Overview of Proposed VUV and Soft X-Ray Projects in the World

FEL 2002 Conference

Argonne (USA) September 9-13, 2002

Giuseppe Dattoli and Alberto Renieri

ENEA -UTS FIS - Frascati (Italy)

SUMMARY

- INTRODUCTION
- WHAT WE LERNT FROM THE PAST
- SCENARIO OF THE VUV AND SOFT X-RAY PROJECTS
- ROAD MAP TOWARD VUV-X SPECTRAL REGION
- CONCLUSIONS

INTRODUCTION

Synchrotron Radiation facilities developed in about 40 years from the stage of parasitic devices (1st gener.) to the so called 3rd generation, which have now been operated for about eight years, and are capable of providing photon beams with peak brilliance of at least 10^{18} *c.u.(photons/sec/0.1%bw/(mm mrad)*^{2})

Such an evolution in terms of brilliance has been made possible by the tremendous effort in the conception, design and technology advancement of the accelerators providing the electron beam and of the insertion devices where the radiation is generated

In a typical 3rd generation light source, the hor. (vert.) r.m.s. emittance ε_x (ε_y) is about 10^{-9} (10^{-10}) mxrad, thus ensuring good transverse coherence in the UV region and partial coherence down to tens of Å or shorter

Notwithstanding the development and the operation of 3rd generation sources did not determine automatically the death of the 2nd generation counterparts

Third generation sources are indeed coexisting with 2nd generation devices, which have recently provided very important and crucial results in condensed matter Physics

This is a clear indication that the number of figures of merit characterizing a specific application is so wide that 3rd generation sources cannot be considered indisputably better for any experiment involving synchrotron light

Such a lesson from the past is not of secondary importance and is a key point to be kept in mind when discussing of any further improvement beyond 3rd generation.

Since 1976 Free Electron Lasers (FEL) produce highly coherent radiation beams with brightness many orders of magnitude larger than that of undulator radiation.

To date the shortest wave-length record of a FEL oscillator is 190 nm from the Storage Ring based FEL oscillator in Trieste. The present wavelength limit of FEL oscillators is mainly due to mirror availability and the relevant technological improvements will certainly allow, in the next future, the operation at shorter wave-lengths.

By keeping as figure of merit the e.b. characteristics of 3rd generation sources we can safely conclude that storage ring FEL oscillators are technologically mature devices, capable of providing highly coherent radiation with peak brilliance exceeding 10^{28} c. u. in the region around 150 nm.

Storage ring FELs have provided us with an important tool of research not fully explored and recognized

In particular the important contribution to the understanding of microwave instability evolution in storage rings, made possible by the study of e.b.-FEL radiation combined dynamics has to be mentioned.

These results could provide a deeper insight into the phenomenology of coherent synchrotron radiation (CSR) and on its cures

What we learnt from the past

Scientific community is pushing for new solutions going far beyond the present status by designing devices capable of delivering X-ray beams with much larger brilliance and shorter pulse length.

What we do expect from the next generation sources:

- *Coherence (transverse, longitudinal)*
- *Pulses with short time duration (hundreds of fs)*
- *Tunability towards the Å region*
- *Brilliance (peak and average), values significantly exceeding by 10-11 order of magnitudes the present levels*
- *Access to a wide number of users*
- *Long operation time.*

The possible options as next generation S.R. sources are:

1) Storage Ring Upgrade
2) Linac Based Sase FELs
3) Energy Recovery Linacs (ERL).

Regarding the first solution, going in the direction of developing S.R. sources without any dramatic change of technology, the minimization of the emittance requires the design of a lattice which compensates the dilution effects induced by the quantum excitation.

Unfortunately, the demands for high brilliance coherent radiation at shorter wavelengths is conflicting with the request of small emittance, which increases quadratically with energy.

Its minimization requires the design of a lattice which compensates the dilution effect induced by the quantum excitations.

The price to be paid to have a low emittance is to have a high energy storage ring with a large circumference to allow the insertion of the optical elements necessary for the quantum diffusion compensation.

To give a more quantitative idea we note that the number of cells N_c necessary to fulfill the condition (K is the usual pinch parameter and γ is the electron energy in rest mass unity)

$$\varepsilon = \lambda/(4\pi),\ \lambda = \lambda_u(1 + K^2/2)/(2\gamma^2)$$

is

$$\boxed{N_c = (2\pi * 7.7 * 10^{-4}\,(1 + K^2/2)\,(\lambda_u/\lambda^2))^{1/3}}$$

With λ_u (length of undulator period) and λ (operating wavelength) given in mm. It is clear that such a condition becomes more and more difficult to satisfy at shorter wavelengths.

E.g., a design of an ultimate Hard X-ray Source (UHXRS) foresees a circumference of 2200 m necessary to allocate 160 bending magnets and 720 quadrupoles [*].

Such a magnet array would provide at 7 GeV, with respect to ESRF at 6 GeV, e.b. with horizontal (vertical) emittance 20 (2) times smaller with a bunch length about 1/3 shorter at 12 keV of photon with average and peak brilliance more than 2 order of magnitudes larger (i.e. $3.5*10^{22}$ c.u. and $1.0*10^{25}$ c.u. respectively)

[*] P.Ellaume, "Synchrotron Radiation: Perspectives and New Technologies" Atti dei Convegni Lincei 179, Roma 2002

There is a second tribute which should be considered when dealing with solutions of this type:

the large number of insertion devices will inevitably increase the machine longitudinal impedance, thus determining current intensity limitations associated with microwave type instabilities, and the increase of Touscheck intra-beam scattering as a consequence of the smallness of the e.b. emittance, will cause the reduction of the beam life-time to few hours.

This fact will require re-injection of a small current every few tens of minutes. In any case the beam transport lattice prevents the achievement of pulse length shorter than few tens of ps.

The use of Energy Recovery Linacs (ERL) is an interesting candidate which prevents all the unpleasing features of Storage Ring sources.

Namely, after the successful operation of the high power IR FEL at the Jefferson Lab., interesting proposals have been issued by many laboratories, aimed at the enhancement of the brilliance, together with the possibility to generate very short radiation pulses (hundred of fs or even less) in the VUV - X range.

Scenario of the proposed VUV and soft X-ray FEL projects

Under development VUV and soft X-ray projects scenario

project	*location*	*type*	*e-beam energy*	λ [nm]	*notes*
TTF2	**DESY, Hamburg (D)**	**SASE**	**1 GeV**	**6**	**start of operation: 2004**
SCSS	**SPring-8 (J)**	**SASE**	**230 MeV (phase I)** **1 GeV (phase II)**	**40** **3.6**	**“compact”:** **- short period in vacuum undulator** **- high gradient C-Band accelerator** **- low emittance beam injector** **start of operation at 40 nm: 2005**
DUV-FEL	**NSLS, BNL (USA)**	**SASE** **HGHG** laser seed	**2000 MeV**	**200-50**	**achieved 400-nm by SASE on Febr. 2002**
LEUTL	**APS, Argonne (USA)**	**SASE** **HGHG**	**220 MeV**	**660-130**	**achieved 130 nm by HGHG**

Proposed VUV and soft X-ray projects scenario (I)

project	*location*	*type*	*e-b.energy* [GeV]	*λ* [nm]	*notes*
TESLA X-FEL	**DESY, Hamburg (D)**	**SASE**	**25**	**0.1 nm**	**considered to be worthy of support by German Science Council (Pressemitteilung 20/2002)** ***start of operation: 2011***
SOFT X-RAY FEL	**BESSY, Berlin (D)**	**SASE**	**2.25**	**1.2 nm**	
LCLS	**SLAC,Stanford (USA)**	**SASE**	**15**	**0.15**	**The project has been receiving funding of $1.5 Million per year from the DoE for the period FY1999-FY2002. Funding is expected to increase in FY2003 to $6.0 Million as listed in the Presidents Budget for FY2003** ***start of operation: 2008***
SPARC	**ENEA,INFN,INFM, CNR,Synch.Trieste, Un. Roma II (I)**	**SASE**	**0.15**	**VIS-VUV**	**(funded)** ***start of operation: 2005***
SPARX	**ENEA,INFN,CNR, Un. Roma II (I)**	**SASE**	**2.5**	**1.5 nm**	**It is intended as a second step after SPARC (awaiting for Government decision)** ***start of operation: 2008***

Proposed VUV and soft X-ray projects scenario (II)

project	*location*	*type*	*e-b.energy* [GeV]	λ [nm]	*notes*
VXFEL	**INFM, Synch. Trieste, Pirelli S.p.A. (I)**	**SASE FEL osc. + Harmonic Generation**	**1**	**6.4 nm**	
FERMI	**INFM, Synch. Trieste (I)**	**SASE**	**3**	**1.2 nm**	**(awaiting for Government decision)** *start of operation: 2008*
4GLS	**Daresbury (UK)**	**SASE (XUV) FEL osc. (VUV)**	**0.6**	**VUV-XUV (IR FEL osc.) ERL scheme**	**Secretary of State for Trade and Industry: on 16th April 2002 it was agreed that 4GLS should proceed to the next stage of the Office of Government Commerce Gateway review process**
SOLEIL FEL	**SOLEIL (F)**	**FEL oscillator**	**1.5**	**150 nm up to 30 nm (5th harmonic)**	**Storage ring FEL**

All these projects, with the exception of SOLEIL FEL, are based on SASE FEL scheme driven by r.f. linac, which appears to be the only suitable for operation in the soft X ray region.

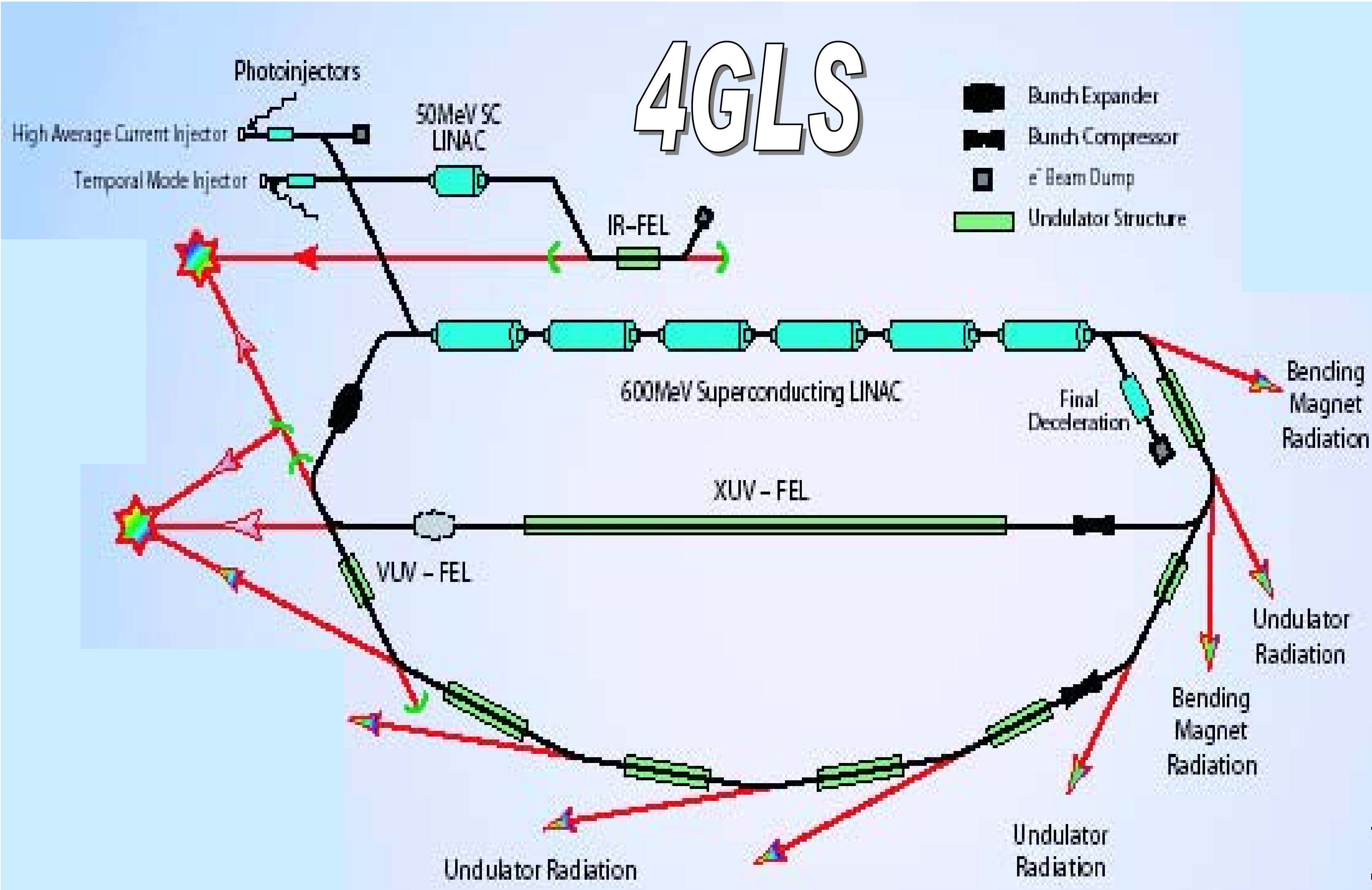
Namely storage ring based devices are limited to the VUV region, due to the lack of suitable mirrors (which, in addition, would have to support a quite high power radiation flux too) and to the extreme difficulty to produce very short (sub-ps) radiation pulses due to the impossibility in a storage ring to shape the e.b. in a suitable way (no memory system).

This fact precludes also SASE FEL operation (long undulators in by-pass sections).

Anyway storage ring FELs maintain a quite large interest, being complementary to the SASE devices in the VUV spectral region.

In this list there is no mention of ERL devices, in which *only* normal (i.e. spontaneous) undulator radiation is generated with a peak brilliance expected to be up to 5 order of magnitude higher than the present 3rd generation synchrotron radiation sources.

As to the devices devoted to FEL operation, only the 4GLS proposal is based on an ERL scheme in a kind of ring configuration, in which XUV (SASE FEL), VUV (FEL oscillator), IR (FEL oscillator) and spontaneous undulator radiation sources are operated and, eventually, utilized together for multiple photon applications.



4GLS
Photoinjectors
High Average Current Injector
Temporal Mode Injector
50MeV SC LINAC
IR-FEL
Bunch Expander
Bunch Compressor
e⁻ Beam Dump
Undulator Structure
600MeV Superconducting LINAC
Final Deceleration
Bending Magnet Radiation
XUV - FEL
VUV - FEL
Undulator Radiation
Bending Magnet Radiation
Undulator Radiation
Undulator Radiation

Road map toward VUV-X spectral region

The challenge related to the realization of very high brilliance short pulse VUV – X sources is considerable.

The cost of this kind of R&D activity is close to that of the so-called “Big Science”.

It does not appear quite convenient that just a single lab. would invest in this field, still in strong evolution, the required large amount of money and man power

For this reason the need of a more or less coordinated effort was clear from the very beginning.

From the analysis of what has been done up to now it is possible to recognise *a posteriori* a kind of road map along which the past R&D has been developed.

In this moment many laboratories are studying new strategies in which a reliable road map toward X-ray spectral region has to be designed.

Milestones of this road map must be those of all the laboratories involved in, in order to share at the best experience and results.

In a quite natural way, due to the formal and informal collaborations, this common road map appears now quite well outlined.

In this analysis we limit ourselves to the case of single passage SASE FEL devices. Alternative options do not appear suitable, at the present status of the art, for operation up to the Å region

The main key-issues relevant to a SASE FEL device can be summarized as it follows:

- ***Physics of the SASE FEL process***
- ***Generation and shaping of suitable e.b.***
- ***Electron beam acceleration and transport***
- ***Undulator magnets***
- ***Electron beam and X-ray diagnostics***

It is out of the scope of this talk to enter into the technical details of all these topics.

What we shall do is to try, for each of them, to single out some relevant milestones measuring the path along the way in the direction toward X –ray spectral region.

Physics of the SASE FEL Process

Physics of SASE FEL has been investigated many years ago in series of papers in which the main features of the process have been clarified. See, e.g., *just to quote some of the oldest*:

P. Sprangle et al., *Phys Rev.* A21, 302 (1980);

G. Dattoli et al., *IEEE J. Quantum Electron.*, QE-17, 1371 (1981);

R. Bonifacio et al., *Opt. Commun.* 50, 373 (1984);

Kwang-Je Kim, *Nucl. Instr. and Meth.* A250, 396 (1986),

The main experimental milestones can be single out as it follows:

• 1984 LLNL: 34.6 GHz radiation propagating along a wave-guide, driven by induction accelerator (very high efficiency: saturation with tapered undulator)

•1989 MIT: 240 – 470 GHz radiation propagating along a wave-guide (FEL (weakly) collective Raman regime)

•1998 UCLA: $\lambda = 12$ ***μm, free space propagation (not saturated)***

With this last experimental result there was a quantitative and qualitative improvement of our knowledge on SASE process. Namely the operating wavelength was about 3 orders of magnitude shorter than LLNL 1984 device and a factor 50 shorter than MIT 1989, and, in addition, the optical radiation propagates in free space and not along a wave-guide.

• 2001 TTF1: $\lambda =$ ***80-120 nm (saturation) : good agreement with the theory***

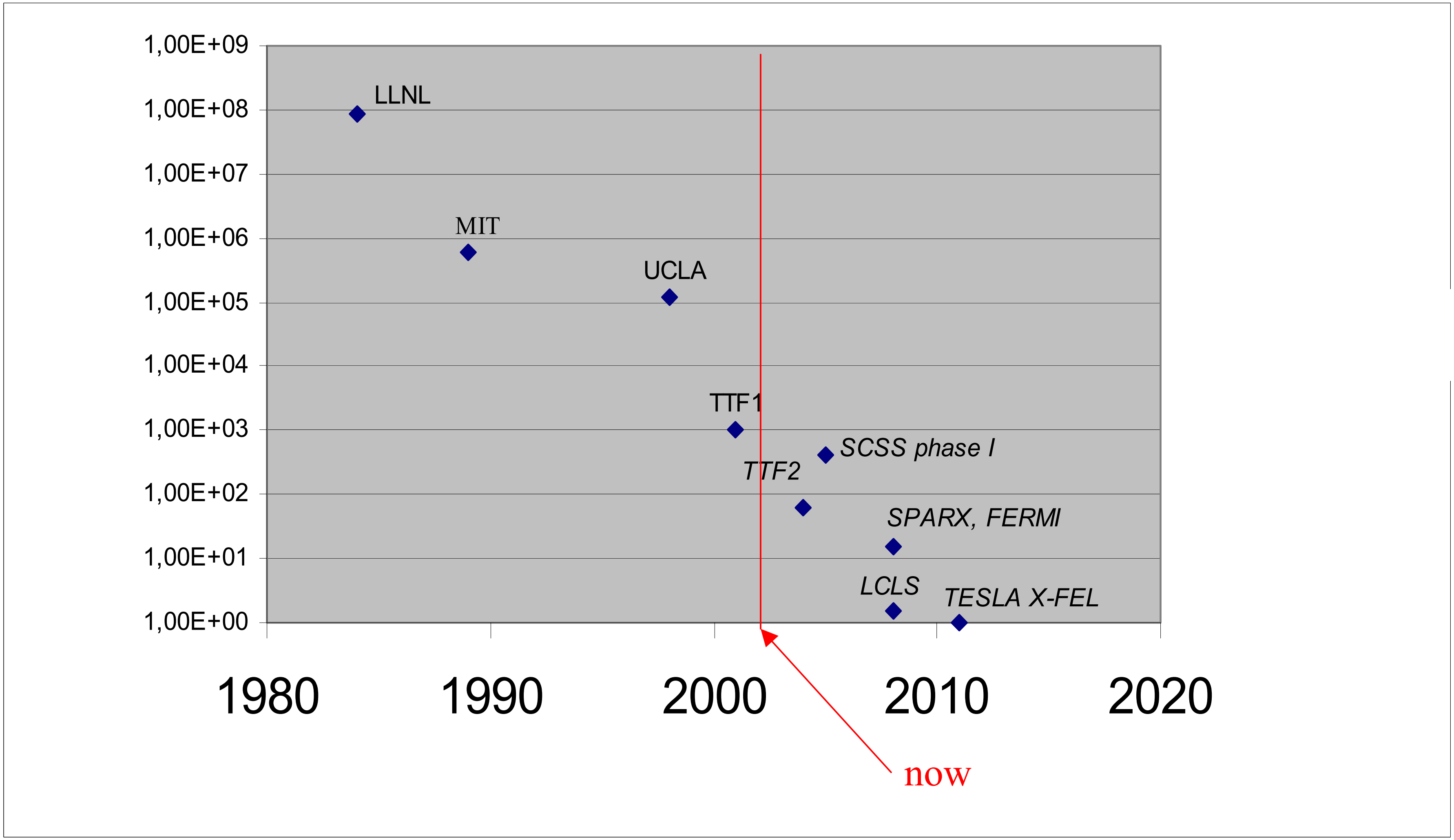
Lasing at 100 nm was a quite big step toward VUV – X ray spectral region (more than two orders of magnitude with respect to first UCLA 1998 result).

The state of the art of SASE FEL theory is now mature.

We can be confident that the process is well understood and, if the requested experimental conditions will be correctly satisfied, it will be possible to operate with the desired spectral and brilliance characteristics up to soft X-rays

A large part of the device previously reported is foreseen to operate between 10 and 0.1 nm (i.e. between only one and three orders of magnitude shorter wavelength with respect to TTF I).

SASE FEL devices operating wavelength (Ångstrom) vs. (foreseen) year of start of the operation



On the other side, a lot of additional work is still required for the investigation and analysis of new schemes, in particular aimed at improving spectral and/or coherence properties of the generated VUV – X radiation.

Specific experimental activity is foreseen in the presently under development devices and in the new proposal. Relevant future milestones can be outlined as it follows:

- *HGHG (High Gain Harmonic Generation) theoretical and experimental R&D*

- *Spectral purification and coherence enhancement (seeding, filtering, low energy electron beam feedback , ...)*

Generation and shaping of suitable electron beams

The important advances in the field of generation and shaping of very high brightness e.b. are mainly related to the development of photo-injectors.

FEL community shared this technology and pushed a strong R&D activity in order to reach goals of specific interest for Visible and UV FEL oscillator, at the beginning, and, now, for SASE FEL devices.

• Photo-cathodes: first devices (at that time called "Lasertron") were developed at SLAC (USA), KEK (J), LAL (Orsay, F) and LANL (USA) in the middle of 80's. In particular it must be underlined the quite big effort made in LANL, where high efficiency photocathodes have been developed just for FEL applications

• Magnetic beam compression: it is interesting to note that this technique have been utilized in a FEL device many years ago (in the middle of 80's) in order to have just the opposite effect, i.e. to reduce the energy spread at the expense of bunch length and peak current (FELIX (Glasgow, UK)

High brilliance cathode development

A first milestone certainly concerns further important improvements of performance and reliability of the photoinjectors and R&D on alternative cathode schemes:

SCSS (J): CeB6 single crystal thermionic gun

TESLA X FEL (D) –first measurements at the PITZ (photo-injector test facility at DESY Zeuthen) (paper TU-P-02)

Furthermore we must underline a milestone related to the realization of a superconducting (s.c.) r.f. photo-injector. Namely the possibility to exploit at the best the high duty cycle of a s.c. linac is related to the availability of a full s.c. device, gun included.

S.c. r.f. photo-injector: first results of collaboration FZR-BINP-DESY-ACCEL-MBI (paper WE-O-03)

STATUS OF SCSS: SPRING-8 COMPACT SASE SOURCE PROJECT

T. Shintake, et al. EPAC 2002

"In the HV pulse gun, 3 A beam with 300 nsec flattop pulse will be pulled out from a single-crystal CeB6 cathode of 3 mm. The R&D issue on this design is (1) development of reliable 500 kV pulsed power supply, (2) reliable heating mechanism for the cathode (nominal operation temperature is 1450 C)."

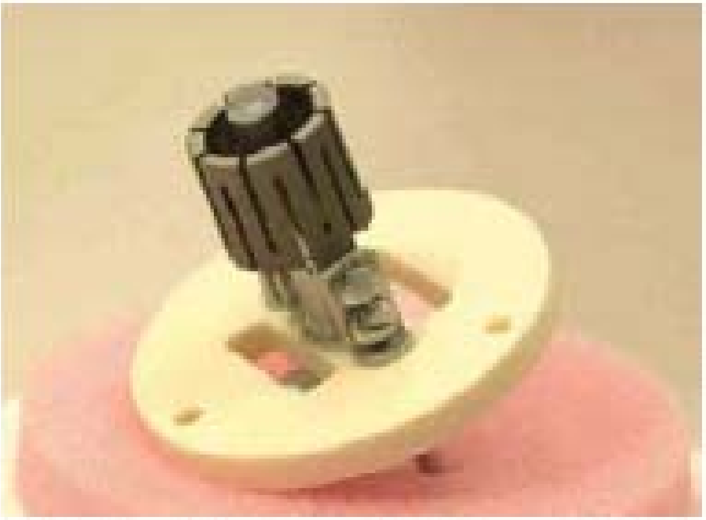


Fig.3. CeB_6 single crystal cathode with graphite heter.

Non magnetic compression schemes

Finally, as to the e.b. shaping, due to the fact that the CSR emitted in the curved electron path can generate severe damage to the e.b. emittance and energy spread, a further milestone related to a non magnetic beam compression scheme must be foreseen.

UCLA: Velocity bunching observed

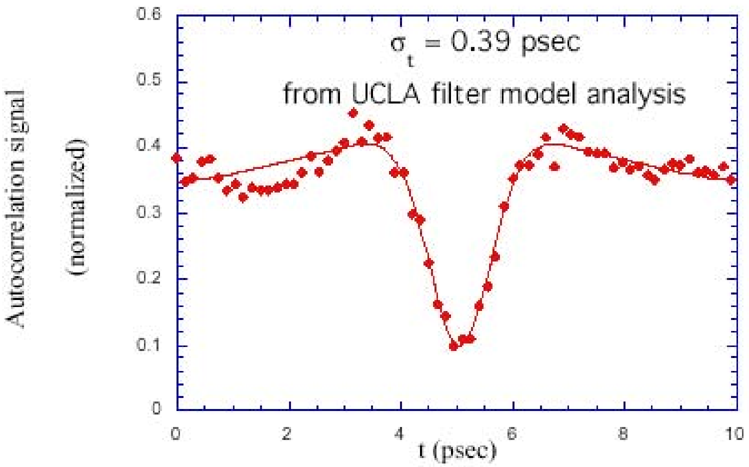
DUVFEL: RF compression (factor 5 of current enhancement)

SPARC– SPARX: longitudinal bunch compressor planned (paper TH-P-14)

Velocity bunching observed

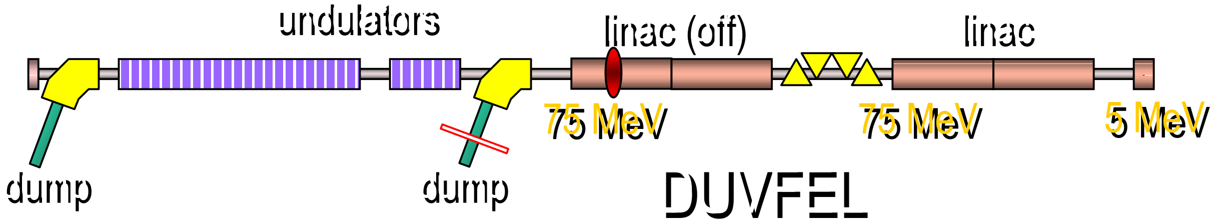
UCLA

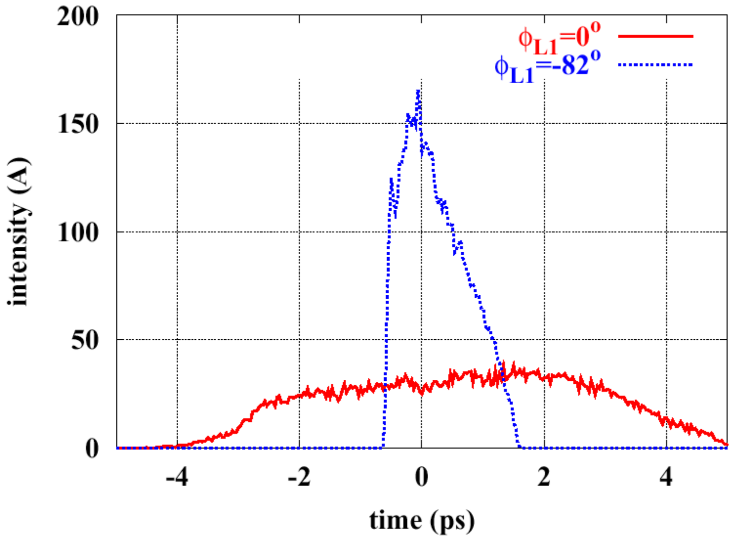
- Compression *better* than chicane (<0.4 ps)
  - Linearity of the rf used to focus gives smaller long. emittance
  - At resolution limit of interferometer
- What are the effects on transverse phase space?

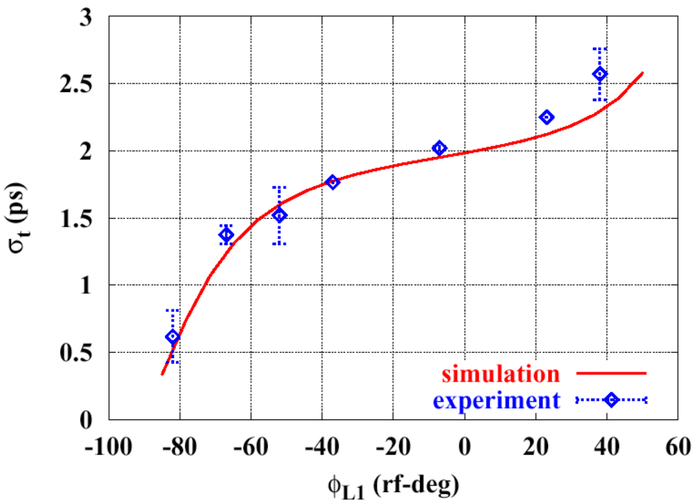


P. Musumeci and J.B. Rosenzweig "Velocity Bunching: experiment at Neptune Photo-Injector", to be published in the Proceedings of ICFA Workshop on "The Physics and Applications of High Brightness Electron Beams", Chia Laguna, Italy, July 1-5, 2002

P. Piot et al.,"Subpicosecond compression by velocity bunching in the DUV-FEL photo-injector at BNL", to be published in the Proc. of ICFA Workshop on "The Physics and Applications of High Brightness Electron Beams", Chia Laguna, Italy, July 1-5, 2002



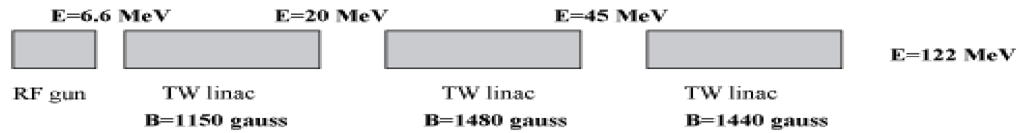




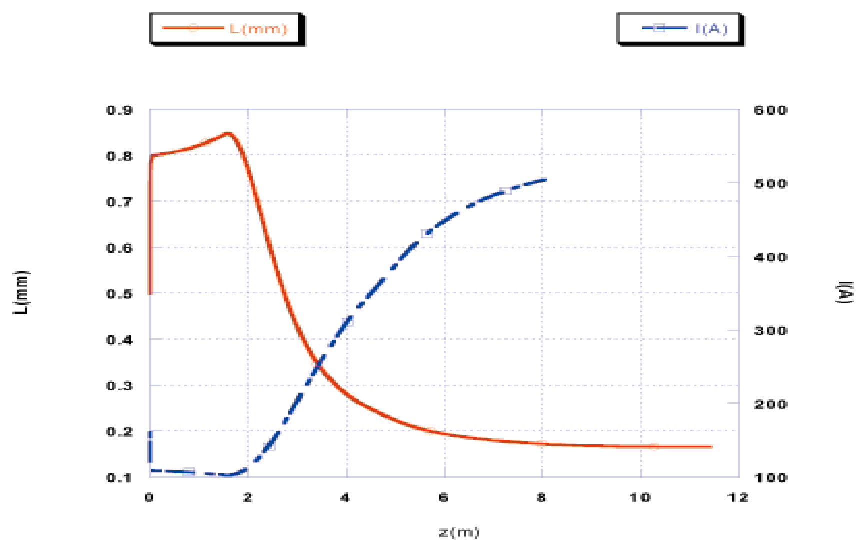
SPARC Project

(paper TH-P-14)

PRELIMINARY LAYOUT



Ipeak=500 A
En=0.6 π mm mrad
ΔE/E= ± 2.25%



Electron beam acceleration and transport

The acceleration and transport of a quite bright, short and monochromatic e.b. is a challenging task.

Namely it is mandatory to preserve the high quality characteristics of the beam in all the stages of injection, acceleration and steering into the undulator magnet.

All the possible sources of perturbation must be well understood and minimized.

The problems related to the magnetic beam compression have been mentioned previously, but the same problems (CSR) holds for the other curved parts of the electron trajectory, in particular at the exit of the accelerator for the steering of the e.b. into the undulator.

Another quite dangerous source of troubles is the interaction of the e.b. with the beam pipe surface (resistive and corrugation effects).

Finally it must be assured a quite good shot to shot stability, in order to provide a radiation beam with the required spectral quality, stable in power and alignment.

The relevant milestones to are:

- Compact Linac R&D: SCSS: C- band linac (40 MV/m)

- Understanding of CSR effects (micro-bunches instability): UCLA, TESLA: theoretical and experimental effort (papers WE-P-19, WE-P-16)

- Characterizing the interaction between electrons and pipe surface (resistive wall, corrugation):

○ TTF (DESY): experimental activity and comparison with predictions on wake fields generated by ps electron bunches on artificially corrugated narrow beam pipes (paper WE-P-11)

○ ATF (BNL): experimental activity and comparison with predictions on wake fields generated on periodically and randomly corrugated beam pipes. Results show that the energy loss is greatly reduced in the random case (paper WE-P-29)

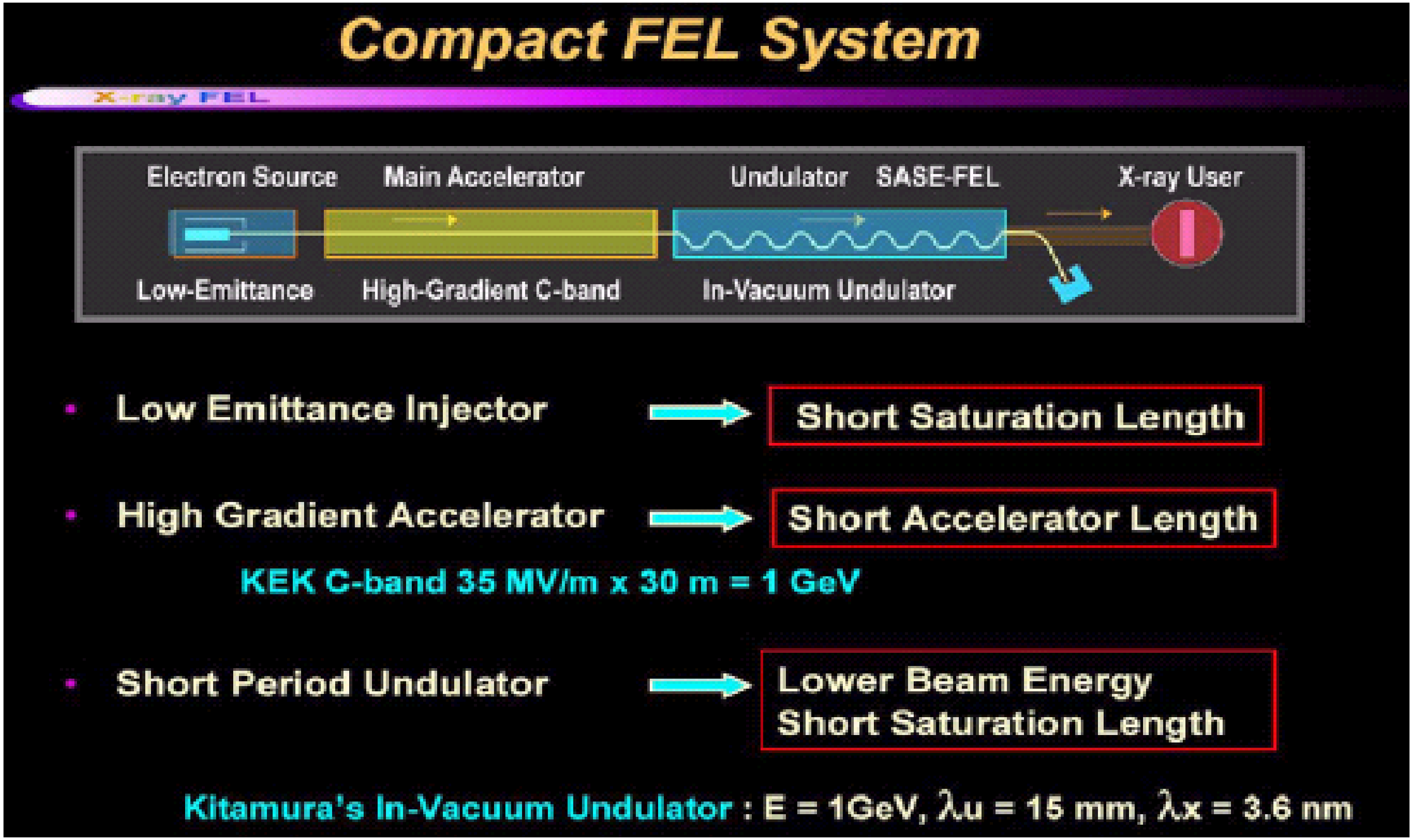


Fig.1 What makes SCSS compact?

STATUS OF SCSS: SPRING-8 COMPACT SASE SOURCE PROJECT

T. Shintake, et al. EPAC 2002

Undulator magnets

The technology of undulator magnets made quite big advances in the last years. In spite of this fact the realization of undulators for SASE FEL devices operating in the VUV – X region is still a challenging task. Namely, just to mention some of the most important issues, we have to consider that tight tolerances required for SASE FEL operation have to be maintained along quit long devices (many tens of meters), the undulator design has to allow to insert a large variety of diagnostics systems and, finally, in the undulator too the e.b. high brightness has to be preserved, this means that beam pipe surface quality and dimensions have to be adequate. In addition, due to the interest to operate at very short wavelengths at lower e.b. energy, new undulator schemes have been proposed.

A quite promising scheme is the so called dual-harmonic undulator for which theoretical and experimental activity is planned, in particular, in the projects LEUTL and SPARX.

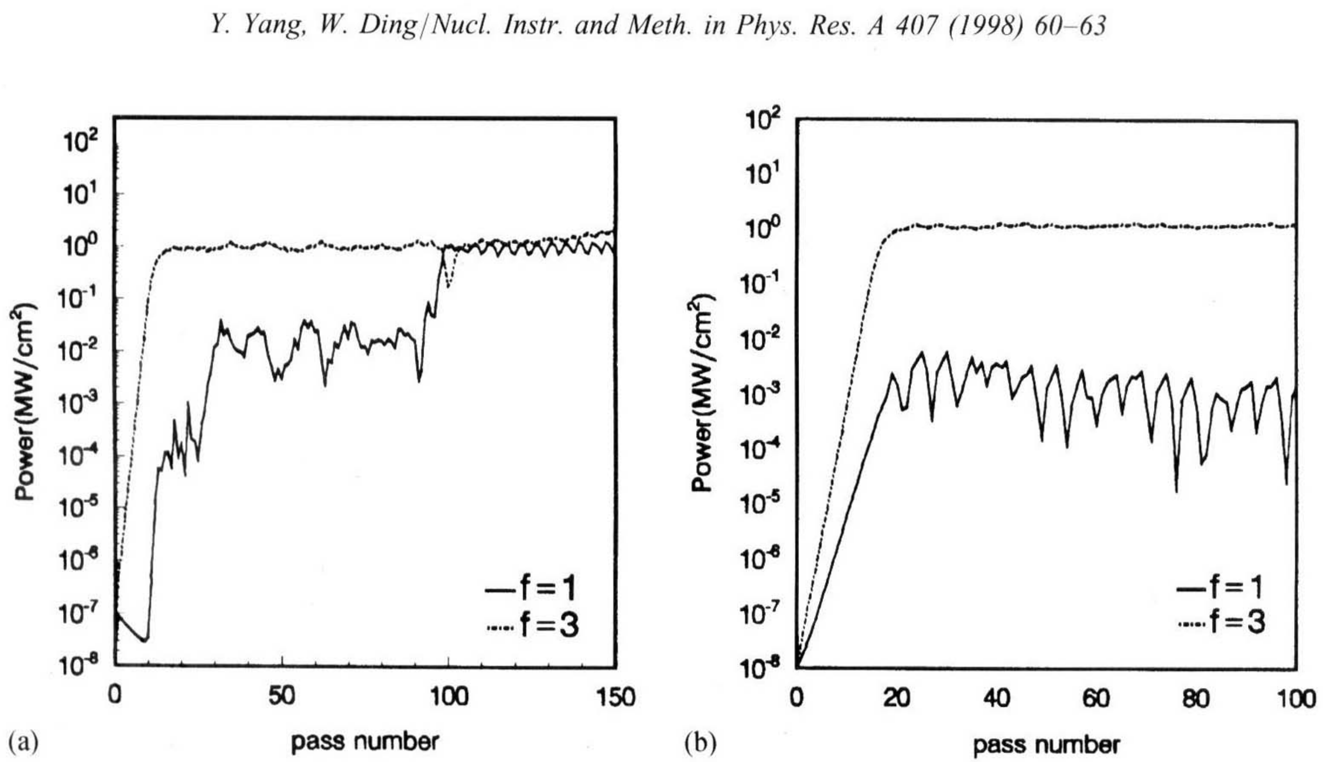


Fig. 1. Output power of the dual-harmonic wiggler at $\gamma = 20$, $I = 20$ A, $a_{w1} = 0.8$, $a_{wn} = -0.3$, $a_{wm} = 0.3$ (a) $\Delta\gamma/\gamma = 1.2\%$, (b) $\Delta\gamma/\gamma = 1.5\%$.

(see also paper TU-P-08, WE-P-34)

Electron beam and VUV – X ray diagnostics

E.b. with normalized emittance of the order of 1 mm x mrad and energy spread less than 0.1 % are not only not easy to generate but they are quite difficult to measure too and the same applies to the X–ray beam

A quite big effort is under way in all the laboratories involved in SASE FEL activity

(see, e.g., for TTF papers WE-P-40, WE-P-47)

Namely reliable on line measuring and diagnostic systems are essential not only for all the research activities related to the SASE devices, but also for the correct commissioning and operation of the final systems

Conclusions (I)

Theoretical and experimental status of the art in the field of VUV – Soft X ray FELs appears quite adequate for a further step toward the Å spectral region.

Namely the first results coming from the devices under development give us a pretty good confidence on the reliability of the theoretical scaling laws governing the SASE FEL process.

The recent advancements in the e.b. generation and manipulation make the technology level quite close to that requested for that ambitious goal.

Conclusions (II)

It must be again strongly underlined that the 4th generation of S.R. sources will not replace the previous ones but it can fruitfully complement them.

The same applies to the UV-VUV FEL oscillators (storage ring and linac based devices), whose potentialities appear far from being completely exploited.