Virtual Laboratory and Computer Aided Design for Free Electron Lasers outline and simulation

Free Electron Lasers (FEL) are becoming mature devices demanding for reliable design tools. In this paper we describe computer assisted design (CAD) programs, conceived to provide fast and accurate means, yielding an outline of the FEL device in its different configurations.
CAD software discussed in the paper is the results of the implementation of analytical and empirical formulae, benchmarked with different codes, modeling the FEL Physics, embedded in an engineering environment. Practical examples illustrating their potentialities are also presented

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Laboratori Virtuali e strumenti CAD per la progettazione e simulazione di Laser a Elettroni Liberi (FEL)

La tecnologia dei Laser a Elettroni Liberi (FEL) sta diventando sempre più consolidata ed esige strumenti di progettazione affidabili. In questo articolo si descrivono programmi CAD, ideati per fornire mezzi veloci e accurati, delineando il dispositivo FEL nelle sue diverse configurazioni. Il software CAD qui descritto è il risultato dell'implementazione in ambito ingegneristico di formule analitiche ed empiriche, la cui validità è stata controllata tramite l'utilizzo di codici indipendentemente sviluppati per lo studio della Fisica dei FEL. Nel presente articolo sono anche illustrate le potenzialità del software proposto

Free Electron Laser (FEL) devices provide electromagnetic radiation with the same coherence properties as those from conventional lasers, although the operating principles are substantively different. Instead of electrons, excited in bound atomic or molecular states, the active medium of FELs consists of a beam of free relativistic electrons moving in a magnetic field.

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In Figure 1 we report two typical layouts of a FEL device, where we have sketched their essential components:

1) a beam of electrons provided by an accelerator (typically a Radio Frequency Linac);
2) the "undulator", namely an array of magnets with alternating poles, forcing the electrons of the beam to follow a sinusoidal path and therefore causing the deceleration of the electrons, with a consequent emission of synchrotron radiation;
3) an optical cavity, if the FEL operates in the oscillator configuration (Figure 1a); in this case the coherence develops after many passages in the optical cavity;
4) a series of undulator sections, if the device is designed for a Self-Amplified Spontaneous Emission

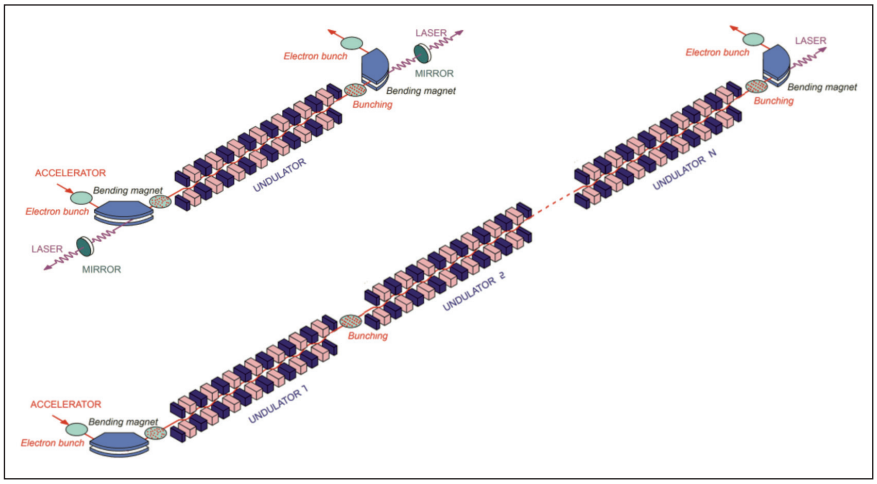

FIGURE 1 FEL layout:
a) oscillator configuration,
b) Self-Amplified Spontaneous Emission configuration

(SASE) operation (Figure 1b); in this configuration the coherence develops in one passage along the undulator chain.

The design of FEL devices has demanded for new engineering issues, capable of connecting a mosaic of different technologies (magnetic materials for undulators, high quality electron beams, new accelerators, etc.). Design methods have to be flexible enough to merge these different aspects: some have been developed in the past and have been accurately benchmarked. The planning of detailed simulation strategies is, therefore, not a secondary problem, and the various institutions interested in the construction of FELs have invested in the development of codes, conceived to satisfy two different requests (often in conflict), namely reliability and computational simplicity.

Simulation and design issues

Simulation and design tools are the answers to different needs. The first is aimed at modeling the physical aspects of a new device including as much Physics as possible; it may become very heavy from the computational point of view, often it is not user-friendly and requires training to be properly used.

The design tool, or better, the CAD tool is a byproduct of numerical (simulation) and of analytical computation merged to provide the embedding, in a logical sequence, of a set of engineering formulae, validated by a theoretical analysis and, possibly, by the benchmarking of more than one code. It must be conceived as a device capable of being:

a) fast and reliable;
b) self- explaining;
c) easy to use.

The use of a CAD tool is in most cases an answer to simple needs: the user could have some equations modeling a physical or logical system and he may want to handle them for different purposes. Requested features are the possibility to easily change some parameters to see how they influence the results and the ability to save a particular configuration of parameters and related results, either for later use with the same simulation tool or for further manipulation by other software applications aimed at, e.g., reporting, graphical visualization, optimization, prototyping, etc.

The benefits of utilizing simulations, when an adequate tool is used, are clear both for the scientist and for the designer, but building up a good simulation code is a great work and many more problems arise in the case of multi-domain and multi-physics systems, which take into account phenomena of different nature, like mechanical, thermal, electrical effects, each one often related to different scales: macro-level, atomic level, sub-atomic level, etc.

In this case, a single software tool is hardly suited for every domain and, on the other hand, a general purpose simulation tool may not be optimized for solving a

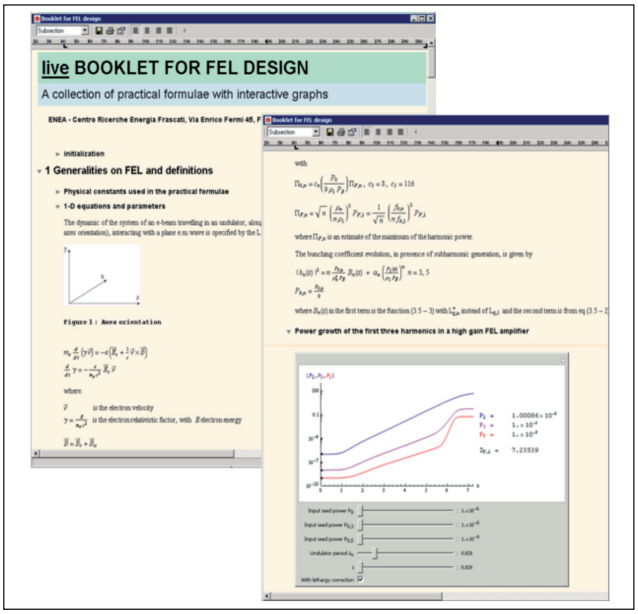

FIGURE 2 Live booklet for FEL design

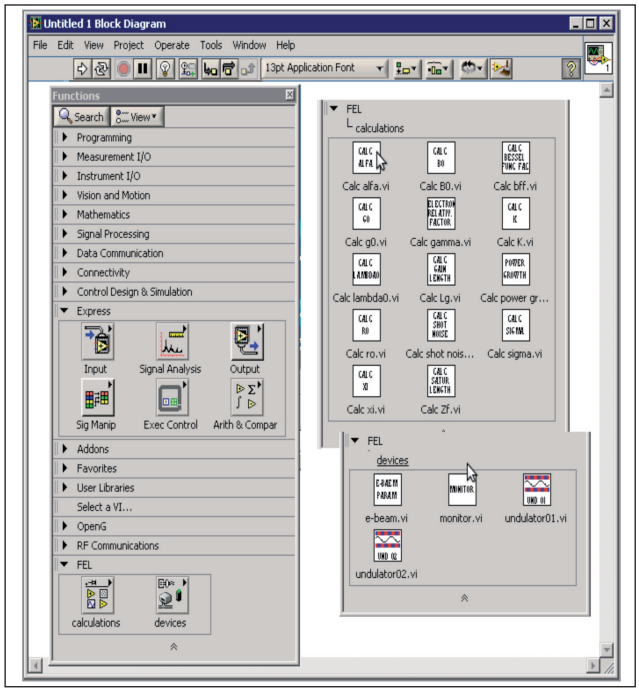

FIGURE 3 Some LabVIEW palettes customized for FEL applications

certain class of problems with the requested accuracy or performance. Thus, one needs to use different tools or develop one's own simulation tools.
This is particularly true for FEL design where a very sophisticated theoretical model has to be considered, with a lot of interdependent parameters.
A reasonable (and usual, in fact) approach is to split the FEL system into functional sub-systems connected in a sort of pipeline (as Figure 1 itself suggests) and simulate them separately. Even in this case, simulations could be very long and difficult, but further decomposition into smaller sub-blocks is not generally advised, due to tightly interconnected phenomena.

Live booklet

In the past years, the strategy we followed to achieve a fast and reliable description of FEL devices was that of combining numerical codes and theoretical models to get a set of semi-empirical formulae capable of describing the FEL in its different configurations. This conception[1] led the Authors to develop an interactive software tool based on these formulas.

It is a kind of multimedia documentation about FEL design, where main formulae and model are presented and briefly commented. Being based on the Mathematica notebook format (by Wolfram Research, see Figure 2), formulae can be easily handled by the user and the results could be immediately visualized by animated graphs, which change their shape in real-time while design parameters are changed.
This simplified practical model allows a second-level, lighter but reasonably accurate simulation. Good accuracy and faster computation times (based on practical formulae, rather than on general models) are the key-point of this type of tools. They could also be a useful instrument to help scientists or students to better understand the behavior of FEL devices and assist the designer in defining project specifications, showing a viable path to build a framework for a future computer aided design environment targeted at FEL applications.
An effective design process requires a quick and reliable evaluation of the results for any change in specifications, constraints or assumptions: trial and error are

part of the process and lead to solutions where sophisticated theoretical models by themselves cannot lead to, as it usually happens in a real world laboratory.
This suggests pursuing the convergence between CAD tools and virtual laboratories (VL).

Virtual labs

In literature[2-4], "virtual laboratories" are often proposed, along with "remote laboratories" for educational purposes. By definition, a remote lab is an experiment conducted and controlled remotely through the Internet. These experiments use real components or instrumentation at a different location from where they are being controlled or conducted. Software tools are used to imitate and replicate the physical interfaces at a distance: no simulation is needed. On the other hand, a virtual lab is based on software to simulate the lab environment while experiments based on the virtual instrument (VI) concept can be easily made ready for Internet delivery. Control devices, materials and devices under test, and the underlying interaction processes are simulated.
The goal of a virtual lab for computer aided design (VLCAD) is to facilitate the design phase by making it possible for engineers, scientists and specialists (maybe from different fields) to develop their own devices, to estimate work hypothesis and run virtual tests. VLCAD should let the functions of single devices be analyzed and the working conditions of the whole system made by different interconnected units be evaluated. It should offer ready-made (virtual, of course) monitor and control devices like data loggers, signal generators, displays and every other equipment to diagnose and interact with the system under test. Being also a CAD tool it should let the user build (from scratch or from databases) both the units to be simulated and the control and monitor ones, along with their user interfaces.

VLCAD for FEL

In setting up a VLCAD, a very critical aspect is choosing the programming environment.
Requested features are:

- modularity, to test individual modules easily and to develop applications quickly;
- extendable libraries, to let the designer build low- or high-level routines and outline the system hierarchically, to naturally second a top-down or bottom-up system design;
- intuitive Graphical User Interface (GUI), for user-friendly programming and application;
- security to avoid alteration, to hide the code or to create standalone applications;
- World Wide Web integration, to let applications, data and documents to be remotely accessed.

After testing a wide range of commercial and non-commercial software suites, the Authors opted for LabVIEW (by National Instruments), which is a *de facto* standard for virtual instrumentations. It also offers a rich library of functions (from mathematics to data and signal processing and beyond) in a graphical programming environment, that can be obviously extended and customized with user functions, as depicted in Figure 3 where some palettes for FEL applications are shown.
Under LabVIEW, programs and models are coded by block diagrams, that is, by putting function blocks on a dashboard and connecting them logically by drawing wires between their input and output terminals. Each program, or even each function block can be set and monitored through a so-called "front panel", which contains interactive controls for setting and displaying quantities, like buttons, numerical indicators, sliders, charts, etc.
Figure 4 shows different typical elements of the proposed VLCAD:

- a block diagram that mimics the logical layout of a possible FEL system: the output of an electronic beam ("e-beam source" block) is fed at the input of a first undulator ("und-01" block), which in turn feeds a second one ("und-02" block) that is also connected to a diagnostic device ("monitor" block) to display related quantities;
- a small front panel with buttons to make specific front panels of the blocks show up in the diagram;
- the front panel of a generic undulator block, which shows, for example, some sliders to set the desired values of working parameters, a chart displaying the power growth along the z axis, plus other control values, coming from the whole system simulation setup.

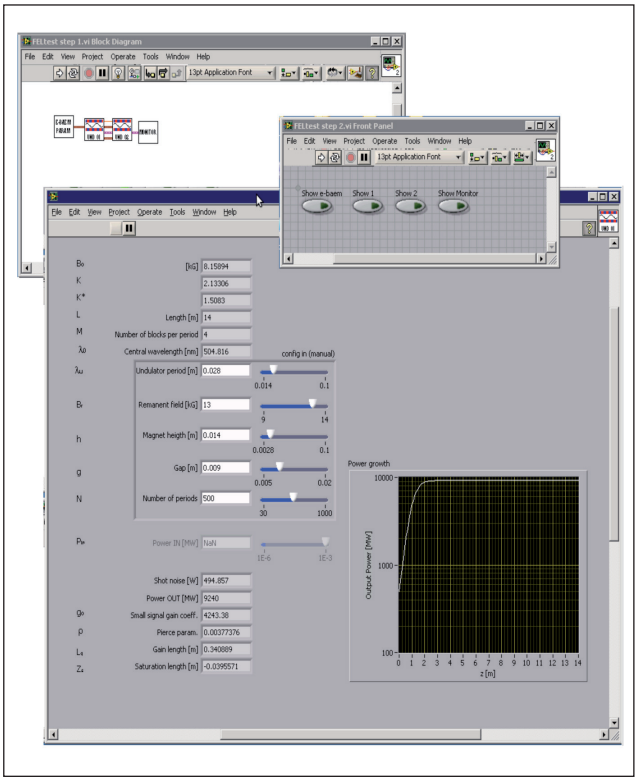

FIGURE 4 Block diagram and some related front panels of a small test FEL application

Conclusion

The international community has strongly appreciated the idea of benchmarking the results of FEL experiments by the use of semi-analytical formulae, which have been successfully exploited to analyze the experimental results at Jefferson Lab [5] where a high power FEL operating in the IR region has been realized and at UVSOR [6] for the analysis of the non- linear harmonic generation.
The "in-house" FEL experiment SPARC [7] has also benefitted from the use of the benchmarking procedure, the remarkable feature has been the possibility of a very fast and accurate analysis of the experimental results and an on-line check of the effect of the transport line on the laser performances.
In the past, we tested the procedure on other experimental configurations like the ELBE mid-IR FEL [8] and the Dutch FEL (FELIX) [9] was designed just using the semi-analytical formulae.
Further developments provide the use of the FEL-CAD to assist the design and the development of X-ray source based on the intra-cavity Compton backscattering of free electron laser Infra-Red photons.
Finally the implementation of the procedure in a virtual laboratory frame will be aimed at "testing" the performances of a FEL device in its different configurations.

Acknowledgments

The Authors express their sincere appreciation to the colleagues who, in the course of the years, supported with their interest our initiative. In particular we wish to thank Prof. W. B. Colson and Dr. S. Benson for testing the semi-analytical method either from the theoretical and experimental points of view. We are also grateful to Drs. G. Lambert, L. Giannessi and V. Petrillo for applying our procedure to the experimental analysis of non-linear harmonic generation at UVSOR and at SPARC.
Finally, we owe our gratitude to Drs. Emanuele Di Palma and Alberto Petralia for many numerical and graphical implementations of the procedure.

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