17TH ADVANCED BEAM DYNAMICS WORKSHOP ON
FUTURE LIGHT SOURCES

# Summary of the 1996 Grenoble Workshop

*J. L. Laclare, SOLEIL*

APRIL 6-9, 1999
ARGONNE NATIONAL LABORATORY, ARGONNE, IL U.S.A.

# Summary of

*10th ICFA beam dynamics panel workshop*

# 4th generation Light Sources

*Grenoble January 22 - 25, 1996*

## by JL Laclare



Objective : to bring together representatives of
Synchrotron Radiation scientists and accelerator physicists
with a view to evaluate

- ¤ the first operation experience of 3rdGLS,
- ¤ the directions to investigate for the 4thGLS
  - ultimate performances of ring sources
  - expectations from linac driven FEL sources

| | | |
|---|---|---|
| WG n°1 | Scientific opportunities for 4thGLS, VUV/soft X-rays | I Lindau |
| WG n°2 | Scientific opportunities for 4thGLS, hard X-rays | J Als Nielsen |
| WG n°3 | Diffraction limited Storage Ring sources : lattice, stability | M Cornacchia |
| WG n°4 | Diffraction limited Storage Ring sources : current, lifetime, time struct | A Hofmann |
| WG n°5 | Linac driven FEL sources | C Pellegrini |
| WG n°6 | Storage Ring driven FEL sources | M Poole |
| WG n°7 | Insertion Devices | R Walker |

# Wish list
# from WG n°1 and WG n°2



## Wish list drawn by the scientists

# Higher performances are welcome
# Science will follow

| | 3rdGLS | 4thGLS |
|---|---|---|
| Lower emittances | 4 nm | 0.01 nm |
| Shorter pulses | 10 -100 ps | 100 fs |
| Average Brilliance, Brightness, Flux | $\leq 10^{22}$ | Higher |
| Peak Brilliance, Brightness, Flux | $\leq 5.10^{24}$ | Higher |
| Tunability | $0.5$ Å $\leq \lambda_1 \leq 1.5$ Å | |

Multiple (~30) beam facility
Fundable construction and operation costs

## Wish List for Source

| | | 4th | 3rd |
|---|---|---|---|
| Lower emittance | $\rightarrow \frac{\lambda}{4\pi}$ | 0.01 mm mrad | 4 mm mrad |
| Shorter pulses, c.f. proton slide; small time jitter | | ~ 0.1 psec | 100 psec |
| Higher time-averaged {brilliance, brightness, flux} | | $\frac{\Delta E}{E} \leq 10^{-3}$ | $10^{-2}$ |
| Much higher peak { do. } | | | |

Circular polarization advantageous

FEL's: $1.5\ \text{Å} \leq \lambda \leq 0.5\ \text{Å}$ Tunability.

Multiple (~ 30) beam facility

Fundable construction & operational cost



## Conclusion

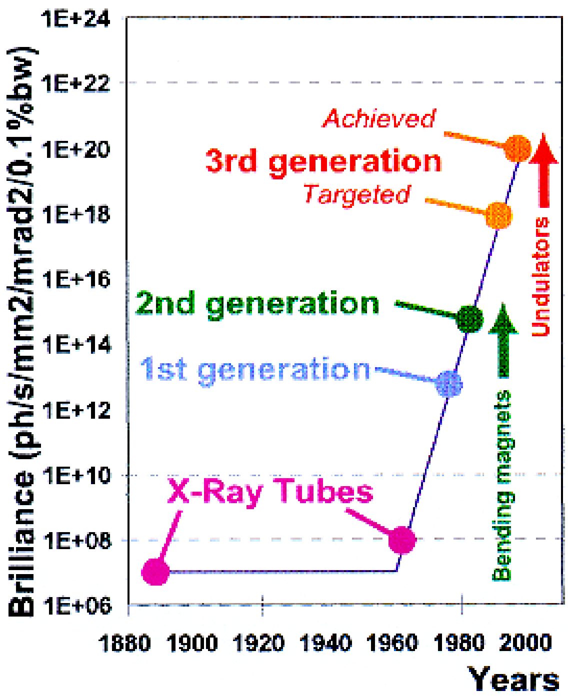
Hard X-ray working group unanimously excited about the FEL project as 4th generation

People. We must see a group of scientists so excited about the prospects that they are willing to put in 10 years of effort in a paper project, work out a convincing scientific case — -- new exp. techniques adapted to FEL source



# WG n°3
# Storage ring Limits
# Higher Brilliance
# More Transverse Coherence

## *Storage ring based X-Ray sources*
## *Chart of achieved Brilliance*




One generation takes about 20 years to reach maturity

1975 1st scientific case for the ESRF

1985 Decision to construct

1995 ESRF experimental hall near completion

Review of 3rd GLS achievements

Target brilliance in the $10^{18}$ range

➪ smaller e beam emittances

➪ undulator sources

reached and surpassed : in the $10^{20}$ range

5 orders of magnitude above 2GLS

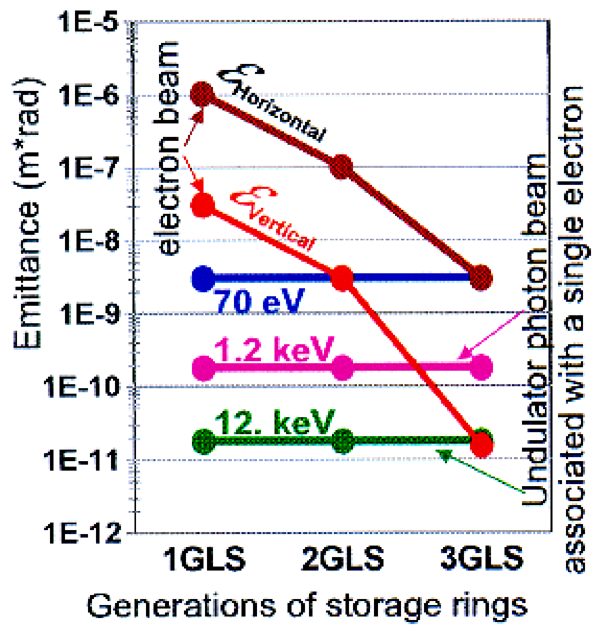
Search for even higher performances



## *How far do we stand from Diffraction Limit ?*

$$\varepsilon_H^{3GLS} \approx 3.10^{-9} \approx \frac{\varepsilon_H^{2GLS}}{30} \approx \frac{\varepsilon_H^{1GLS}}{300}$$

$$\varepsilon_V^{3GLS} \approx 1.10^{-11} \approx \frac{\varepsilon_V^{2GLS}}{300} \approx \frac{\varepsilon_V^{1GLS}}{3000}$$




Undulator photon beams associated with a single electron

$$\varepsilon_r \approx \frac{\lambda}{4\sqrt{2}}$$

$= 3.10^{-09}$ at 70 eV UV

$= 180.\ 10^{-12}$ at 1.2 keV X-rays

$= 18.\ 10^{-12}$ at 12 keV hard X-rays

Most advanced 3GLS undulator beams are diffraction limited in

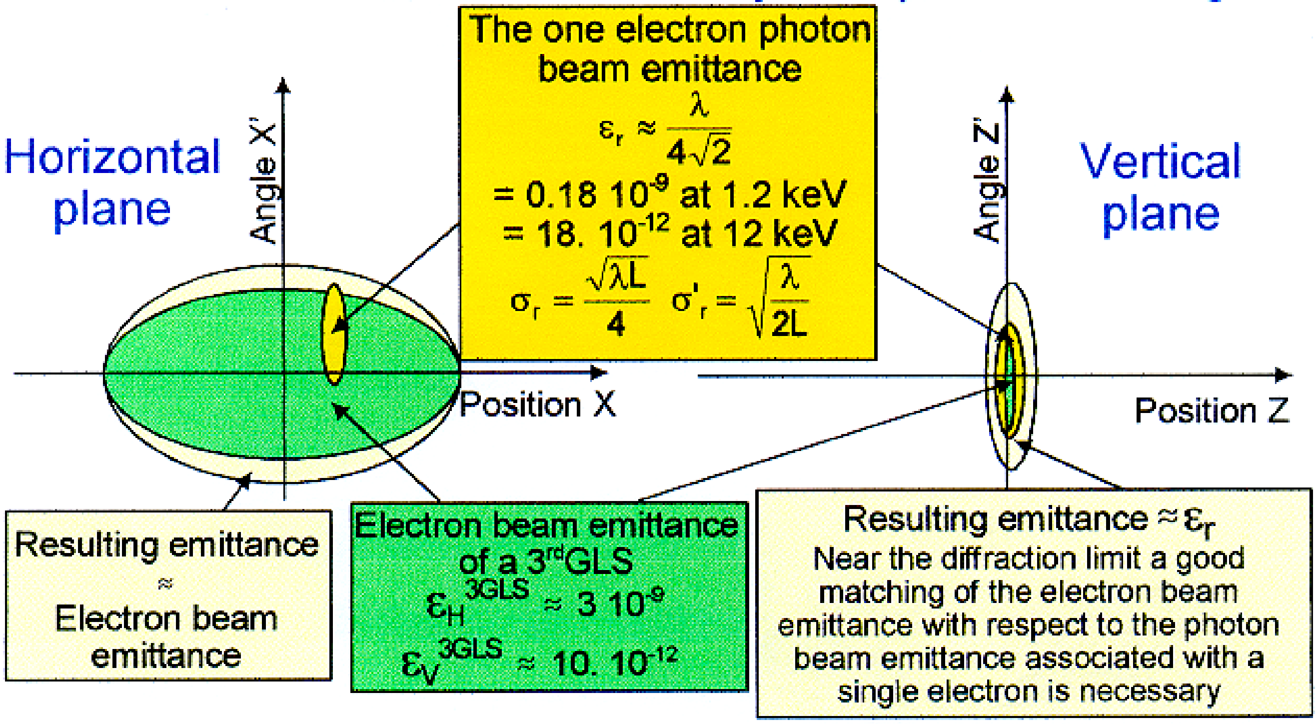
➪ both V and H planes for UV beams

➪ V plane only at shorter $\lambda$'s

**Based on the present radiation principle in an undulator the ultimate limit is reached**

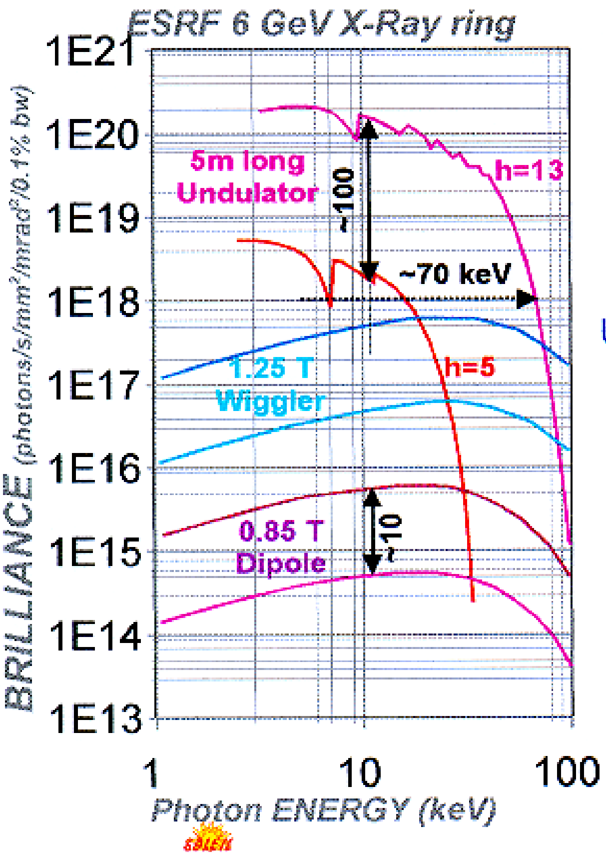
➪➪A factor 30 (300) could still be gained in the H plane for X-ray (hard X-ray ) sources

# X-Ray case : To obtain a high degree of coherence, constraints are to be satisfied by the optics of the ring






# Higher brilliance at higher undulator harmonics




| Target | FPR | 1999 operation |
|---|---|---|
| Current | 0.1 A | 0.2 A |
| $\varepsilon_x$ | 7 nm*rad | 3.7 nm*rad |
| $\varepsilon_z$ | 0.7 nm*rad | 18 pm*rad |
| Und Gap | 20 mm | 8 mm+shims |
| Brilliance | $10^{18}$ (14keV) | $10^{20}$ |

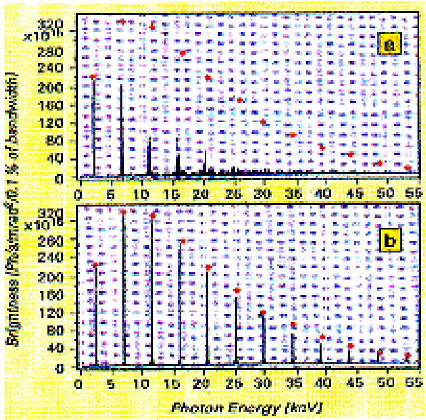
No energy widening + spectrum shimming

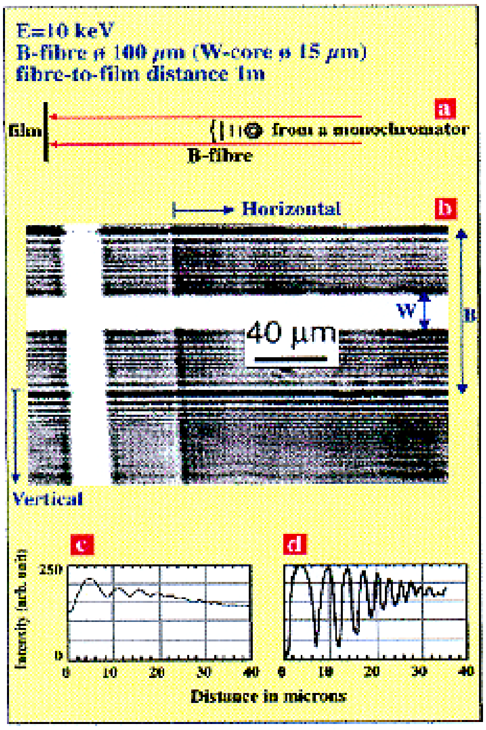
⇨ Undulator radiation up to h=13

$10^{18}$ at 70 keV better than wiggler

Up to now no big interest in higher energies :

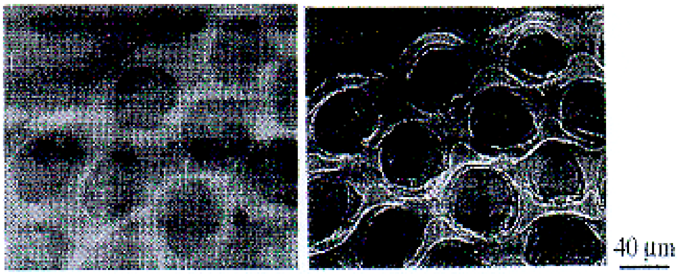
6 GeV a conservative choice





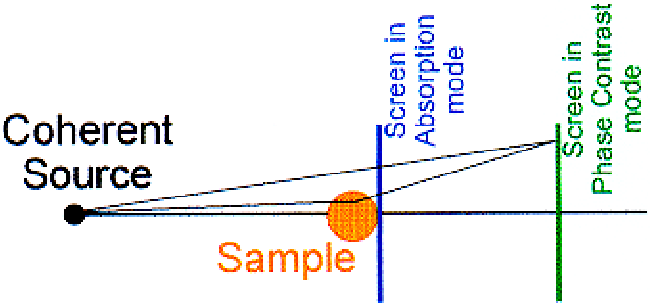

Diffraction of coherent X-rays by a Borum fibre

## *Imaging technics can benefit from more coherent X-ray beams*




Picture in Absorption mode

Picture in Phase Contrast mode




*A. Snigirev et al... ESRF www*



## *Can we further reduce H emittances ?*

### *to produce X-ray diffraction limited beams in both planes*

*➪ a reduction of $\varepsilon_H$ by a factor ≈100*

**Increased storage ring size** (Chasman-Green)

$N_D = 2\ N_{D0}$ ; ($\theta_D = \theta_{D0}/2$) number of cells x by 2 ; circumference x 2

for a 3 GeV ring, 32 periods, 700 m circumference (~ ESRF)

$\eta = \eta_0/4$ stronger $\xi$ sextupoles, lower dynamic aperture, ($\alpha = \alpha_0/4$) ; $\varepsilon_c = \varepsilon_{c0}$ ; $\tau_x = 2\tau_{x0}$ ;

➪ gain a factor $2^3 = 8$ (heating by radiation/16 and damping/2)

significant reduction of **H** (V maintained at the limit) and // beam sizes . Intrabeam scattering makes emittance reduction (<4 for 500 mA) much less effective

**Increased damping**

All $\eta$=0 ID straight sections (200 metres) filled with damping wigglers thus occupying all the high brilliance sections ; $\Delta E = 4\ \Delta E_0$

reduction of the damping time $\tau_x = \tau_{x0}/4$

➪ gain another factor ≈ 4

Resulting Touschek lifetime is dramatically shortened (factor 15 V at the diff. limit)

➪ Acceptable for damping rings but not for light source storage rings

➪ Saturation of SR X-Ray light source Brilliance in the $10^{22}$ range slightly below the diffraction limit in the horizontal plane

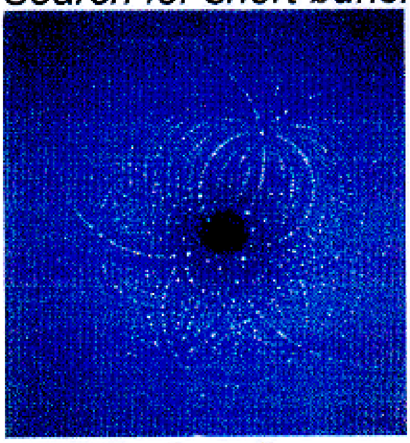
# WG n°4
# Time structure
# Short bunches
# Lifetime
# Permanent Injection



## *Use of the time structure of synchrotron radiation*

*Scientific case for dynamic studies with short or extremely short bunches (single bunch and a few bunches) presently 10 - 20 % of the experiments*

***Search for short bunches higher peak brilliance*** (5.10[24] upper limit)



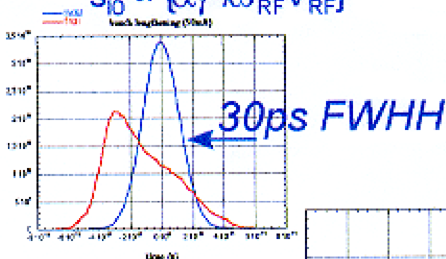
*Diffraction pattern of a biological specimen*

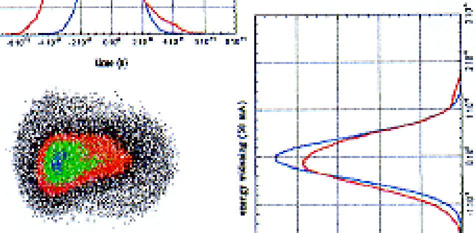
*Single passage of a bunch of $2.10^{11}$ $e^-$. About 10 000 identifiable spots allowing for detailed characterization of the specimen and its possible evolution with time*

Low emittance ($\alpha$<<1) lattices are not the solution for very short bunch production

currently $\sigma_{l0}$ ~ a few 10's ps

$s_{l0} \propto \{\alpha\gamma^3/\omega_{RF} V_{RF}\}^{1/2}$



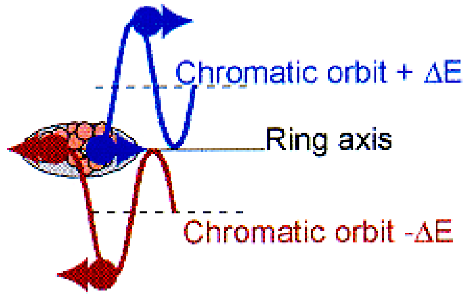
*Lengthening and widening of a $2.10^{11}$ $e^-$ single bunch*

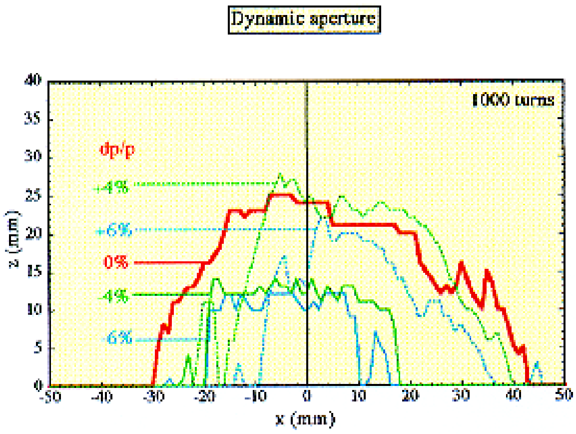
*$\hat{I}$ ~1 kA ; $Re(Z_{//}/p)$ ~ 0.04 $\Omega$*

Microwave Instability

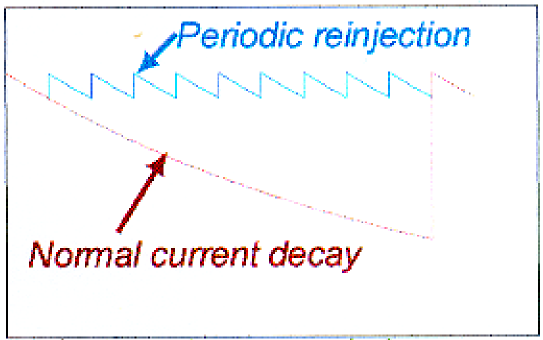
# Compromise between Brilliance and Touschek lifetime

High density-Touschek scattering of particles - large longitudinal transfers of energy - loss unless large acceptance : RF acceptance, physical aperture, dynamic aperture for large E deviations




*Permanent injection*
*a way to improve performances ?*




At many places ΔE/E acceptance is too small and brilliance is spoiled on purpose to lengthen lifetime

Tested at several places
Integrated in the design of new projects



In the mean time, all pending questions on rings were answered

More coherence
- Lower emittances,
- IBS,
- Touschek,
- Energy acceptance

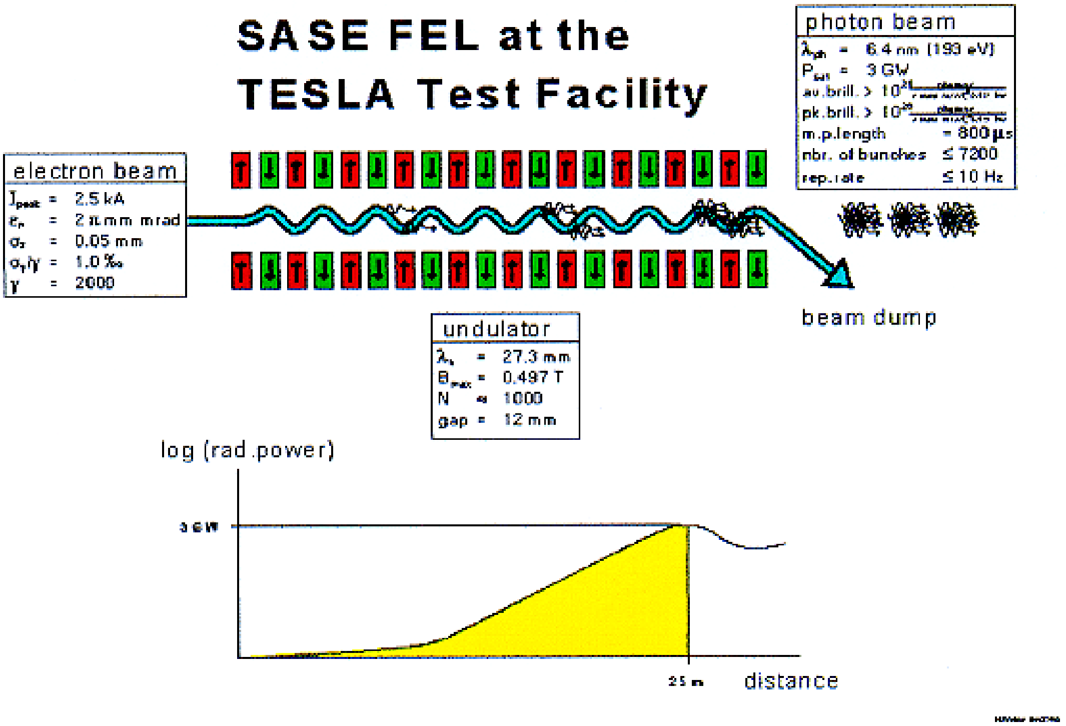
Higher peak brilliance
- Operation in quasi-isochronous mode,
- $\alpha 1 << 1$, longitudinal chromaticity $\alpha 2$
- short and intense bunches,
- $\alpha 1 < 0$
- Bunch lengthening and widening

ID's
- Minigap and in-vacuum undulators

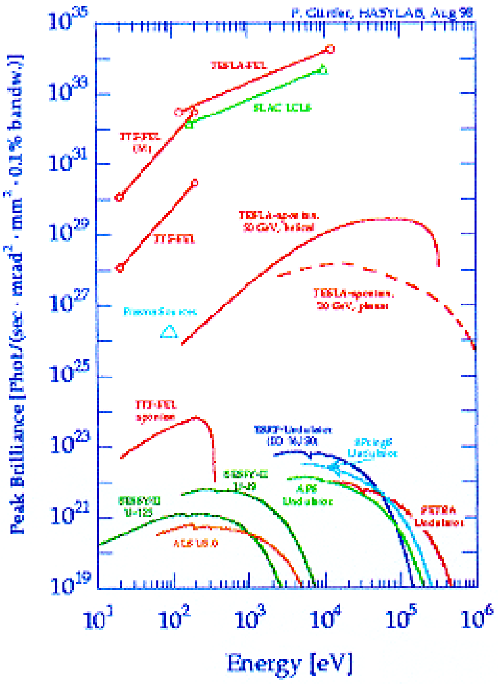
Permanent injection

# WG n°5
# Linac driven FEL's

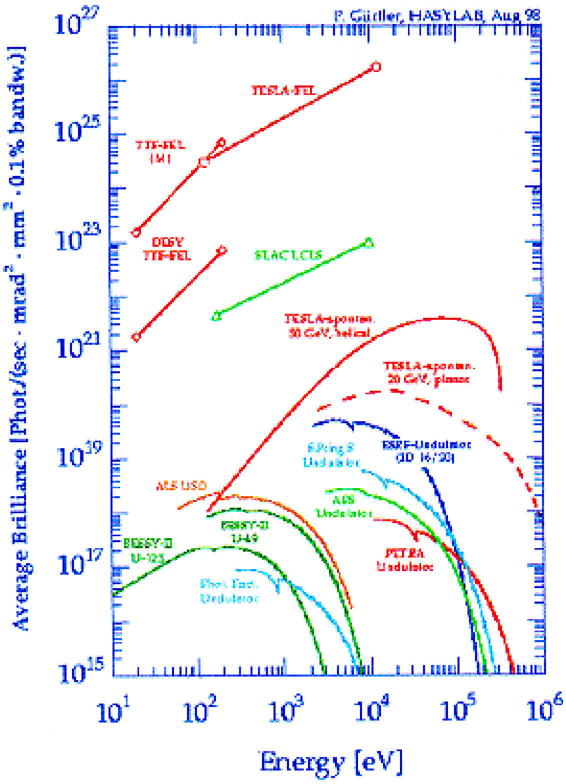
Up to 12 keV the demanding e-beam conditions for SASE to develop in a long undulator are achievable



The peak brilliance is the figure of merit of linac driven SASE FEL's
10 orders of magnitude higher than that of 3rd GLSrings
extra short pulses, very small emittances and energy spread




| *Modified from C Pellegrini EPAC 98 plenary session* | 3rdGLS Rings | Linac driven FEL | 3rdGLS Rings | Linac driven FEL |
|---|---|---|---|---|
| Radiation λ (Å) | 1 000 - 10 | | 10 - 1 | |
| Radiation energy (eV) | 12.4 - 1 240 | | 1 240 - 12 400 | |
| e- beam emittance (π nm rad) | 4 | 0.2 | 2 | 0.05 |
| **Pulse length** (ps) | **30-100** | **1** | **15-30** | **0.06** |
| Average Brilliance [phot/s/mm$^2$/mrad$^2$/0.1%] | $10^{18}-10^{20}$ | $10^{22}-10^{24}$ | $10^{20}-10^{21}$ | $10^{22}-10^{25}$ |
| **Peak Brilliance** [phot/s/mm$^2$/mrad$^2$/0.1%] | **$10^{20}$ (5 $10^{23}$)** | **$10^{30}$** | **$10^{23}$(5 $10^{24}$)** | **$10^{33}$** |
| **Peak Power** (W) | **$10^{2}$** | **$10^{9}$** | **$10^{3}$** | **$10^{10}$** |



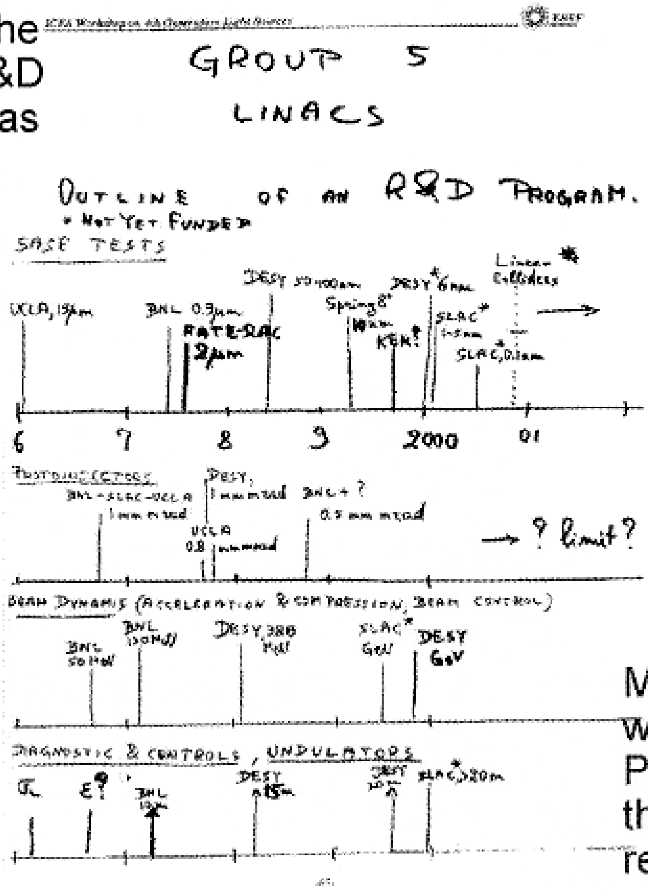

Up to 12 keV, linac driven SASE FEL's are 4 (6) orders of magnitude better in Average Brilliance when compared with ring ultimate limits (achieved perfomances) **TESLA > 1000*LCLS**

| **Parameter** | **TTF FEL Phase1** | **TTF FEL Phase2** | **TESLA X-ray FEL** |
|---|---|---|---|
| e- beam energy (GeV) | 0.3 | 1. | 25. |
| Radiation λ (Å) | 710 | 64 | 1 |
| Radiation energy (eV) | 17 | 193 | 12 000 |
| undulator period (mm) | 27.3 | 27.3 | 50 |
| undulator length (m) | 13.5 | 27 | 87 |
| emittance ε (π nm rad) | 3.4 | 1.0 | 0.04 |
| Peak electron current (A) | 500 | 2 490 | 5 000 |
| N° of electrons per bunch | 6.24 $10^{9}$ | 6.24 $10^{9}$ | 6.24 $10^{9}$ |
| N° of photons per bunch | 1.7 $10^{14}$ | 4 $10^{13}$ | 7 $10^{12}$ |
| rms energy spread $\sigma_\gamma/\gamma$ | 1.7 $10^{-3}$ | 1. $10^{-3}$ | 0.04 $10^{-3}$ |
| rms bunch length $\sigma_s$ (μm) | 250. | 50. | 25 |
| Lg (power gain length) (m) | 0.6 | 1.00 | 4.1 |
| Psat (satur peak power) (GW) | 0.3 | 2.6 | 65 |
| **Average brilliance [phot/s/mm$^2$/mrad$^2$/0.1%]** | **Up to 2 $10^{21}$** | **Up to 6 $10^{22}$** | **8 $10^{25}$** |
| Bunch train length (μs) | 800 | 800 | 1 052 |
| Number of bunches per train | Up to 7 200 | Up to 7 200 | Up to 11 315 |
| Repetition rate (Hz) | 10 | 10 | 5 |

Between12 and 70 keV, the Average Brilliance produced by the spontaneous emission from a 25 (50) GeV e-beam in a ~100 m undulator is 1 (2) order(s) of magnitude larger than that of rings

**FIGURES FOR FLUX ?**

In Grenoble, the outline of a R&D programme was given



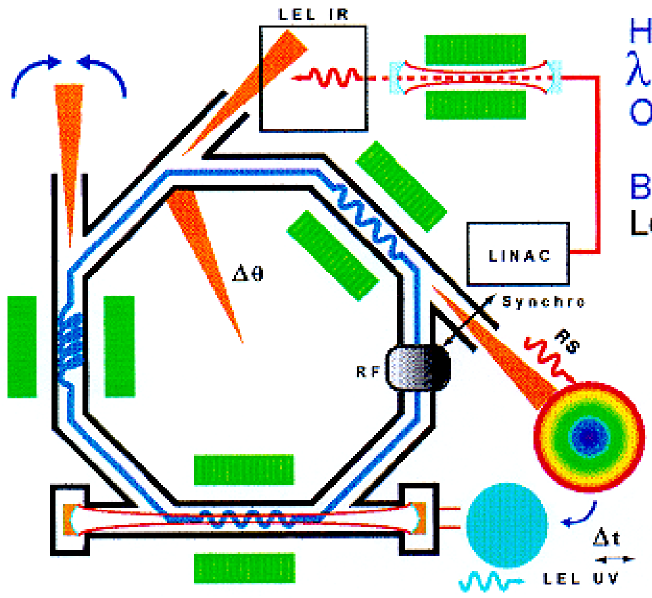

Most of the activities were launched
Progresses slower than anticipated but results expected soon

# WG n°6
# Ring FEL's

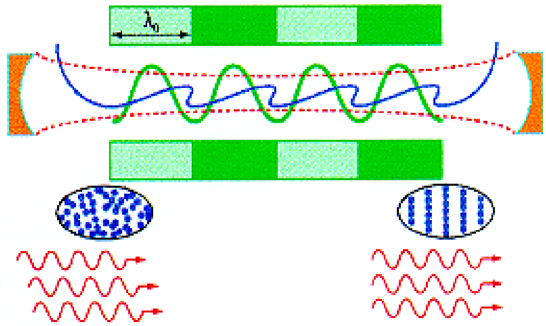
## *Ring driven FEL*

Output power 0.1 - 1 W down to 200 nm,6 eV (fundamental) in user facility mode
Brilliance ~$10^{23}$ [phot/s/mm$^2$/mrad$^2$/0.1% bw]

- damages to mirrors
- achievements of high Î at low e-beam E = bunch lengthening and widening




Harmonic generation very promising
$\lambda \leq$100 nm - 20 nm or less (4nm, 300 eV ?)
Output powers 10 - 100 W (average)
10 - 100 MW (peak)
Brilliance ~$10^{24}$ - $10^{26}$
Long SS in ring design




In the mean time,

several ring FEL devices were started Duke, Delta,
bunch length was reduced on Super-ACO,
R&D on mirrors is continuing,
a european R&D programme was launched

# WG n°7
# Insertion Devices

The conclusions of the working group were :

1) Technology adequate for construction of ID's for both :
   - Diffraction limited Rings
   - Storage Ring FEL's

   (Fantastic progresses were made in the mean time)

2) R&D required for linac driven SASE FEL's :
   - Quality for long devices (phasing ?)
   - Introduction of focusing in the ID structure or between segments