In memory of Rodolfo Bonifacio

Rodolfo Bonifacio: 1940-2016

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Outline

1. Contributions to quantum and non linear optics
2. Contributions to FEL theory
3. Legacy

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Early career: quantum optics

Rodolfo Bonifacio studied at the University of Milan where he graduated under the supervision of Prof. Piero Caldirola in 1964. During that decade the first infrared laser was built by Ted Maiman, starting an exciting new field of optics research and applications. Having a powerful source of coherent radiation led to the fast development of quantum and non linear optics. Many scientists, worldwide, started working in these areas and on the laser development, to extend its operation to more wavelengths and increase its power. A group formed at the University of Milan to study laser physics and applications, including, among others, Arecchi, Lugiato and Bonifacio.

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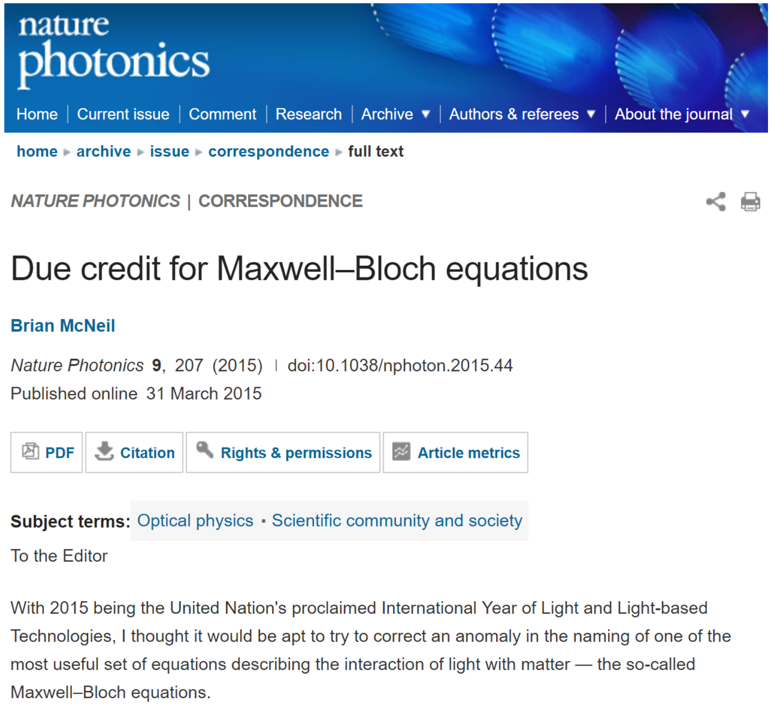
Bonifacio-Arecchi equations

One of Bonifacio's early period important contributions was a paper, co-authored with Arecchi , giving a self consistent description of the interaction of an electromagnetic pulse with an ensemble of two level atoms. To solve this problem they introduced the electromagnetic field Slowly Varying Envelope Approximation, which later played an important role in the FEL theory. The set of equations derived in this paper is now known as the Arecchi-Bonifacio equations.

$$\begin{cases} E_0\left(c\dfrac{\partial \varphi}{\partial x} + \dfrac{\partial \varphi}{\partial t}\right) = \dfrac{\omega}{2\epsilon} C \\ c\dfrac{\partial E_0}{\partial x} + \dfrac{\partial E_0}{\partial t} + \dfrac{\sigma}{2\epsilon} E_0 = -\dfrac{\omega}{2\epsilon} S, \end{cases}$$

F. T. Arecchi and R. Bonifacio, Theory of optical maser amplifiers, IEEE J. Quant. Elec. QE-1, 169 (1965).


nature photonics

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NATURE PHOTONICS | CORRESPONDENCE

Due credit for Maxwell–Bloch equations

Brian McNeil

Nature Photonics **9**, 207 (2015) | doi:10.1038/nphoton.2015.44
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Subject terms: Optical physics • Scientific community and society

To the Editor

With 2015 being the United Nation's proclaimed International Year of Light and Light-based Technologies, I thought it would be apt to try to correct an anomaly in the naming of one of the most useful set of equations describing the interaction of light with matter — the so-called Maxwell–Bloch equations.

Quantum Optics

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Bonifacio's work on lasers continued in the late '60s at Harvard, where he was invited by Glauber, and on his return at Milan in 1970s. In 1970 Rodolfo formulated, in collaboration with Paolo Schwendimann and Fritz Haake, a classical and a quantum theory of Cooperative Spontaneous Emission. He coined the name Superfluorescence to designate the emission from a collection of two-level atoms in the excited state, under conditions of vanishing atomic dipole. Later, together with Luigi Lugiato, he provided the theoretical description of oscillatory Superfluorescence. His predictions were nicely confirmed experimentally.

PHYSICAL REVIEW A VOLUME 4, NUMBER 1 JULY 1971

Quantum Statistical Theory of Superradiance. I*

R. Bonifacio and P. Schwendimann
Istituto di Fisica, Università di Milano, Milan, Italy
and
Fritz Haake†
Lyman Laboratory, Harvard University, Cambridge, Massachusetts 02138

(Received 10 September 1970)

We discuss the cooperative decay of initial atomic excitation for a pencil-shaped active volume filled with two-level atoms. As long as the length of the sample is much smaller than a certain maximal cooperation length, the atom-field interaction producing the superradiant pulse can be treated in terms of the simplest possible laser model (single mode). The basic

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Quantum optics

In the mid-1970s, in collaboration with Luigi Lugiato, Bonifacio proposed the mean field theory of Optical Bistability, which was generally adopted by the community, and described the quantum features of the transmitted light and of the photon statistics. Bonifacio and Lugiato were awarded the Michelson Medal from the Franklin Institute for their studies of optical bistability in 1987.

They also formulated an exact theory of optical bistability in a ring cavity, which allowed the prediction of the phenomenon of optical self pulsing, later observed in experiments.

ELSEVIER

Optics Communications

Volume 19, Issue 2, November 1976, Pages 172-176

Cooperative effects and bistability for resonance fluorescence

R. Bonifacio *, L.A. Lugiato

LASERS and FELs

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In the late 1970s and in the 80s Rodolfo turned his attention to Free Electron Lasers (FELs). He was part of a group of laser physicists, including also Scully and others, that became interested in this new generators of coherent radiation and brought with them their knowledge of laser physics and the properties of electromagnetic radiation. Many of the concepts introduced in laser physics, for instance cooperation length, superradiance and more, were introduced in FELs physics theory in later years. The collaboration between the laser physicists and the accelerator-particle beam physicists, has been very important for the successful development of FELs.

FELs

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One of the first contributions of Bonifacio to FEL theory was published in a 1982 paper co-authored with Federico Casagrande and Giulio Casati. It described a 1-dimensional Hamiltonian model of an FEL and showed that when the amplitude of the wiggler field or the electron beam density exceeds a critical value, a first-order-like transition to strongly coupled chaotic motion takes place and the system radiates strongly and cooperatively.

ELSEVIER

Optics Communications

Volume 40, Issue 3, 1 January 1982, Pages 219-223

Cooperative and chaotic transition of a free electron laser Hamiltonian model ☆

R. Bonifacio, F. Casagrande, G. Casati

FELs: Bonifacio, Pellegrini, Narducci

This was followed by further studies of the FEL throughout the 1980s and 1990s. One important paper, in 1984, in collaboration with Claudio Pellegrini and Lorenzo Narducci, described the 1-dimensional, high gain FEL physics as a collective instability characterized by a single universal parameter, the FEL parameter, ρ. This single parameter gives the FEL gain length, saturation power, and the limit on thermal effects, the beam energy spread. This model, and its later extension to 3 dimension to include diffraction effects, has been widely used in the development and design of FEL amplifiers starting from noise or from an input signal.

ELSEVIER

Optics Communications

Volume 50, Issue 6, 15 July 1984, Pages 373-378

Collective instabilities and high-gain regime in a free electron laser

R. Bonifacio *, C. Pellegrini

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L.M. Narducci

Physics Department, Drexel University, Philadelphia, PA 19104, USA

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Ve la darà lui la luce!

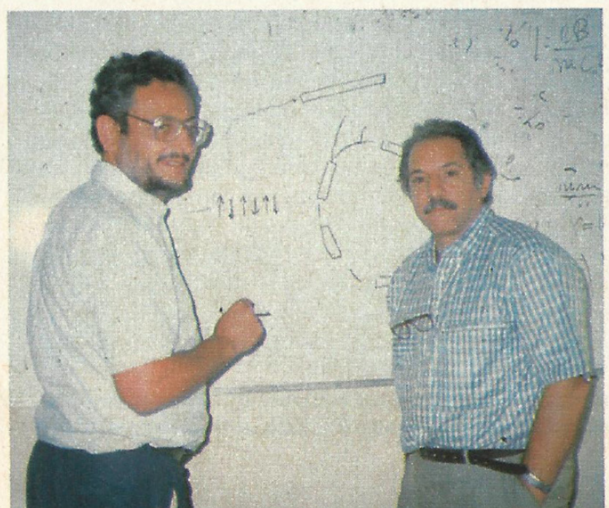
di Michela Fontana

Radiografare il corpo umano in tre dimensioni. Colpire con precisione assoluta le cellule cancerogene. Studiare la struttura interna di tutto ciò che ci circonda. Questo e altro permetterà il Fel. Ma chi vincerà la gara per costruire il più potente?

Pochi miliardesimi di secondo saranno sufficienti: con un unico impulso di radiazione laser i medici potranno ricostruire una perfetta copia tridimensionale (un ologramma cioè) di qualsiasi parte del corpo umano, dalla singola cellula al neurone, all'intero cervello. E sulla copia potranno studiare nei minimi dettagli la struttura interna, l'esatta posizione di eventuali anomalie e programmare con precisione assoluta il modo migliore per colpire, sempre con un impulso di radiazione laser, solo le cellule malate. Ma il nuovo laser a elettroni liberi (in sigla Fel, «free electron laser»), il primo capace di emettere radiazioni in tutte le lunghezze d'onda, compresi i raggi X, servirà anche per studiare la struttura interna di qualsiasi materiale, o per rivelare i segreti del Dna.

L'idea di costruire un laser capace di emettere raggi era considerata fino a pochi anni fa impossibile, spiega Rodolfo Bonifacio dell'Istituto di fisica di Milano, uno dei più avanzati nella ricerca sul nuovo rivoluzionario laser, «perché non esistevano radiazioni X coerenti e quindi monocromatiche e direzionali, dotate cioè di quelle caratteristiche che permettono alla luce laser di non disperdersi e di essere direzionata con precisione assoluta». I primi tentativi erano stati fatti per scopi militari, nell'ambito del progetto americano delle guerre stellari e su consiglio di uno dei padri della bomba atomica, il fisico Edward Teller.

Ma, secondo Teller, per far funzionare un laser a raggi X era necessario alimentarlo con un'esplosione nucleare. E questo creava non pochi problemi. Oggi però la soluzione sembra sia stata trovata (e completamente al di fuori dei programmi militari) grazie al Fel, che verrà messo in funzione da un fascio di elettroni accelerati fino quasi alla velocità della luce, e, secondo gli scienziati, potrà essere



Il fisico italiano Claudio Pellegrini che lavora negli Stati Uniti e Rodolfo Bonifacio, dell'Istituto di fisica di Milano

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FELs

The collective instability work was later generalized to include harmonics in a planar undulator and space charge effects in planar undulators.

ELSEVIER

Optics Communications

Volume 53, Issue 3, 1 March 1985, Pages 197-202

Collective instability of a free electron laser including space charge and harmonics

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Brookhaven National Laboratory, Upton, NY 11973, USA

R. Bonifacio

University of Milan, Milan, Italy

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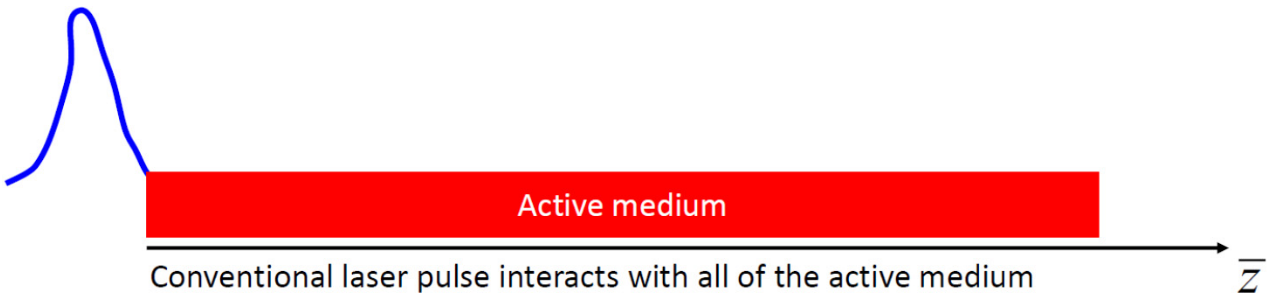
Superradiance and FELs

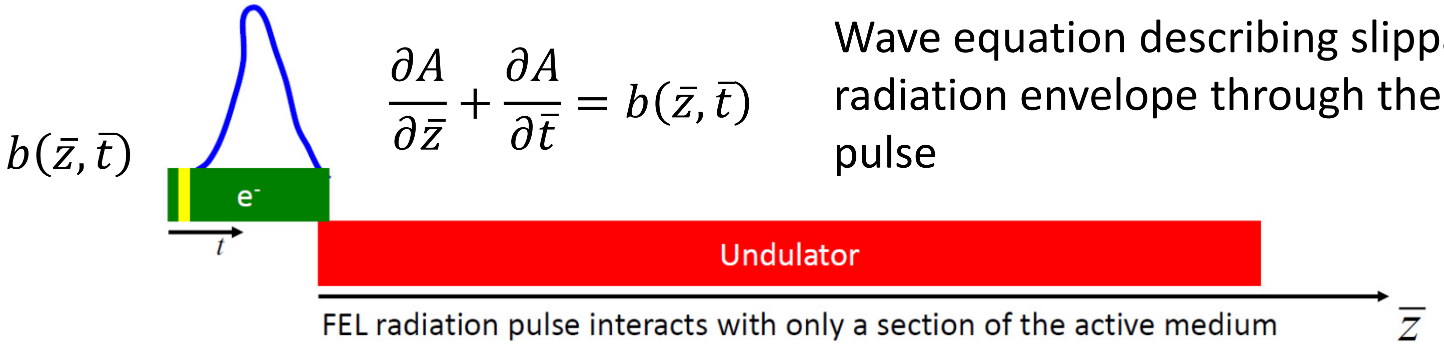
Towards the end of the ‘80s and beginning of the ‘90s, Bonifacio, now a leader in the FEL community formed a very active group in Milan including among others Piovella, Casagrande, Pierini, and McNeil. Among other studies, they generalized the collective instability 1-D model to include time dependent and slippage effect, introducing in FEL physics the concept of cooperation length and its connection to the gain length and the FEL parameter.

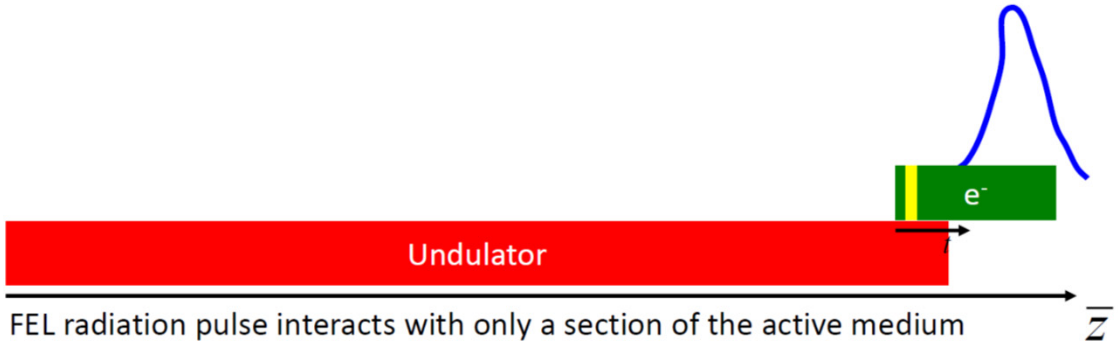
Conventional laser Vs FEL pulses



$$\frac{\partial A}{\partial \bar{z}} + \frac{\partial A}{\partial \bar{t}} = b(\bar{z}, \bar{t})$$

Wave equation describing slippage of radiation envelope through the electron pulse





Courtesy of B. McNeil

PHYSICAL REVIEW A VOLUME 40, NUMBER 8 OCTOBER 15, 1989

Superradiance in the high-gain free-electron laser

R. Bonifacio, B. W. J. McNeil, and P. Pierini

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The electron pulse length is clearly important. It is best measured with respect to the relative slippage between the electron pulse and the radiation pulse in one gain length. This is defined as the ***cooperation length***:

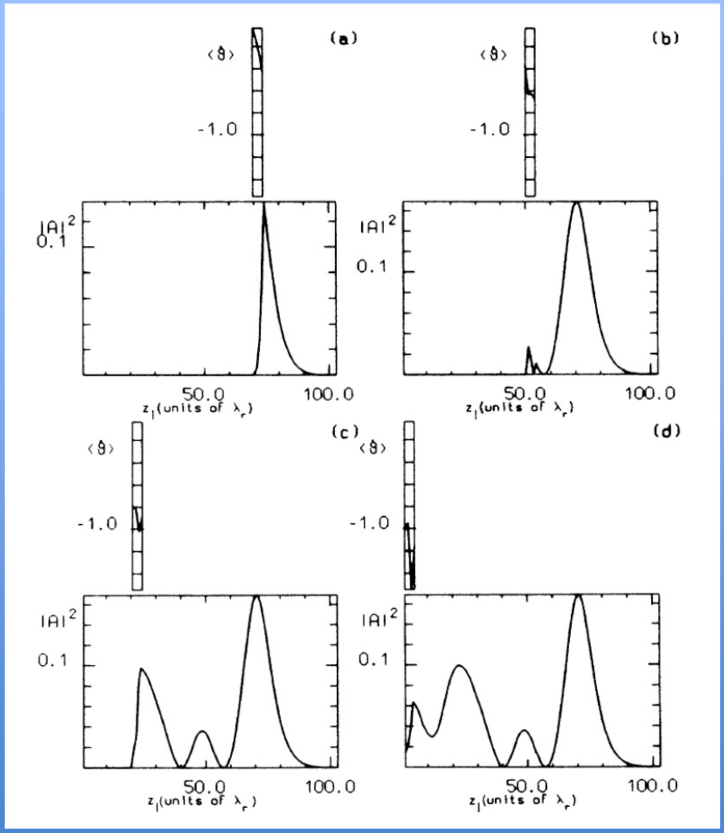
$$l_c = \frac{1-\bar{\beta}_z}{\bar{\beta}_z} l_g = \frac{1-\bar{\beta}_z}{\bar{\beta}_z}\frac{\lambda_w}{4\pi\rho} = \frac{\lambda_r}{4\pi\rho}$$

The length of the electron pulse with respect to this length determines how the electron/radiation FEL interaction evolves:

$$\frac{l_e}{l_c} \lesssim 1 \quad \text{- Short pulse}$$

$$\frac{l_e}{l_c} \gg 1 \quad \text{- Long pulse}$$

Short pulse regime



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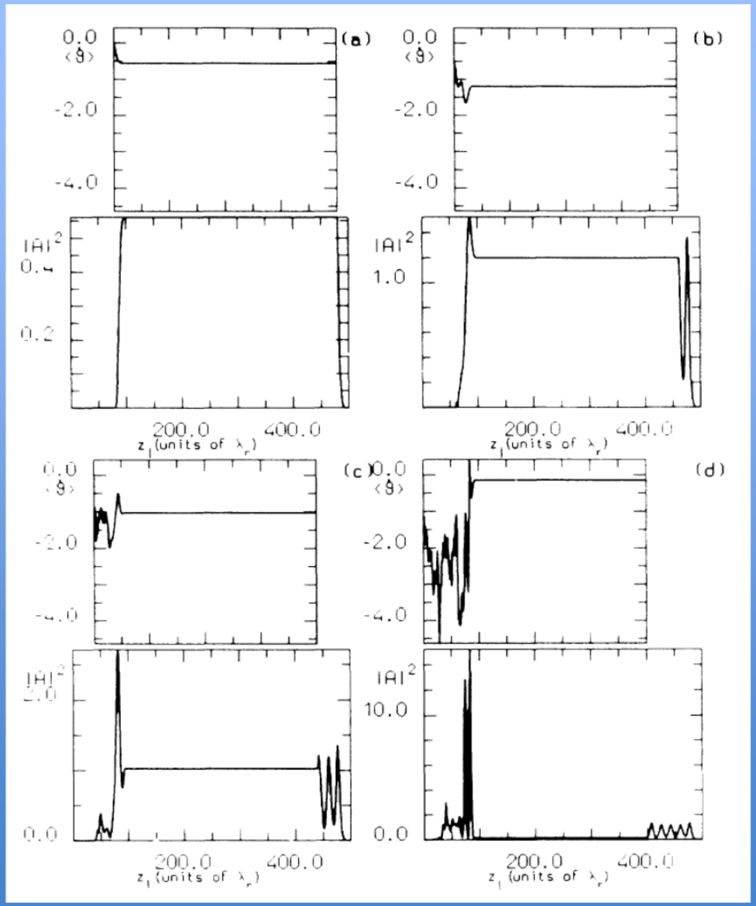
Long pulse regime



Note added in proof

We note that the SR regime of a high-gain FEL combined with tapering of the wiggler may lead to higher extraction efficiencies than with a tapered wiggler alone. Such a scheme may be useful in high gradient electron accelerators, by replacing klystrons with the high efficiency FELs. Such a device (a 'FELTRON') will be investigated elsewhere.

Temporal structure of FEL pulses and the cooperation length

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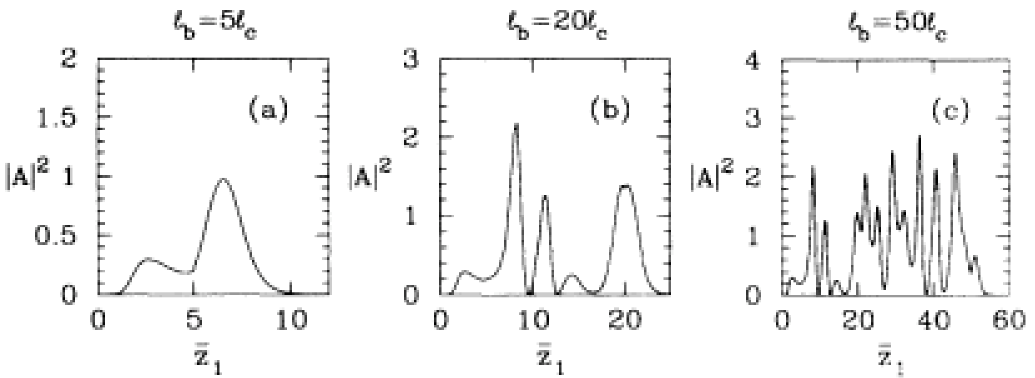
This analysis has been very important and ultimately let to understanding the temporal characteristics of the FEL pulse starting from noise, which is the SASE regime typically used in X-ray SASE FELs, like LCLS, and has been well verified experimentally.

VOLUME 73, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1994

Spectrum, Temporal Structure, and Fluctuations in a High-Gain Free-Electron Laser Starting from Noise

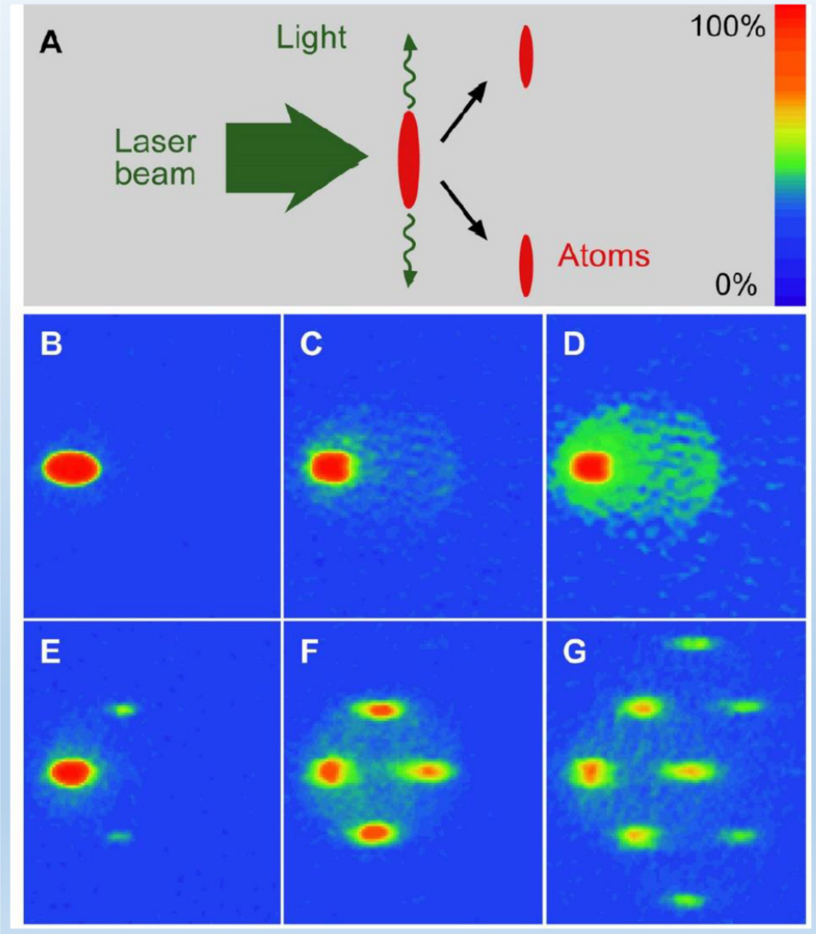
R. Bonifacio,[1,2] L. De Salvo,[1] P. Pierini,[2] N. Piovella,[1] and C. Pellegrini[3]



Field power profile along the bunch for different ratios of the bunch length to the cooperation length. Measurements of the related power spectrum have been used to determine the bunch length down to a few femtoseconds.

CARL

Rodolfo's experience with conventional "atomic" and FEL led him in the mid-1990s to investigate light-matter interactions in atomic gases by borrowing concepts from both fields. At this time, experimental progress on cooling and trapping atomic gases was advancing rapidly, but little consideration had been given to how the extremely low temperature of a gas would affect its interaction with light. In 1994 Rodolfo led the development of the "Collective Atomic Recoil Laser" (CARL) – a theory of light amplification in a cold atomic gas which relies on both the internal bound atomic states and atomic centre-of-mass motion to produce a collective bunching of the atoms and subsequently coherent scattering of an incident pump field. CARL has since been observed in experiments involving cold, thermal gases but also in Bose-Einstein Condensates (BECs) as a process termed "Superradiant Rayleigh Scattering (SRyS)".

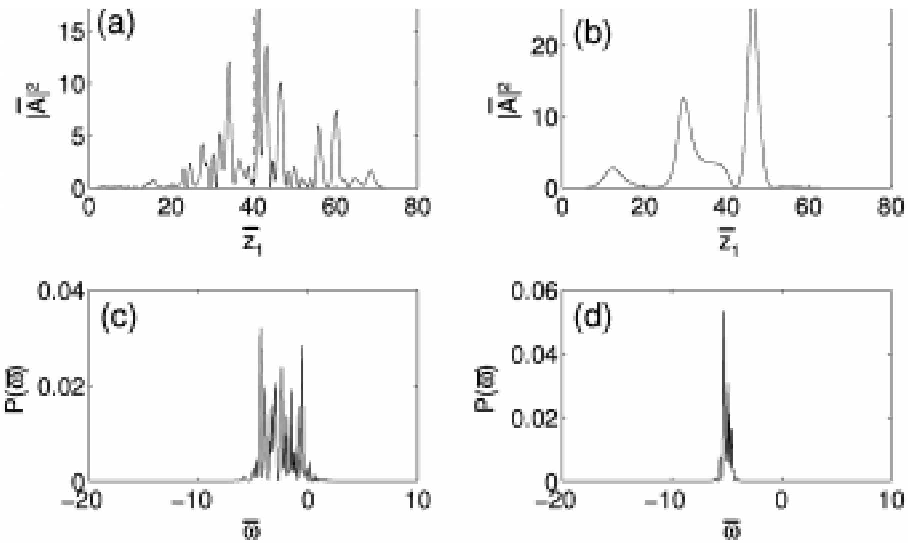


Q-FEL

Experiments involving ultra-cold BECs stimulated the extension of the CARL model to include a quantum description of the atomic recoil due to photon scattering. This in turn led Rodolfo to revisit high-gain FEL theory in the early 2000s and investigate the possibility of a high-gain Quantum FEL (QFEL). The quantum regime is defined in term of the FEL parameter when the energy of one emitted photon is larger than the gain bandwidth, or *hv/E>ρ* . Bonifacio and collaborators showed that in this case the radiation linewidth can be strongly reduced, and the spectrum changes substantially respect to the SASE case.

Quantum regime of free electron lasers starting from noise

R. Bonifacio, N. Piovella, G. R. M. Robb, and A. Schiavi
Phys. Rev. ST Accel. Beams **9**, 090701 – Published 5 September 2006



Power and spectrum along the bunch (L_B $=40L_C$). Left: SASE regime; right, quantum regime.

The QFEL could be a very promising x-ray source generating quasi-monochromatic radiation (although at a lower power than in a classical SASE FEL) and a formidable tool for ultra-high-resolution process studies.

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QFEL

I would like to close with Bonifacio's last paper and its conclusions: Design of a sub-Angstrom compact free-electron laser source, R. Bonifacio, H. Fares, M. Ferrario, B. W. J. McNeil and G. R.M. Robb, Optics Comm. 382, 58, (2016).

Conclusions

Using a Compton backscattering scheme, we have described the design of proposed sub-Angstrom FEL operating in the quantum SASE mode. The practical constraints and optimum conditions for efficient operation of QFELs are discussed.

It was shown that the main requirement is very high beam quality. Therefore, *it is desirable to operate at low charge (in pCs range) to generate low emittance, low energy spread, and short bunch lengths.* While beam degradation effects due to space charge as the QFEL Interaction proceeds have not been modeled here, they have been considered in [19–21] and do not appear to be a factor that cannot be managed. We numerically demonstrate that the QFEL has a number of potentially attractive features, including extremely narrow bandwidth, short pulse structure, and high photon flux. This study suggests that a compact QFEL source in the sub-Angstrom range should be experimentally realizable using current laser and electron beam technologies.

He has left us with a good challenge!

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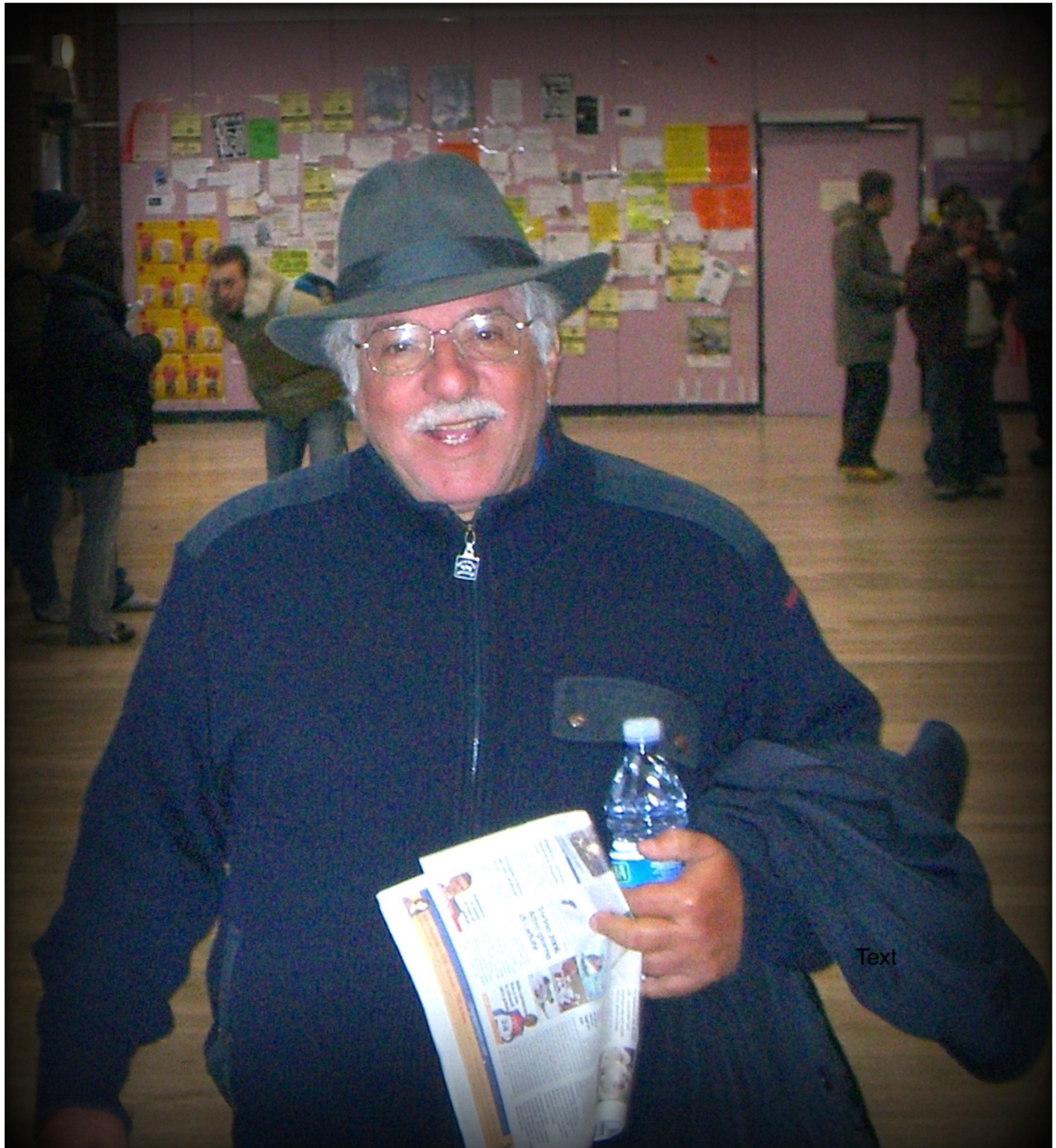
Legacy

- Rodolfo Bonifacio was an outstanding and enthusiastic teacher and many of his students are now members of the FEL/accelerator physics communities.
- He collaborated with many scientists in many countries, from Italy to Brazil, to Scotland, and more, always bringing with him his enthusiasm for physics, and his willingness to work on new challenging problems.
- He will be missed by our community and his many colleagues and friends.



Rodolfo Bonifacio 24.2.1940 - 1.11.2016