REVIEW OF EXISTING SOFT AND HARD X-RAY FEL PROJECTS

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Abstract

The existing soft and hard X-Ray FEL Projects are discussed, along with the underlying design and technological strategies. We consider two main categories: large facilities, which will involve the joint efforts of big laboratories and will take benefit from the heritage of high energy Physics facilities and smaller devices, which are aimed at exploiting high quality accelerators with modest e-beam energy to reach shorter wavelengths with alternative schemes. We will discuss advantages and drawbacks of the different conceptions and give an outlook to the future developments, with particular attention to combinations of different solutions like exotic undulators, seeding and so on, aimed not only at improving X-ray beam qualities but also at reducing device complexity and cost.

INTRODUCTION

Free Electron Laser (FEL) R&D activity spans over about thirty years. When it was conceived, 29 years ago there was the first successful amplification experiment, the FEL was just a parasitic device, running on the Superconducting Stanford Linac. In three decades there have been significant changes in Physics and in the role of electron accelerators, which are now being designed to provide ultra-fast and high quality e-beams for the production of high brightness X-ray bursts. Within the framework of this revolution, the large scale laboratories are redesigning the research strategies of the next years by planning fourth generation Synchrotron radiation sources, with the ultimate goal of reaching the hard X-ray region. On the other side the strategy of laboratories of smaller dimensions is that of developing “smart” solutions based on exotic undulators, seeding, hybrid devices (oscillator-amplifier)… to reach shorter wavelength using high quality accelerators with relatively modest energy. It is evident that these activities are not flourishing for the joy of accelerator physicists but because new interests and directions in Physics are emerging. Just to give a quick look to what happened within the last thirty years we can say that

1. the FEL emerged during a period in which the accelerators were strongly polarized towards the high energy Physics,
2. almost at the same time the Synchrotron Radiation Sources where envisaged as interesting tools to explore the structure of matter,
3. second and third generation synchrotron facilities where developed independently from high energy Physics programs and determined a vigorous effort in providing the design of small emittance e-beams in Storage Rings,
4. the FEL devices started to become a mature subject, they operated under a variety of conditions, with either single pass and recirculated devices and stimulated important technological developments in the materials for the cavity optics and in the magnetic materials for the undulator
5. it started to be clear that the brightness of the third generation synchrotron radiation sources could hardly be overcome using Storage Ring based devices, the demand for brightness ten order of magnitudes larger suggested new perspectives in their conception and design
6. FEL and Synchrotron Radiation started to merge their fates.

Regarding this last point it is worth stressing that the transition to X-ray FELs has been made possible by three joint technological efforts, in FEL Physics, in accelerator Physics and in the Physics of high quality undulators.

SOFT AND HARD X-RAY FEL PROJECTS

Two strategies as to the realization of X-FELs have been developed, one of these, aiming at realizing large scale facilities, is going to benefit from the heritage of the big science, dominated for many years by elementary particle Physics. The scientific institutions interpreting this role are listed in Tab. 1 along with the foreseen performances of the X-FEL source.

Table 1: Large scale X-FEL projects [1]

	LCLS (USA)	European X-FEL (D)	SCSS (J)
Pulse duration	<230fs	100fs	80fs
Wavelength	1-64A	1-15A	1-50A
Repetition Rate	120Hz	10Hz	60Hz
Electron Bunches/pulse	1	≤1000	1
Electron beam energy	4-14 GeV	≤20 GeV	≤8
Ph/pulse at 1 Å	1.2×10^{13}	1.2×10^{13}	0.76×10^{13}
Linac length	$10^3\ m$	$2\times10^3\ m$	350m
Cost (extimated)	379×10^6 US Dollars	10^9US Dollars	330×10^6 US Dollars
Estimated start date	2009	2012	2010

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Table 2: Small scale X-FEL projects (private communications and web sites)

	SPARC-SPARXINO (with up-graded Dafne Linac) (I)	FERMI (FEL-2) (I)	BESSY (D)	4GLS (UK)	Arc en Ciel seed @ 19nm (F)
Pulse duration [fs]	130	40-1000	20	10	200
Wavelength [nm]	10	10-40	1.24-51	10	1.2-2.1-6.3
Repetition Rate [Hz]	50	50	10^3		10^3
Electron beam energy [GeV]	1	1.2	2.3	0.6	1
Ph/pulse	10^{13}	7.5×10^{12}	2×10^{11}-7×10^{16}	7×10^{13}	~10^9-10^{10}-10^{13}
Linac length [m]	~ 10^2	~ 10^2	~ 10^2	~ 10^2	~ 70
Cost (estimated)	~ 20 M€	~ 40 M€	~ 200 M€		
Estimated start date	2009	2009	2010		proposal

It is evident that in these devices most of the effort is dedicated to the e-beam source, which will drive the laser process, if it will provide the e-beam with the desired characteristics. In Tab. 2 an analogous synopsis for the devices belonging to the alternative strategy is reported (the reported parameters are relevant only to specific configurations of the devices when operated in the shortest wavelength region). It is worth to note that size and energy of the accelerators listed in Tab. 2 differs from those in Tab. 2 by one or two orders of magnitudes.

Namely in these last ten years a huge theoretical and experimental activity (from IR to VUV) has been performed with the aim to clarify technical and scientific aspects related to the generation of coherent synchrotron light in FEL SASE, HGHG and seeded regime. The results of these variety of researches have been the basis for the proposals of large scale and small scale soft hard X ray projects previously reported (Tab. 1 and 2 respectively). Large scale devices can reach the X-ray region “simply” by operating in first harmonics FEL SASE mode while small scale devices have to exploit “exotic” configurations like high gain harmonic generation and seeding, see previous section. Obviously large scale devices too can operate in these less conventional modes, but, in this case, the reason lies in the request of enhancing the radiation beam qualities, in terms of shot to shot stability of power, spectrum, timing, pointing and in terms of transverse and longitudinal coherence.

In Fig. 1 we have reported a kind of scaling relation vs. years, starting from 1985, showing the trend of FEL wavelength, requested e-beam of energy and normalized emittances.

A better idea of the needed technological effort is given in Fig. 2, which more clearly shows the present and future trend for the first decade of the third millennium as to e-beam energy and emittances for high gain

In Figs. 1, 2 we have reported the trend of the large facilities, in Fig. 3 we have included the future trend of the smaller scale projects

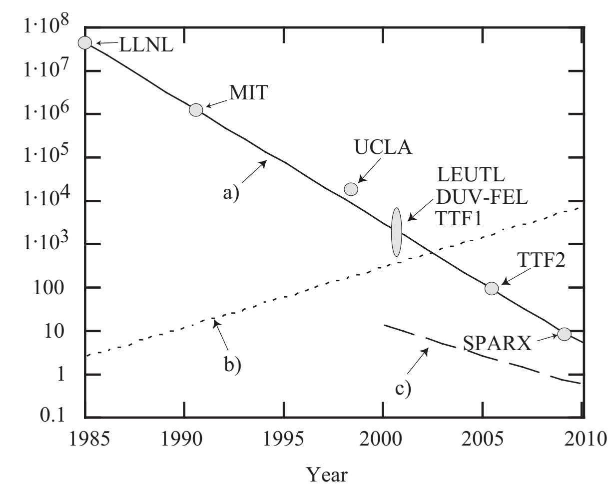

Figure 1: a) Wavelength in Å (continuous line), b) e-beam energy in MeV (dot), c) normalized emittances in mm×mrad(dash).

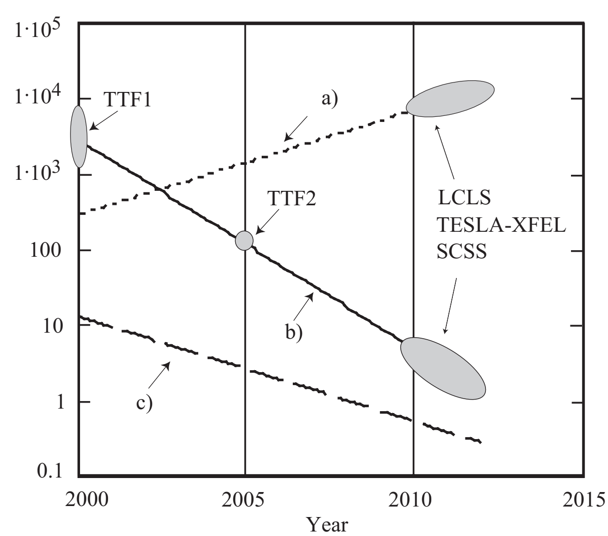

Figure 2: Same as 1 for the third millennium first decade.

The use of higher order harmonics allows the possibility of operating at wavelengths close to that of

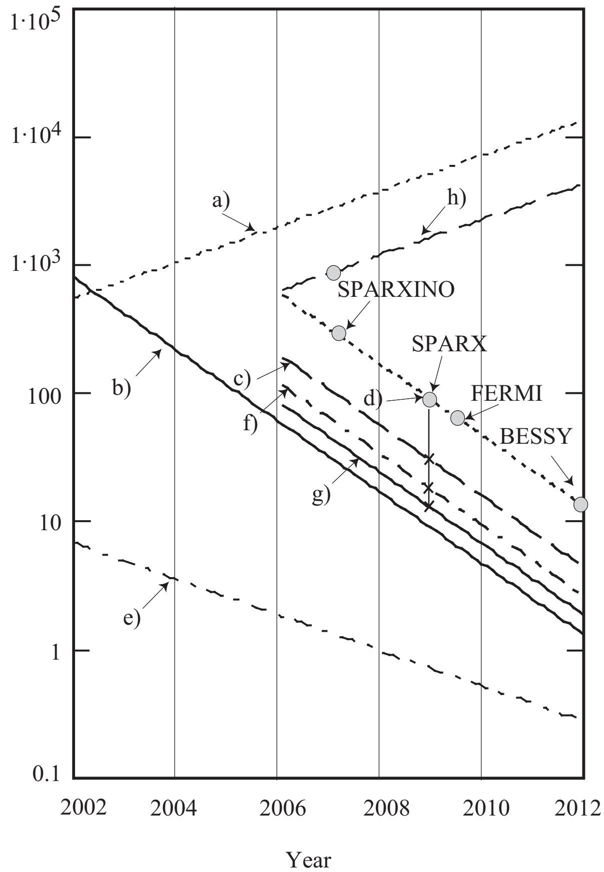

Figure 3: a), b), c) as in Fig. 1; d) small size FEL devices e-beam energy; e) small size FEL devices wave-length; f), g), h) 3rd, 5th, 7th harmonic operation.

larger facilities employing accelerators with an energy smaller by an order of magnitude and with a comparable reduction of costs. In the following we will comment on the combination of non linear harmonic generation and micro-undulators which may provide further improvements.

THEORETICAL BACKGROUND

The theoretical and mathematical concepts, underlying the design of a high gain FEL device, lie in a nut-shell. We can indeed use one key parameter only, namely the Pierce parameter ρ [2], which can be exploited to characterize design quantities and laser performances.

The gain length $L_g = (\lambda_u / 4\pi\sqrt{3}\rho)$ ruling the linear growth of the laser power along the undulator, is a quantity of central importance and can be exploited to characterize the laser power growth up to the saturated power $P_F = \sqrt{2}\rho P_E$ in a length $Z_s = 1.066 L_g \ln(9P_F/P_0)$ (see Ref. [3]), with P_E and P_0 being the e-beam and the input seed power. If the process starts from a pre-bunched e-beam, the equivalent seed, due to the beam bunching, is $P_b \cong 0.22 \cdot \|b_1\|^2 \rho P_E$, with b_1 being the bunching coefficient.

The induced energy spread is, in the small signal limit, linked to the square root of the FEL power, and the relevant behaviour vs. the longitudinal undulator coordinate are shown in Fig. 4

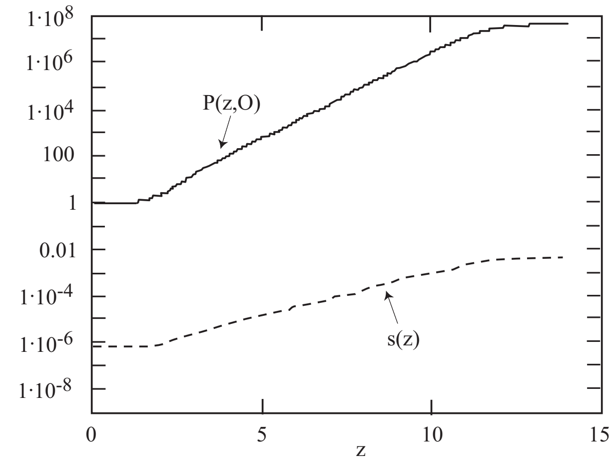

Figure 4: FEL power (continous line) and induced energy spread (dotted line) vs the longitudinal coordinate z for ρ=220×10^{-3}. λ_u=2.8 cm, K=2.143. P_E=15GW.

The induced energy spread is an interesting quantity for practical purposes, it can be exploited to understand the level of induced e–beam quality dilution. We can indeed define a characteristic length for such a process, as the undulator length necessary to get $\sigma_i = \rho/2$, which corresponds to $Z_B \cong 0.94 Z_s - 2.44 L_g$. At such a length, the system is far from the saturation, but the e–beam has acquired a fairly strong bunching, which may provide a conspicuous amount of coherently generated power at higher harmonics. The use of such relation can therefore be helpful to determine the length of the pre-bunching section in segmented undulator schemes, where the undulator consists of two (or more sections), the first of which is used to provide a suitable prebunching of the e-beam which will be then injected in a second section operating at a subharmonic of the first.

The possibility of emitting radiation at sub-harmonics of the fundamental is well documented in literature (Ref. [4]). In linearly polarized undulators the bunching may provide a significant amount of coherent radiation at odd harmonics of the fundamental, namely at $\lambda_n = (\lambda_u / 2n\gamma^2)(1 + (K^2/2)), n = 3,5...$ and the interest for such a mechanism is evident, since it provides a practically free extension of the tunability of the system.

The non linear harmonic generation is a well known by product of the FEL SASE dynamics. The harmonic gain length is given by

$$L_{g,n} = \frac{\rho_1}{\rho_n^*} L_g \qquad (1).$$

$$\rho_n = \left(\frac{f_{b,n}}{f_b}\right)^{\frac{2}{3}} \rho, (\rho = \rho_1)$$

where

$$f_{b,n} = J_{\frac{n-1}{2}}(n\xi) - J_{\frac{n+1}{2}}(n\xi), \quad f_{b,1} = f_b$$

$$\xi = \frac{1}{4}\frac{K^2}{1+\frac{K^2}{2}},$$

The evolution of the 3-rd and 5-th harmonics, along with that of the fundamental is shown in Fig. 5, and it is worth stressing that the harmonics reach a final power given by

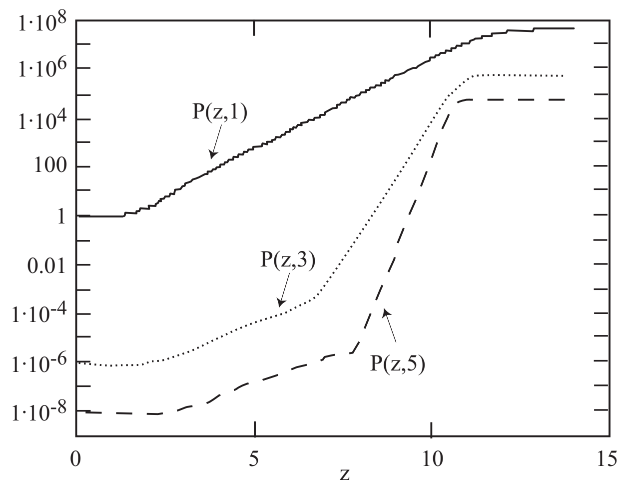

Figure 5: Evolution of the power of the first three harmonics (1-st continuous line, 3-rd dotted line, 5-th dash line) same parameters of fig. 3.

$$\Pi_{n,F} = \frac{1}{\sqrt{n}}\left(\frac{f_{b,n}}{n f_{b,1}}\right)^2 P_F \qquad (2),$$

Starting from an equivalent seed specified by

$$\Pi_{n,0} = b_n{}^2 \Pi_{n,F},$$

$$b_n = \left(\frac{P_o}{9\rho_n^* P_E}\right)^{\frac{n}{2}} \qquad (3).$$

The results we have summarized so far contains the design philosophy of different types of high gain FEL devices, from the plane SASE configuration, to other possible schemes including harmonic generation and segmented undulators, in which the undulator is properly cut at a given length to introduce a further undulator section, tuned at an harmonic of the first to produce shorter wavelength laser power, as shown in Fig. 5, while in Fig. 6 we have reported the ratio between the harmonic power and the fundamental. For example, by using values of the strength parameter k of the order of 2 one can get, e. g. for the third harmonic, an amount of power which is larger than 1% of the fundamental.

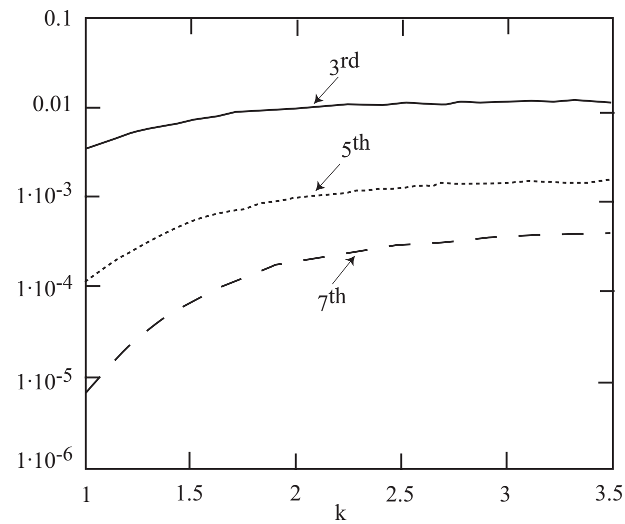

Figure 6: Ratio of the harmonic power to the saturated power of the fundamental vs k a) 3^{rd}: b) 5^{th}; c) 7^{th}.

CONCLUDING REMARKS

In this contribution we have presented a review of the existing soft and hard X-ray FEL devices. Before concluding we would like to stress that a significant effort has been done towards the realization of mirrors for laser resonators, capable of confining short wavelength radiation in the region below 170 nm. In the next years it will be possible to have optical resonators confining radiation in the range of 150nm or less, the use of the mechanism of intra-cavity non linear coherent harmonic generation can therefore exploited to produce a significant amount of coherent radiation in the region of 10nm, without all the problems associated with SASE devices.

The combined use of intra-cavity harmonic generation and of micro-undulators may provide compact tools reaching short wavelengths with very modest e-beam energies. In Fig. 7 we have reported the FEL wavelength vs. energy for a micro-undulator with $\lambda_u = 1\text{cm}, k = 1$,

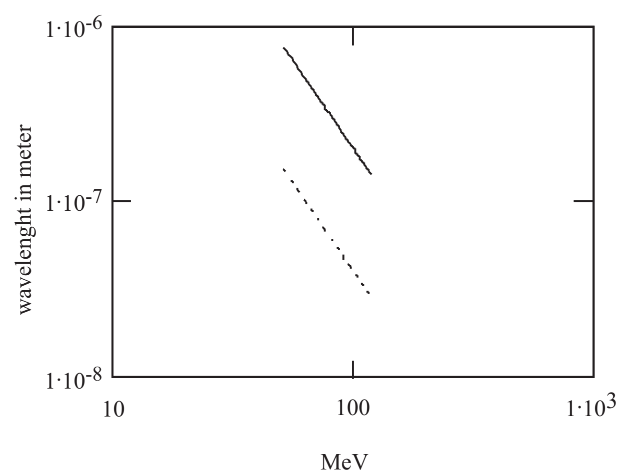

Figure 7: FEL wave-length vs. e-beam energy for an oscillator using a micro-undulator with $\lambda_u = 1\text{cm}, k = 1$.

assuming as technological limit for the mirrors 150nm it might be possible to reach, with the 5-th harmonics, less than 30nm using a 100 MeV linac.

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