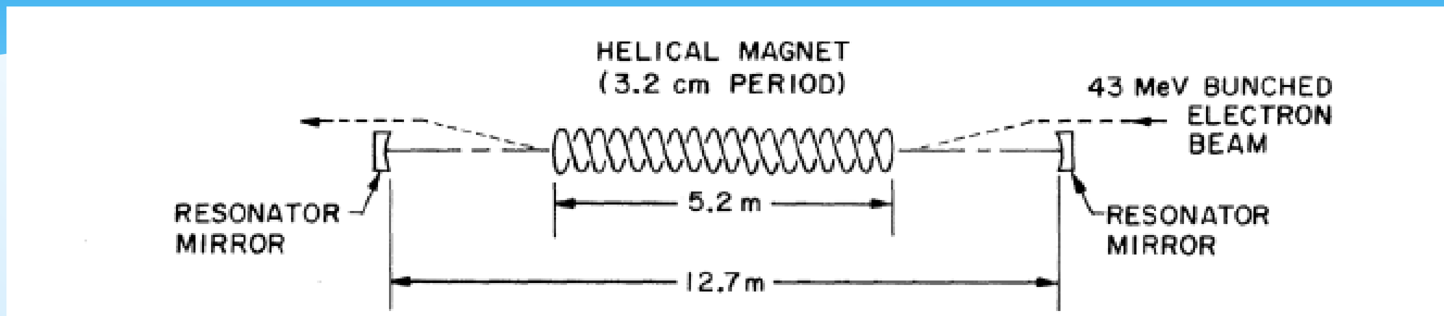
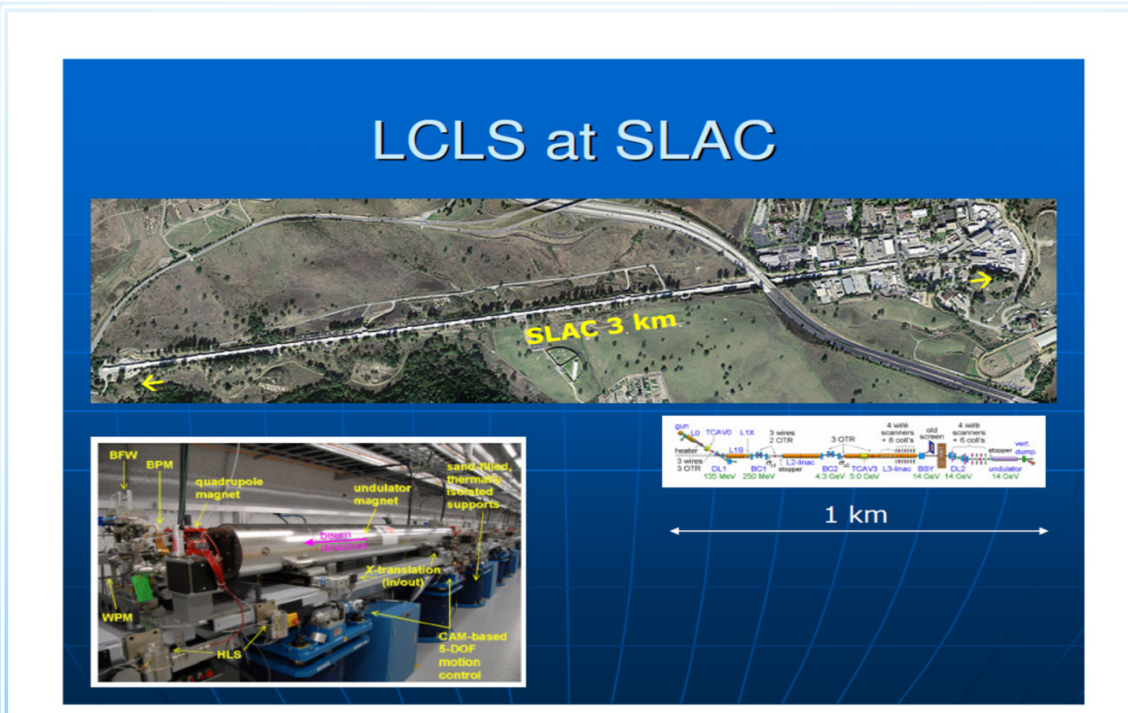
To Commemorate Alberto

Pino

The Survivor of an Epoch





Notwithstanding…

* I Had The Privilege to work with the leading "heros"
  * Alberto Renieri
* Was one of them

A bit of hystory

* 1976 amplification of a CO2 laser, propagating with an electron beam moving in an undulator magnet
* 1977 FEL oscillator in the IR
* 1976-78 Colson produced the FEL pendulum equation
* 1977- Bambini -Renieri Introduce the Hamiltonian picture of FEL
* 1984-Bonifacio Pellegrini Narducci opened the way to fourth generation synchrotron radiation sources

LETTERE AL NUOVO CIMENTO VOL. 21, N. 11 18 Marzo 1978

The Free Electron Laser: A Single-Particle Classical Model.

A. Bambini

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A. Renieri

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(ricevuto l'11 Gennaio 1978)

The classical, nonrelativistic, Hamiltonian is [8]

$$H = \frac{1}{2m}\left(\boldsymbol{p} - \frac{e}{c}\boldsymbol{A}_\perp\right)^2 + \frac{1}{2}(\tilde{P}_L^2 + \omega_L^2\tilde{Q}_L^2) + \frac{1}{2}(\tilde{P}_W^2 + \omega_W^2\tilde{Q}_W^2)\,, \tag{2}$$

What is an FEL?

* It is a device conceived to steel power to an electron beam and transform it into coherent (?) e.m. radiation
* It produces laser like radiation
* Its phenomenology is not dissimilar from those of travelling wave tubes
* The growth of the FEL intensity is the result of an instability (…Renieri (1981)…)
* FEL induced beam heating SATURATION

LETTERE AL NUOVO CIMENTO VOL. 24, N. 4 27 Gennaio 1979

Classical Multimode Theory of the Free Electron Laser.

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(ricevuto il 13 Novembre 1978)

The free-electron laser (FEL) ([1]) has been the subject of many theoretical works, which can be, roughly, divided in two groups: the first one explains the FEL operation in terms of a collective phenomenon ([2]); the second one, on the other hand, explains the effect in the framework of a single-particle theory ([3,4]).

The purpose of the present work is to calculate the small signal gain for a FEL operating in a multimode regime. This case is relevant for a FEL oscillator where the multimode feature is provided by the discontinuous structure of the electron beam (for details see ref. ([5])). The approach will be performed in the framework of the single-

IL NUOVO CIMENTO VOL. 61 B, N. 2 11 Febbraio 1981

The Free-Electron Laser Single-Particle Multimode Classical Theory.

G. DATTOLI and A. RENIERI

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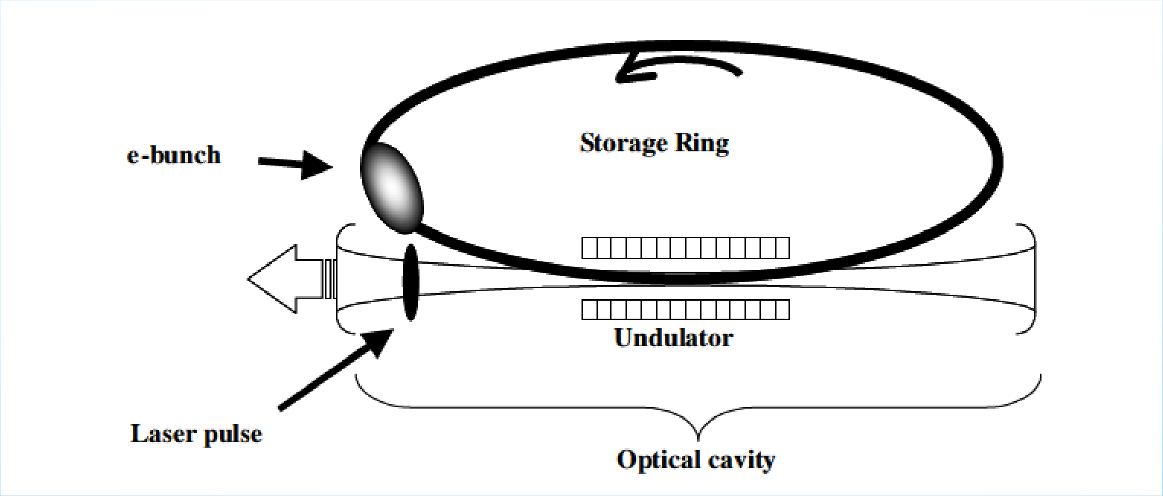
C.P. 65, 00044 *Frascati* (*Roma*), *Italia*

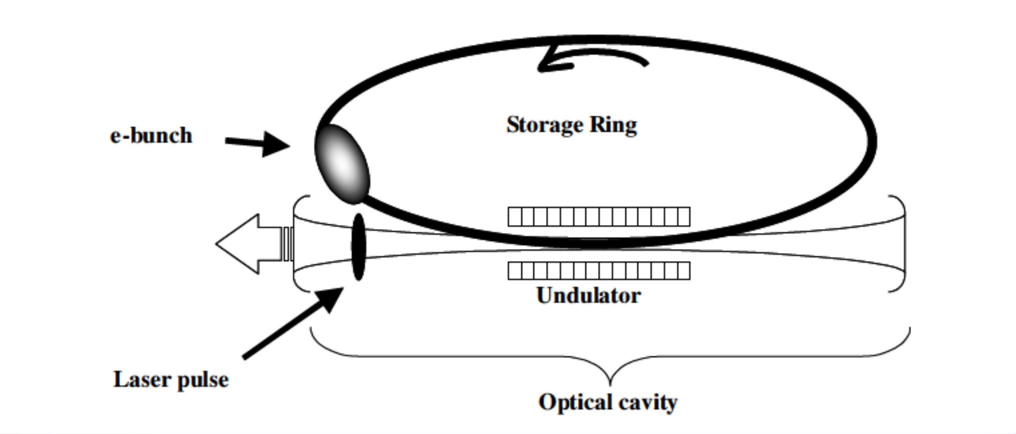
(ricevuto il 29 Settembre 1980)

Summary. — In this paper the essential features of the free-electron laser operation are investigated in the multimode regime and in the framework of a single-particle theory. The theory is formulated under completely classical hypotheses; particular attention is devoted to the time evolution of the *interaction variables*, by means of which the free-electron laser relevant quantities can be expressed. The limits of validity of the model are shortly discussed.

Storage Ring FEL Landau Damping Renieri Limit

* saturation is a complex mechanism Landau damping plays a role





The beam is circulated many times inside and acquires, at each interaction, a certain amount of spread

$$\langle \Delta E \rangle \leq \frac{E}{4N},$$

$$N \equiv number\ of\ undulator\ periods$$

The laser re-starts after a damping time

$$P_L \leq \frac{1}{4N}\frac{E}{\tau_s} = \frac{1}{4N}P_s$$

RENIERI LIMIT 1979-1980

$$P_L \le \frac{1}{4N}\frac{E}{\tau_s} = \frac{1}{4N}P_s$$

IL NUOVO CIMENTO VOL. 59 B, N. 1 11 Settembre 1980

Storage Ring Operation of the Free-Electron Laser: the Oscillator.

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(ricevuto il 18 Aprile 1980)

Summary. — In this paper we investigate the steady-state features of the free-electron laser oscillator, operating with an electron beam stored in a circular accelerating machine (storage ring). The electron and laser beam parameters are evaluated. In particular, it comes out that the average laser output power is proportional to the power radiated, via synchrotron radiation, in the bending magnets of the storage ring.

STORAGE RINGS

* The Storage Ring is a complex environment
* electrons move inside the vacuum chamber
* generate wake fields. These fields called “wakes”
* The saw-tooth (microwave) instability manifests itself through an anomalous increase of the beam energy spread

Renieri 1998-2001

* The Boussard criterion: threshold beam current

$$\delta^2 = \frac{I}{I_{th}} \qquad \sigma_A^2 = \delta^2 \sigma_0^2$$

$$P^* \cong \chi \frac{P_s}{4N},$$

$$\chi = 1.673 \frac{\delta^{\frac{2}{3}} - 1}{g_0} \mu^2, \mu = 4N\sigma_0$$

$$g_0 \equiv small \quad signal \quad gain \quad coefficien \quad t$$

VOLUME 87, NUMBER 13 PHYSICAL REVIEW LETTERS 24 SEPTEMBER 2001

Suppression of the Sawtooth Instability in a Storage Ring by Free-Electron Laser: An Example of Nonlinear Stabilization by Noise

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(Received 20 November 2000; published 10 September 2001)

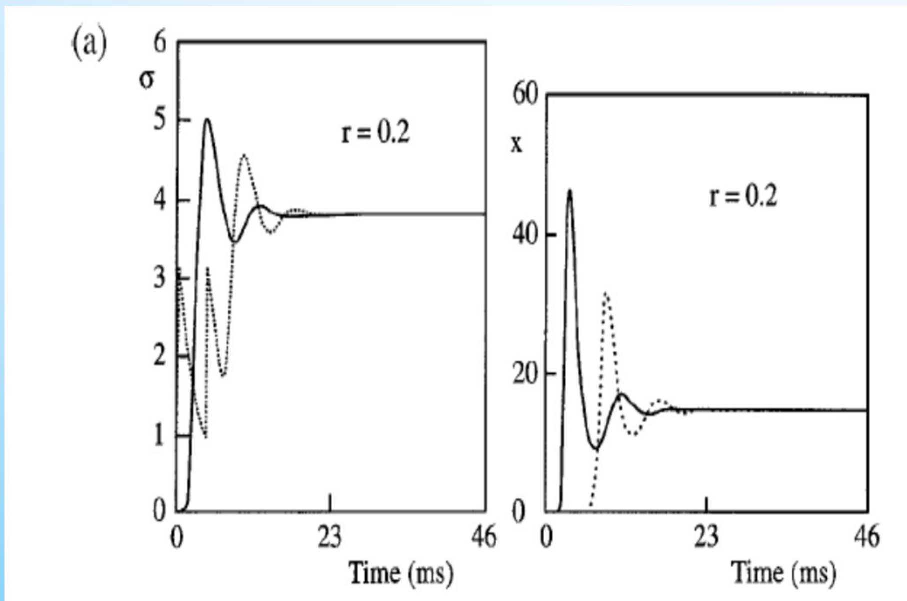
The stabilization of nonlinear excitations by noise is a topic of fundamental importance in many physical problems. We discuss a genuine example within the context of storage ring-free electron laser physics, by presenting a model which allows the characterization of the system evolution and the determination of the conditions leading to the suppression of instabilities of sawtooth type. The conclusions of the model are confirmed by a comparison with experimental results on the Super Aco Storage Ring-Free Electron Laser.

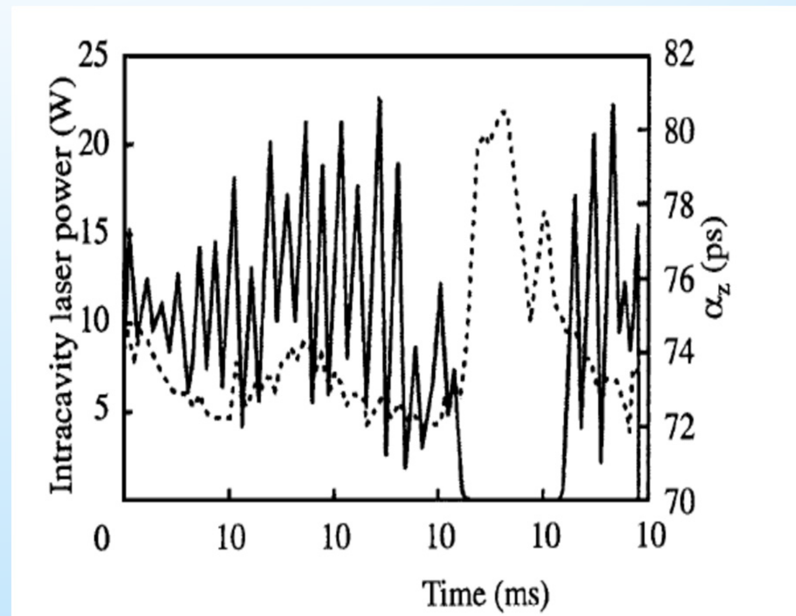
Renieri 1998-2001

Energy spread

FEL power

Measurements on the Super-ACO FEL





1998-2001

* The SR-FEL dynamics displayed complex phenomena, going well beyond the mere generation of coherent radiation.
* The non linear effects in accelerators and the associated instabilities make the study of the relevant dynamics very much interesting.
* The study of the competition of different instabilities has opened an entire new world.
* FEL may contribute to the regulation of
* saw-tooth, head tail instabilities, Touscheck beam lifetime… The relevant studies dynamics taught us how the whole system (in Storage Rings and other accelerator as well) should be considered from a unitary point of view, and within this context the FEL appears as one of the intrinsic feedback mechanisms contributing to the electron-beam equilibrium with the accelerator environment.

* Alberto Renieri has been a decisive contributors to these studies.
*

Renieri (1981)

- FEL INTEGRAL EQUATION

$$\frac{da}{d\tau} = i\pi g_0 \int_0^{\tau} \tau' e^{-i\nu\tau'} a(\tau - \tau')\, d\tau'$$

$$\left(\hat{D}_\tau^3 + 2i\nu \hat{D}_\tau^2 - \nu^2 \hat{D}_\tau\right) a(\tau) = i\pi g_0 a(\tau)$$

$$a|_{\tau=0} = a_0, \quad \hat{D}_\tau a|_{\tau=0} = 0, \quad \hat{D}_\tau^2 a|_{\tau=0} = 0$$

….

$$a(\tau)=\frac{a_0}{3(\nu+p+q)}e^{-\frac{2}{3}i\nu\tau}\left\{(-\nu+p+q)e^{-\frac{i}{3}(p+q)\tau}+\right.$$

$$\left.+2(2\nu+p+q)\,e^{\frac{i}{6}(p+q)\tau}\left[\cosh\left(\frac{\sqrt{3}}{6}(p-q)\tau\right)+i\frac{\sqrt{3}\,\nu}{p-q}\sinh\left(\frac{\sqrt{3}}{6}(p-q)\tau\right)\right]\right\}$$

$$p=\left[\frac{1}{2}(r+\sqrt{d})\right]^{\frac{1}{3}},\quad q=\left[\frac{1}{2}(r-\sqrt{d})\right]^{\frac{1}{3}}$$

$$r=27\pi g_0-2\nu^3,\quad d=27\pi g_0\left[27\pi g_0-4\nu^3\right],$$

$$\tau=\frac{Nz}{\lambda_u},\nu\equiv\text{detuning parameter}$$

Growth, Saturation, Induced Energy spread Renieri (1990-2000)

* **Power growth**

$$P_1(z) = P_0 \frac{A(z)}{1 + \frac{P_0}{P_{F,1}}\left[A(z) - 1\right]}$$

$$A(z) = \frac{1}{9}\left[3 + 2\cosh\left(\frac{z}{L_g}\right) + 4\cos\left(\frac{\sqrt{3}}{2}\frac{z}{L_g}\right)\cosh\left(\frac{z}{2L_g}\right)\right],$$

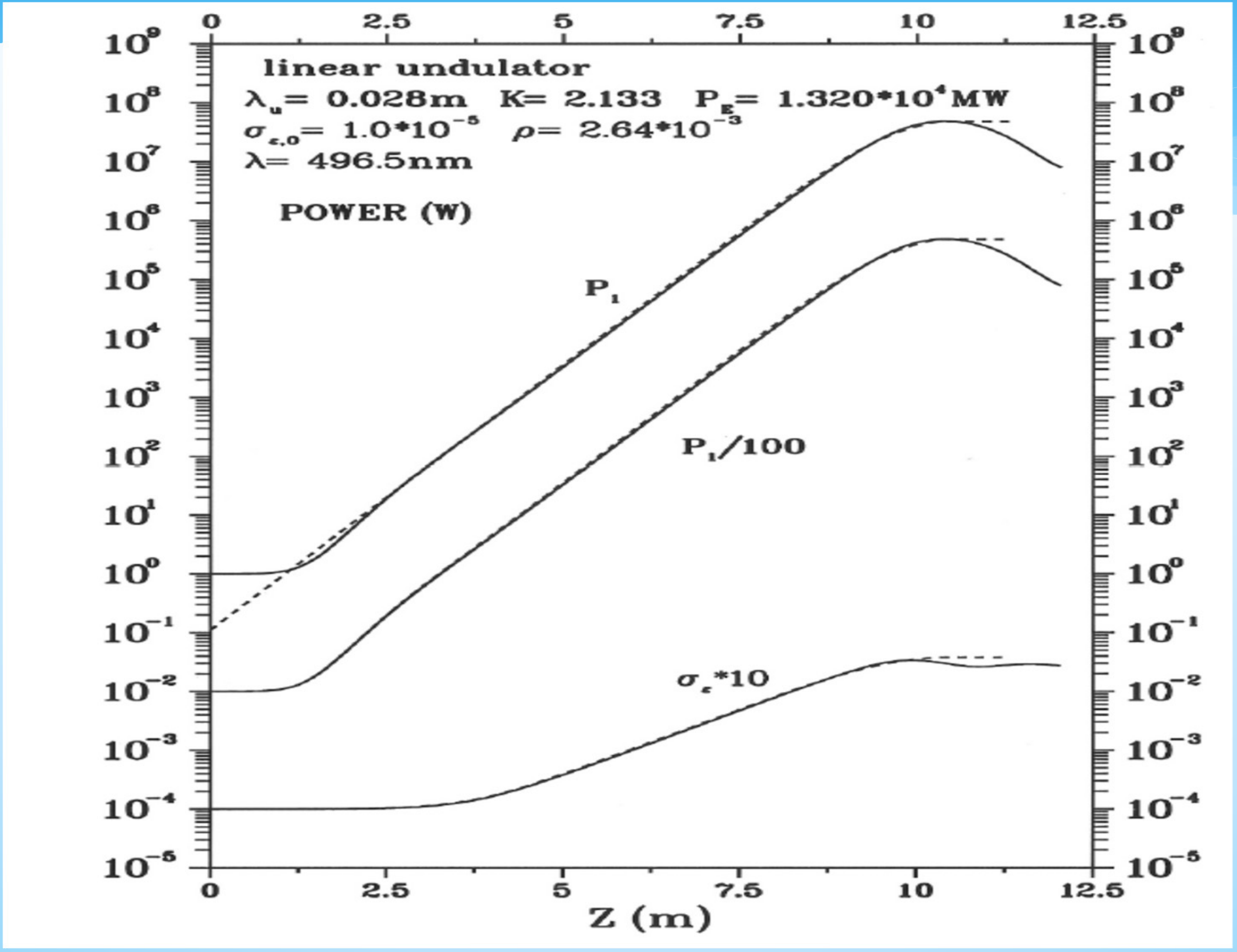
$P_0 \equiv$ Input Seed power, $L_g \equiv$ gain length

$P_F = \sqrt{2}\rho P_E$

$\rho \equiv$ FEL Pierce parameter

$P_E \equiv e - beam \quad power$

Energy spread and Intensity growth



…

* Induced Energy Spread

$$\sigma_i(z) \cong 3C\sqrt{\frac{A(z)}{1+9B\left[A(z)-1\right]}}$$

$$C = \frac{1}{2}\sqrt{\frac{\rho P_0}{P_E}}, \qquad B \cong \frac{1.24}{9}\frac{P_0}{P_F}$$

$$\sigma_{i,F} \cong \frac{C}{\sqrt{B}} \cong 1.6\rho$$

Renieri (1981-2000)

* The derivation of the previous relations can be framed within different analytical models, Ginzburg-Landau, asymptotic solution of pendulum field equations, wise combination of numerical and scaling relations…. Whatever the procedure is, they represent the result of a non common ability of combining physical intuition and analytical means to provide results of practical interest. Alberto mastered all these aspects and left an important lesson for all of us as man and scientist.

2018 Annus Horribilis
Franco and Amalia Left us

PHYSICAL REVIEW A VOLUME 37, NUMBER 11 JUNE 1, 1988

Lethargy of laser oscillations and supermodes in free-electron lasers. I

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(Received 13 July 1987)

We propose an analytical solution to the propagation equation of the optical pulse both in free-electron lasers and in optical klystrons. Our results include in a natural way the lethargy and wave-packet spreading.

…

- *They were distinguished members of the “Frascati FEL school”*
- *They thaught me a lot*
- ….
- *I am now moving go around looking at empty offices…*
- *It is time for me to quit*

Dr. Alberto Renieri and Dr. Giuseppe Dattoli win the 1994 International Free-Electron Laser Prize

The International Free-Electron Laser Prize, awarded annually at the Free-Electron Laser Conference, recognizes outstanding and pioneering contributions in the field of free-electron lasers. At the 16th International Free-Electron Laser Conference, which took place at Stanford University, the 1994 Prize was awarded to Dr. Alberto Renieri and Dr. Giuseppe Dattoli of the ENEA, Frascati, Italy, for their incisive contributions to the theory of free-electron lasers and their leadership role in the FEL and accelerator community.

Alberto Renieri has been involved in research on particle accelerators, colliding beams, and quantum optics since 1969. Dr. Renieri presented one of the earliest classical explanations of the FEL mechanism soon after the first Stanford FEL experiments in the 1970s. He derived an expression for the maximum coherent radiation power in a storage-ring FEL. This well known result is now known as the ‘‘Renieri limit’’. This important result was obtained by noting that the growth in the energy spread on an electron beam that is recycled many times through an undulator is eventually balanced by synchrotron radiation damping. Dr. Renieri has been Director of the ENEA Applied Physics Division since 1993.

Giuseppe Dattoli started his career in high energy physics, working on the electromagnetic properties of charmed particles. He has been involved in quantum optics and FEL research since 1977, working on a broad range of problems, from pulse propagation dynamics to the design of FELs. Dr. Dattoli and Dr. Renieri developed the supermode theory of mode evolution in the FEL oscillator, and used it to describe short pulse effects in RF driven FELs. Dr. Dattoli has used a quantum mechanical analysis to provide a fundamental picture of the FEL interaction from basic principles. Many researchers have found Dr. Dattoli’s empirical formulae describing FEL gain to be an important guide in the design of new experiments. Dr. Dattoli is presently the Head of the ENEA Frascati Theory Division.

Dr. Renieri and Dr. Dattoli have made many outstanding contributions to FEL science and technology. We wish them continued success in their endeavors.

Phillip Sprangle
Chairman FEL-Prize Committee

* 7th FEL prize after
* J. M. J. Madey
* W. Colson
* T. Smith, L. Elias
* P. Sprangle, N. Vinokurov
* R. Phillips
* R. Warren

RIDING THE INSTABILITY (DEDICATED TO ALBERTO RENIERI)

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C. Pellegrini†, UCLA, Physics & Astronomy, 475 Portola Plaza, [90095-1547] Los Angeles, CA

Abstract

The Free Electron Laser (FEL) transforms the kinetic energy of electrons into coherent light. The underlying mechanism occurs through the FEL instability, leading to the growth of coherent radiation from noise, characterizing all the generators of coherent radiation from free electrons (Gyrotrons, $CARM$ ...). The FEL instability shares many features with other instabilities occurring in Plasmas and electron beams, sometimes competing with them. In this paper we give a short description of these analogies, their relevant physical roots and comment on the importance and role of their interplay.

FEL INSTABILITY

The FEL, in its modern conception, started in 1976 with the amplification of a CO_2 laser, co-propagating with an electron beam in an undulator magnet [1]. The experiment confirmed what Madey had predicted few years before [2],

Hamiltonian, leading to the pendulum equation and opening the way to the investigation of the FEL quantum coherence properties [5,6]. This is the gross picture before the eighties. It became slowly clear that the FEL phenomenology had not to be dissimilar from the Physics of travelling wave tubes. The analogy between FEL and other generators of light by other free electron devices (Klystron, Gyrotron, $CARM$, ...) was pointed out in [7] (see also ref. [5] for a more recent discussion).

The common feature emerging from the relevant theoretical picture was that the optical field growth is associated with a dispersion relation leading to a third (or fourth) order ODE [8–10]. The roots of the associated characteristic polynomial fix the condition for the onset and rise of the electromagnetic field. Within this context the field grows as the result of the FEL instability, with a rise time or gain length, given by the “fast growing" root.