence of the emitted radiation the signal of the pyroelectric detector was recorded as a function of the *e*-beam current measured at the entrance of the undulator and at the beam dump. The result is shown in Fig.7 in a double logarithmic scale; the output power clearly increases as the square of the *e*-beam current, confirming the occurrence of coherent spontaneous emission.

A maximum emitted power of about 1.5 *kW* in a 5 μs pulse duration was measured at the peak of the phase-tuning curve when the RF field in the PMD (E_{PMD}) was set to about 0.5 the field in the linac (E_{linac}). This power level was obtained after a single pass of the electron through the undulator without any optical cavity. The central wavelength of the emission in these operating conditions is 760 μm (0.4 *THz*).

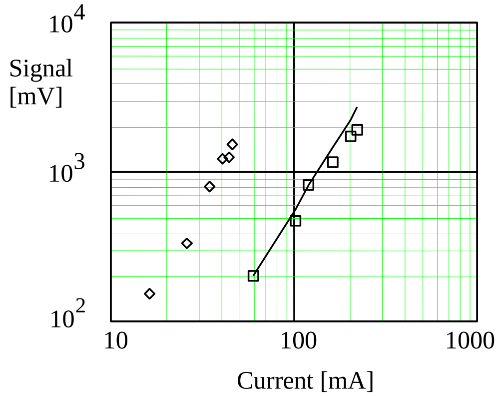

Fig. 7 P4-35 signal as a function of the electron current collected by the upstream (boxes) and downstream (diamonds) targets respectively. The straight line shows the expected quadratic dependence. Source [4].

Fabry-Perot interferograms of the output radiation showed a spectrum with a relative bandwidth of about 10%. The finesse of the instrument was calculated to be F=22 at λ = 700 μm and was enough to resolve the structure within the output bandwidth due to the emission at discrete frequencies, which are integer harmonics of the 3 *GHz* RF [2]. Easy and reproducible wide band tunability of FEL-CATS was achieved by varying the phase in the PMD demonstrating operation between 600 μm and 800 μm (0.4-0.5 *THz*) as it is shown in Fig. 8. As the phase is varied, the requirement on the energy-phase correlation is gradually released and the mean kinetic energy of the e-beam is either increased or decreased. This results in the emission at a different frequency and, in general, at a lower power level.

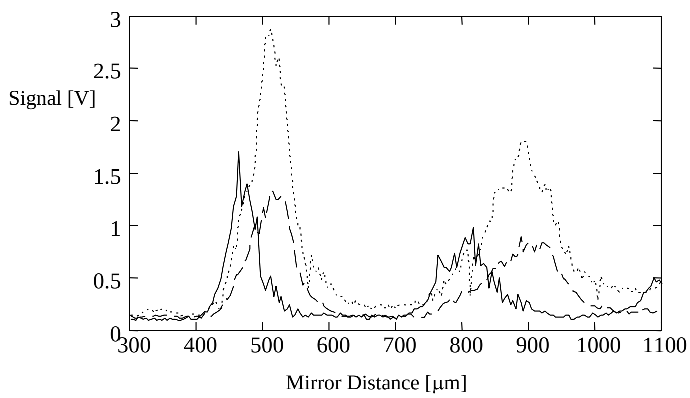

Fig. 8 FP interferograms of the emission at different values of the PMD phase $\Delta\theta$: dotted line $\Delta\theta = 0$ (zero-crossing); dashed line $\Delta\theta = +9°$; solid line $\Delta\theta = -9°$. Source [4].

8. Conclusions

Novel THz sources have been developed and successfully tested at ENEA-Frascati. It has been proved that high peak power compact sources can be built, which fit the size of an optical table. The characteristics of high peak power and short pulse duration make unique experiments possible, particularly in the biological field, such as effects induced on the cell membrane [13]. Another interesting development to be pursued in the future is the generation of ultra-short electron pulses (100-250 *fs*) to realize broadband THz radiators. In such a device a short undulator (N=5-10) could be used to set the central frequency of the radiation. CW operation would also be desirable to allow coherent detection schemes to be used, as in the case of solid state THz emitters. Preliminary calculations show that coherent spontaneous radiation could be generated with an average power level in the 10 *W* range at modest electron currents (10-20 *mA*).

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