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High power THz sources and applications at ENEA-Frascati

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Abstract ENEA has a long term expertise in the development of powerful short-pulse mm-wave and THz radiation sources driven by free electrons. Various electron-wave interaction schemes were successfully tested in the past, including Cerenkov and Smith-Purcell radiators as well as undulator devices. Two THz-FEL sources are currently available, covering altogether the spectral range from 90 GHz to 0.7 THz. Recently a novel Electro-Magnetic pulser, capable of providing both nanosecond THz electromagnetic (EM) radiation pulses and electrostatic (ES) pulses with identical time duration in one device has been designed and is currently under development. The pulser will allow, for the first time, direct comparison of EM and ES pulses on biological systems with peak electric fields that are significantly higher than any reported to date.

Keywords Terahertz · Free electron radiation sources · coherent emission

1 INTRODUCTION

Free Electron Laser (FEL) sources, emitting in spectral regions where conventional laser sources are not easily available (e.g. UV, FIR, mm-wave), have been realised in different laboratories all over the world. In past years the research development led to the construction of "FEL User Facilities" that provide tunable electromagnetic radiation in wide spectral ranges to users. The spectral region between 100 GHz and 10 THz (3 mm to 30 μm wavelength) is particularly attractive because conventional laser sources usually do not satisfy the requirements of continuous tunability and high brightness at the same time, and because small size, moderate cost FELs can be built at such frequencies [1]. With a proper optimization of the layout, in a table-top free electron radiator based on an RF modulated electron beam with short bunches, the various components, including modulator, klystron, electron gun, accelerating structure, waveguides, magnets, and other peripherals could be fitted into the space of one cubic meter. Moreover FELs utilising as a driver a radio-frequency (RF) accelerator turn to be unique sources capable of providing picosecond pulses of coherent radiation at such wavelengths.

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2 CERENKOV AND SMITH-PURCELL DEVICES

Since the late ’80s the research effort at ENEA Frascati has been devoted to the design and operation of long wavelength FELs [2]. This resulted in the realisation of a facility (see Fig. 1), based on a 2 to 5 MeV Microtron accelerator powered by a 2.5 MW magnetron. The set-up shows a a straight line electron transport channel fitted with a vacuum chamber designed to host different interacting structures, like metal gratings, dielectric loaded wave-guides and short-period undulators.

The first device to be installed in the facility was a dielectric loaded waveguide hybrid resonator designed to test the Cerenkov emission mechanism. During such a process electrons passing at grazing incidence close to the surface of a dielectric film deposited on a metallic substrate, couple to the longitudinal electric field of a TM-like surface mode of the waveguide. For this esperiment [3], the Microtron energy was set to 5 MeV and a both a single and double slab waveguide geometry were tested. The dielectric film was deposited on a diamond machined copper plate with optical quality of the surface. A quasi-optical resonator provided feedback and confinement of the radiation. The assembly of the dielectric slab and the quasi-optical resonator are shown in Fig. 2.

A miniaturised e-beam injection scheme composed of two pairs of permanent magnets, placed symmetrically sideways at the entrance of the resonator, allowed the e-beam to enter the resonator above the input mirror and then be displaced so as to travel parallel and close to the surface of the dielectric film. Two different polyethylene films, with a thickness of 25 μm and 50 μm respectively, were successfully tested. The wavelength of the emitted radiation was 1660 μm for the 50 μm-thick film and 900 μm for the 25 μm-thick film.

More recently a Smith-Purcell device based on the excitation of an evanescent wave by electrons passing close to the surface of a metal grating was successfully tested [4]. The Aluminum grating was mounted in the multipurpose interaction chamber of the facility. It had a profile consisting of two facets, one at a blaze angle of 14° relative to the beam direction and the other vertical to the first. Its period was 2.5 mm, its overall length 100 mm, and its width 20 mm. It was mounted on an insulated support so that any current intercepted could be measured. A rotating mirror assembly allowed the measurement of the radiated intensity as a function of the observation angle (see Fig. 3).

Coherent spontaneous radiation was measured at angles in the 40° to 120° range, which correspond to wavelengths from 0.65 to 4 mm, approximately [4].

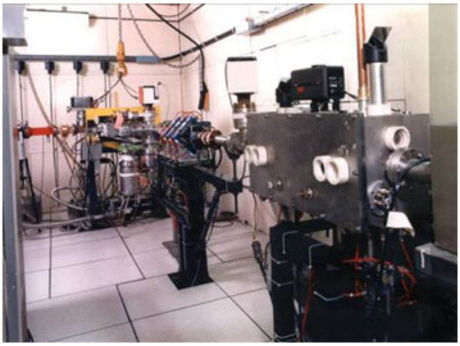

Fig. 1 Lay-out of the Microtron FEL Facility

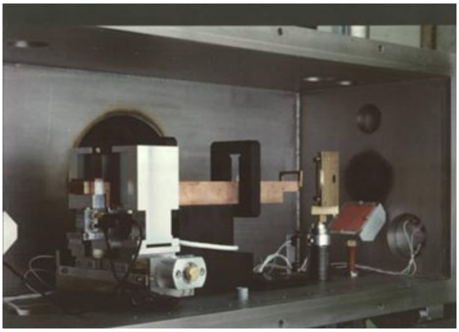

Fig. 2 Cerenkov-FEL, view of the quasi-optical resonator

3 TERAHERTZ FREE ELECTRON LASERS

At present, two Free Electron undulator based sources of THz radiation are available at the ENEA-Frascati, covering altogether the spectral range from 90 GHz to 0.7 THz.

The ENEA Compact FEL utilizes the Microtron at an electron energy of 2.3 MeV to provide 13 ps electron bunches with 4 A peak current [2]. The electron beam is injected into a 8-period permanent magnet undulator (λ_u = 2.5 cm) and the emitted radiation is stored in a hybrid resonator, which utilizes a WR42 waveguide for transverse confinement of the mode and wire-grids electron transparent mirrors (ETM) for the longitudinal confinement (Fig. 4). Micropulses occur with 330 ps spacing in a 4 μs long macropulse, which is repeated at 10 Hz. Peak power in excess of 3 kW is obtained in the micropulse at 130 GHz. When the beam is focused to a spot size of about 0.5 × 1 cm^2 a peak electric field greater than 2 kV/cm is obtained in the micropulse.

The second FEL source, named FEL-CATS (Compact Advanced THz Source), is a small scale device that occupies an area of 0.5 m × 1 m × 2 m, comparable to that of a standard optical table (see Figs. 5a and b).

It exploits a high-efficiency generation scheme based on the mechanism of coherent spontaneous emission [5]. FEL-CATS utilizes a 2.5 MeV RF linac to generate the electron beam, which is injected into a linearly polarized magnetic undulator composed of 16 periods, each 2.5 cm long, with a peak magnetic field of 6000 Gauss.

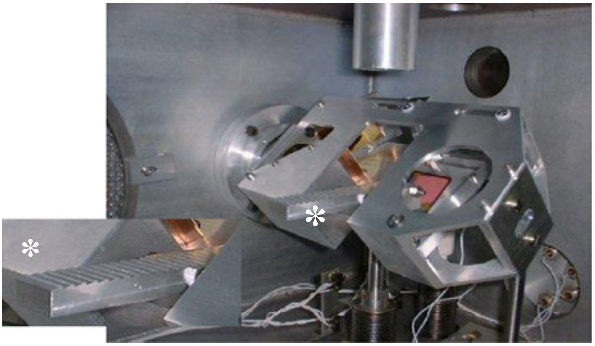

Fig. 3 Smith-Purcell device, Aluminum grating and rotating mirror assembly

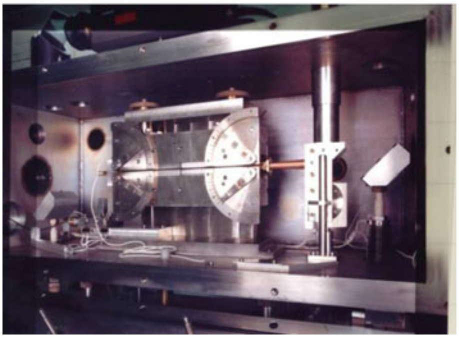

Fig. 4 Compact FEL, undulator and waveguide resonator

The electrons accelerated by the Linac enter a second RF structure, called Phase Matching Device (PMD), placed between the linac and the undulator, which is controlled in phase and amplitude to correlate the electron distribution in energy as a function of time in the bunch. In

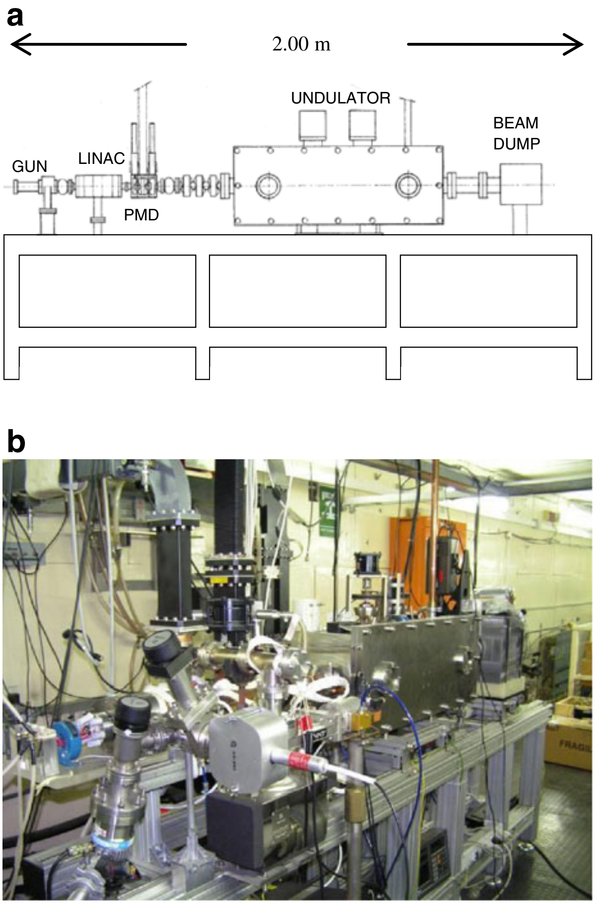

Fig. 5 a. Lay-out of the FEL-CATS source. b. Photo of the FEL-CATS source

this way the contributions to the total radiated field by individual electrons in the bunch are added in phase, leading to a manifold enhancement of the coherent emission in a single pass through the undulator and without the use of any optical cavity. Power levels up to several kilowatt have been measured over a pulse length of about 5 μs. The absence of resonators, and the use of a short length undulator, result in a broad band emission.

Tunable operation has been obtained in the spectral region between 0.4 and 0.7 THz (800 μm to 400 μm wavelength) with a relative linewidth of about 10 % FWHM [6].

A variety of biological systems have been studied with the ENEA Compact FEL in the frame of the European project THz-BRIDGE [7, 8]. The peculiar temporal structure of the emitted radiation allows the investigation of the effects of high peak power, while maintaining a low average power incident on the sample, typically few mW, thus avoiding heating effects. A review of biological applications is reported in [9]. More recently a reflective THz imaging setup has been developed and devoted to the study of hydration conditions in living plants and soils [10] as well as to the investigation of artworks [11].

4 TERAHERTZ IMAGING

THz imaging has seen a tremendous development in recent years with a range of applications extending from biomedicine to art conservation, from material inspection to security systems [12]. A versatile reflective imaging system has been developed at ENEA-Frascati and is illuminated by the THz Compact FEL operating at 150 GHz [13] (see Fig. 6). The FEL radiation is coupled first into a focusing cone followed by a circular to rectangular waveguide

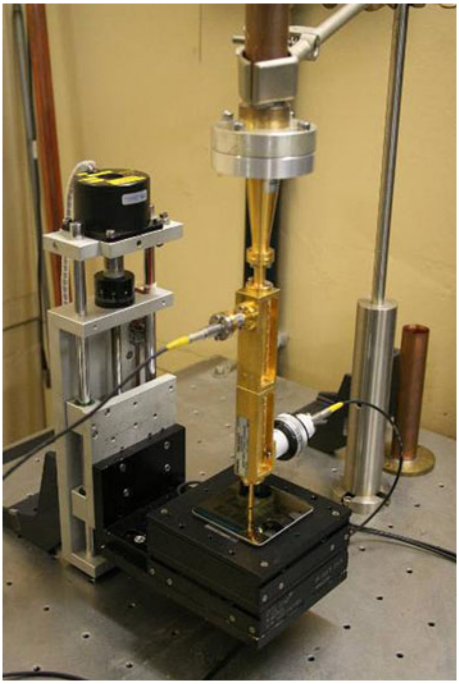

Fig. 6 Imaging set-up at 0.15 THz

transition, which matches the cone output to a series of two WR6 10 dB directional couplers. A probe end is attached to the second directional coupler directing the 150 GHz radiation to the surface of the sample under investigation. The side outputs of the two directional couplers provide a reference signal of the FEL radiation incident on the sample and the signal reflected by the sample respectively. Both signals are detected by Schottky diodes at room temperature. A variable attenuator allows the relative adjustment of the reference signal to the reflected signal within the response range of the Schottky diode during calibration.

The sample under investigation is placed on top of a XY translational stage driven by piezo-motors with 50 mm travel range on both axes. The distance between the sample and the imaging probe along the z axis can be adjusted by means of a stepper-motor driven stage. To obtain an image the sample is scanned at a maximum rate of 5 pixel/s, the reflected signal is normalized to the reference signal to compensate for any power fluctuation of the source during the scan.

Collected data are stored in matrix form to be subsequently analyzed by an image processing software. A spatial resolution of 200 μm has been obtained at 150 GHz. A review of imaging applications performed with this device is reported in references [13, 14].

5 ELECTROMAGNETIC PULSER

A novel Electro-Magnetic pulser driven by a short pulse electron gun has recently been designed. It is capable of providing nanosecond THz electromagnetic (EM) radiation pulses as well as electrostatic (ES) pulses with identical time duration in the same device [15]. The pulser will allow, for the first time, direct comparison of EM and ES pulses on biological systems. The pulser will produce peak electric fields in the samples that are significantly higher than any reported to date, while keeping the average power low enough to avoid sample heating. The pulser diagram is schematically reported in Fig. 7.

The electron gun is composed by a 20 kV power supply charging a capacitor bank C_0 that is the primary energy reservoir. A six-stage magnetic pulse compressor reduces the pulse from a discharge time of 1 μs down to about 30 ns and rises the voltage up to 350 kV. The final condenser of the compressor is a double pulse-forming line (PFL). The PFL charges a transmission-line transformer made by three coaxial cables which are charged in parallel and discharged in series on a diode. If the diode load is mismatched the voltage pulse can reach 1.5 MV.

A Free Electron Laser based on this accelerator can be assembled in a compact configuration as shown in Fig. 8.

The electron beam, generated by the cathode is transported into the undulator by means of a solenoidal magnetic field to minimize space-charge effects. The cathode and the magnetic undulator are contained inside a single vacuum chamber to simplify the e-beam transport system and the vacuum pumping system. A peak current of about 5 kA makes the pulser useful as a driver for a high pulsed power FEL. The expected e-beam quality parameters, emittance and energy spread ($\varepsilon_{x,y}$ = 30 mm mrad, σ_e = 1 %) are good enough for long wavelength operation. The characteristics of the magnetic undulator considered for this device are the same as the ones of undulator currently used in the Compact-FEL (Fig. 4). At a gap of 8 mm a field of 3.5 kG is obtained on-axis with a parameter K = 0.8. Preliminary simulations have shown that the described source is capable of reaching saturation at megawatt level at a central frequency of 200 GHz.

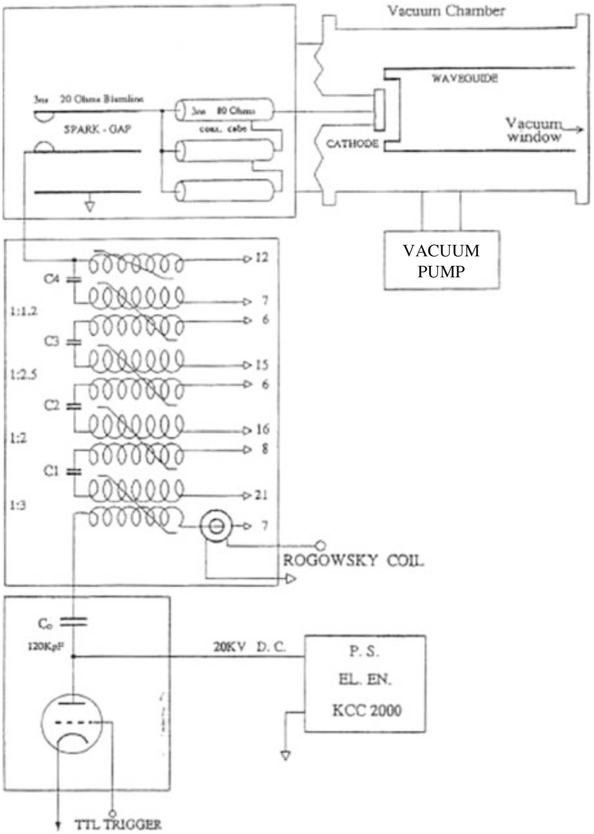

Fig. 7 Schematic diagram of the Electromagnetic Pulser

6 CONCLUSION

A number of 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

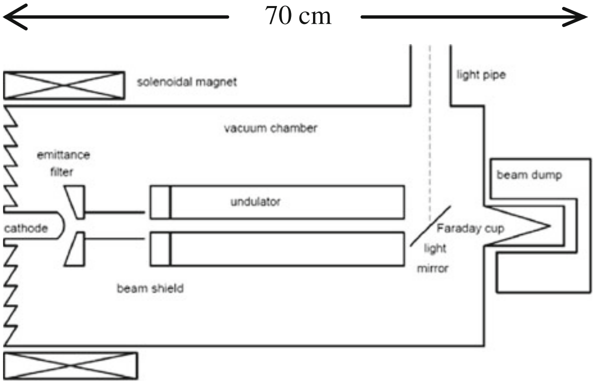

Fig. 8 Schematic diagram of the E-M Pulser FEL

optical table and can effectively be used as a laboratory tool in a variety of applications. The characteristics of high peak power together with short pulse duration permit to carry out unique experiments particularly in the biological field.

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