Le Laser à électrons libres (LEL) : une aventure au fil de ses développements
Prix Charpak-Ritz

M. E. Couprie,

Synchrotron SOLEIL

Avec J. M. J. Madey, l'inventeur du LEL, Suède, 2015, Nobel Symposium

Remerciements :
Société Française de Physique et Société Suisse de Physique
J. Daillant, J. M. Filhol, A. Nadji, A. Taleb-Ibrahimi, P. Morin, M. Van der Rest, D. Raoux
Équipes « GMI » et « COXINEL / LUNEX5 »
Mes anciens collaborateurs

Ma vie scientifique centrée sur les sources de lumière sur accélérateur:

- Les sources de rayonnement synchrotron sur anneau de stockage (actuellement à SOLEIL)
  - Des developments technologiques (mirrors, onduleurs-collaboration PSI -, aimants …)
- Laser à Électrons libres (Free Electron lasers)

Thomas Schmidt, DELTA/PSI

Marco Calvi, PSI

Free Electron Laser (FEL):

«simple and elegant gain medium» : an electron beam in a magnetic field

- broad wavelength tunability (vibration frequency can be adjusted by changing the magnetic field or the speed of the electrons), free electrons ≠bound electrons in atoms and molecules : vibrate at specific frequencies
- excellent optical beam quality
- high power

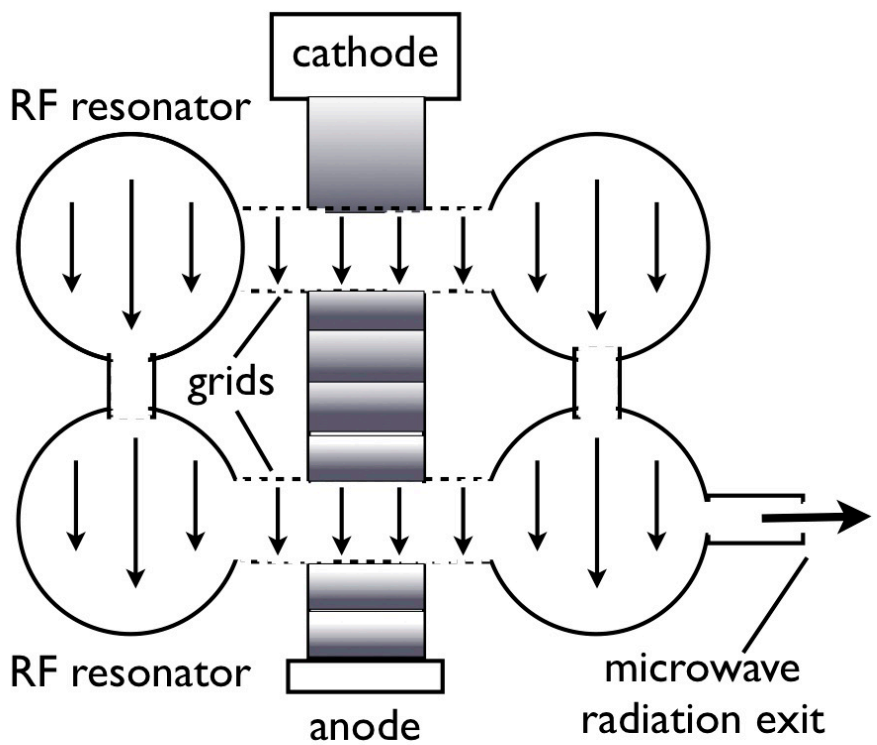
C. Brau, Free Electron Lasers, Advanced in electronics and electron physics, edited by P.W. Hawkes, B. Kazan, supplement 22, Academic press (1990)

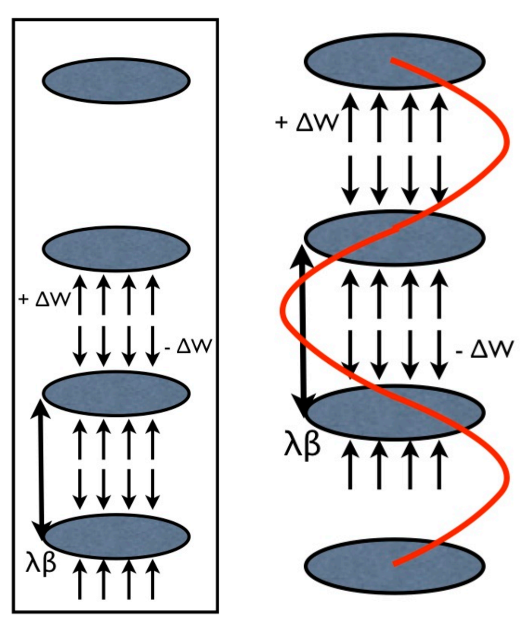
Les origines du LEL: le développement des tubes à vide

Klystrons, magnétrons, accélérateurs, voire le début de l' électronique
Découverts à la fin des années 1930, largement développés après la seconde guerre mondiale.
Applications : radiodiffusion, détection radar detection, nécessitant des oscillateurs haute fréquence.

Ces sources utilisent en général un faisceau d'électrons soumis à un champ électrique ou magnétique, avec le "bunching" concept clef pour l'amplification de l'onde.

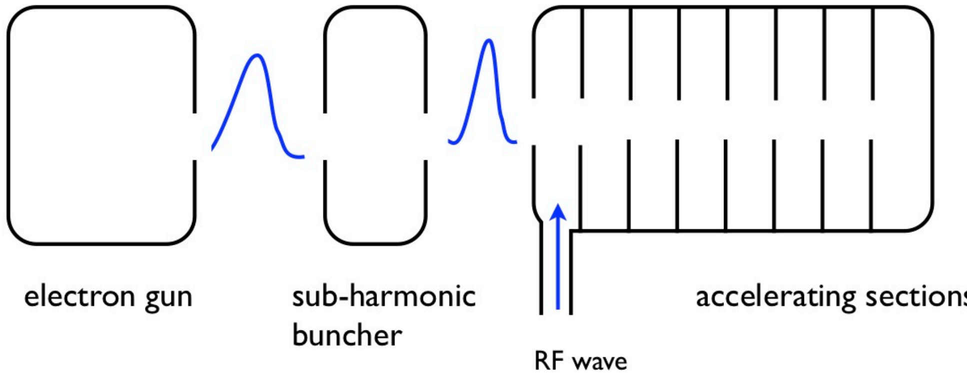
Emploi de cavités résonnantes à la fréquence de l'onde émise => rétroaction efficace pour la production de needed de l'onde cohérente => amplification.
Boucle sur un amplificateur large bande => oscillateur avec production de rayonnement monochromatique.





R. H. Varian, S. F. Varian J. Appl. Phys. 10(5), 321–327 (1939)

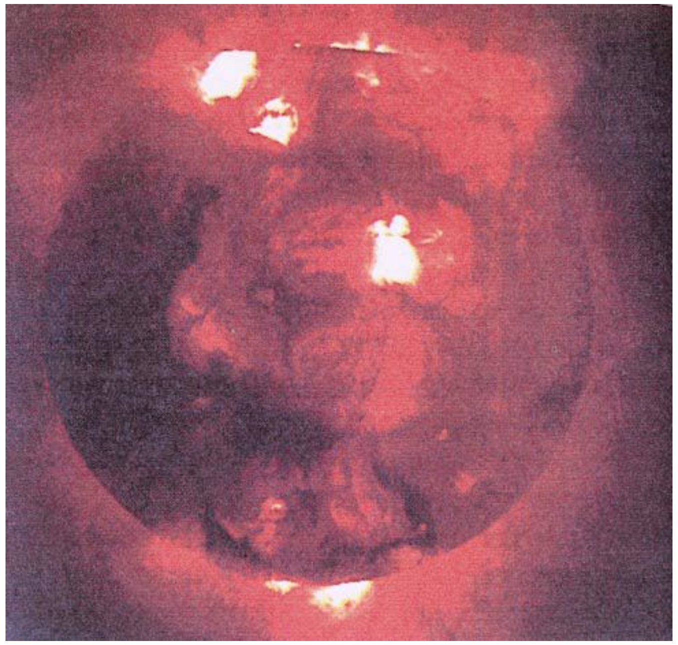
K. Landecker, hys. Rev. 36 (6) (1952) 852-855J.
Schneider, Phys. Rev. Lett. 2(12) (1959) 504-505
R. H. Pantell, G. Soncini, H. E. Puthoff, 4 (11) 906-908 (1968)
R. B. Palmer,. Appl. Phys. 43(7)(1972)3014-3023
K. W. Robinson , Nucl. Instr. Meth. A239 (1985), Csonka (1976)



Les origines du LEL: le Rayonnement Synchrotron

Rayonnement électromagnétique produit par des particules chargées et accélérées

Naturellement (astrophysique)

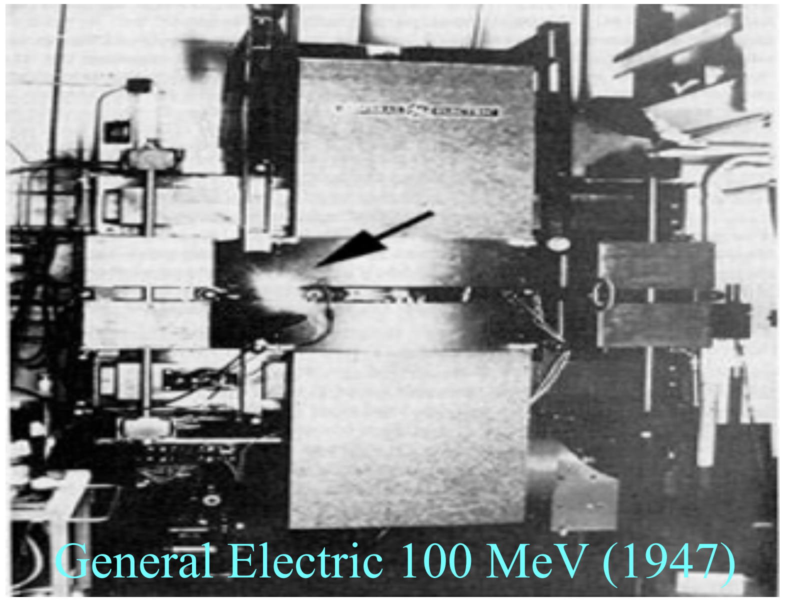


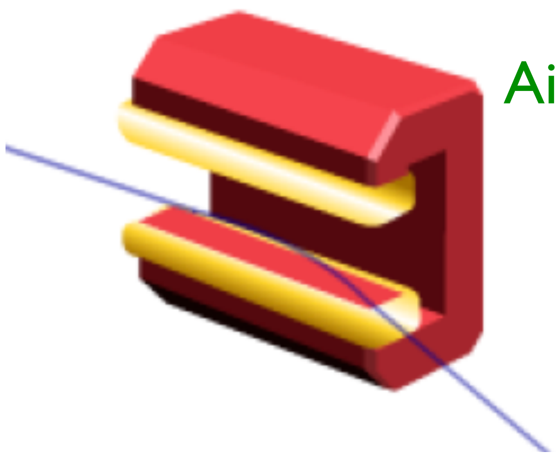
Le soleil : Hydrogène, boucles de champ magnétique émettant du rayonnement synchrotron visible (centre) X (bords)

Artificiellement (accélérateurs de particules)

1947 : première observation

F. R. Elder et al., Physical Review, 71, 11, (1947), 829-830
J. P. Blewett, 50 years of synchrotron radiation, J. Synchrotron Rad. , 5, 135-139 (1998)



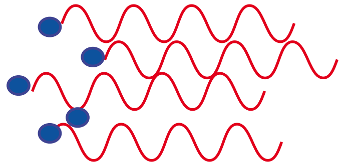


Aimant de courbure

Collimaté $\frac{1}{\gamma}$

$$\gamma = \frac{E}{m_o c^2}$$ Facteur de Lorentz

e bunch of N_e electrons

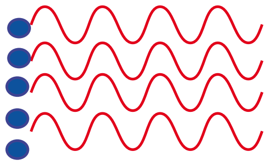


$I \propto N_e$

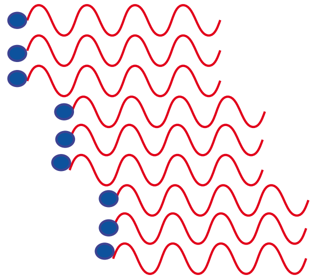
Coherent Synchrotron Radiation

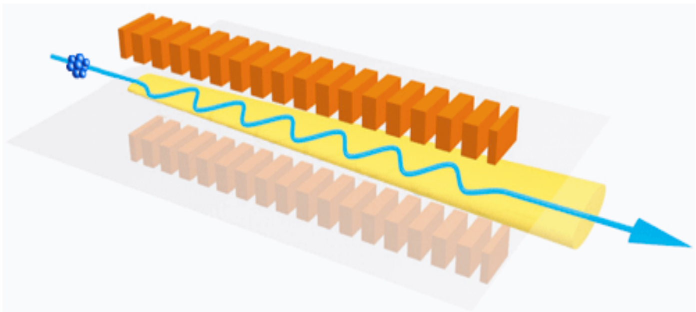
$$I \propto N_e^2$$

Short bunch



Bunched beam



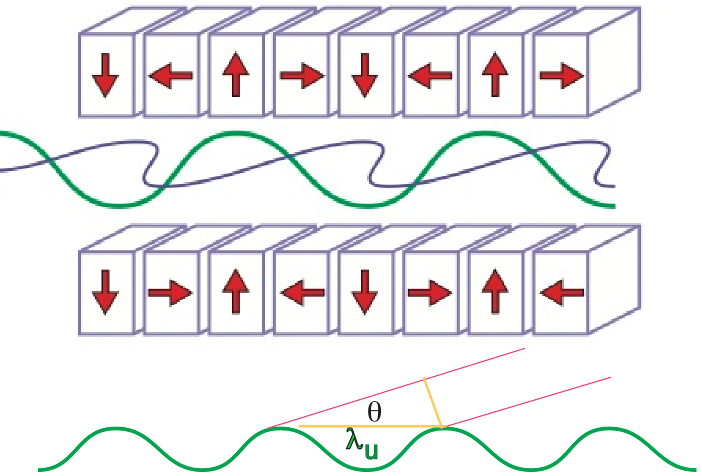


Onduleur:
Champ magnétique périodique permanent

V.L. Ginzburg, Bull. Acad. Sci. USSR. 11 (1947) 165–182.
Motz H. Journ. Appl. Phys. 22, 527–535 (1951)
Motz H. Et al., Journ. Appl. Phys. 24, 826–833 (1953)
Combes R., Frelot T. , presented by L. de Broglie, CRH. Scéance Acad. Sci. Paris, 241, 1559 (1955)

Les origines du LEL: propriétés du rayonnement synchrotron

Onduleur plan (champ crête B_u, nombre d'onde k_u, période λ_u, nombre de période N_u)

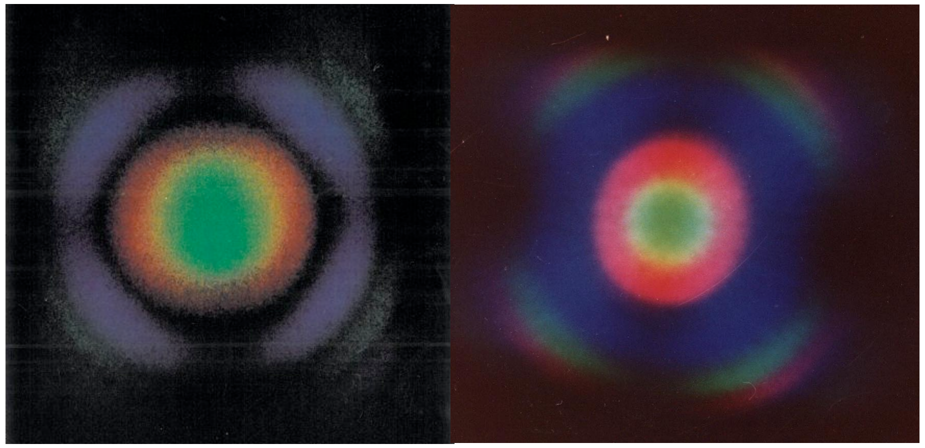


$$\lambda_n = \frac{\lambda_u}{2\gamma^2 n}\left(1 + \frac{K_u^2}{2} + \gamma^2\theta^2\right)$$

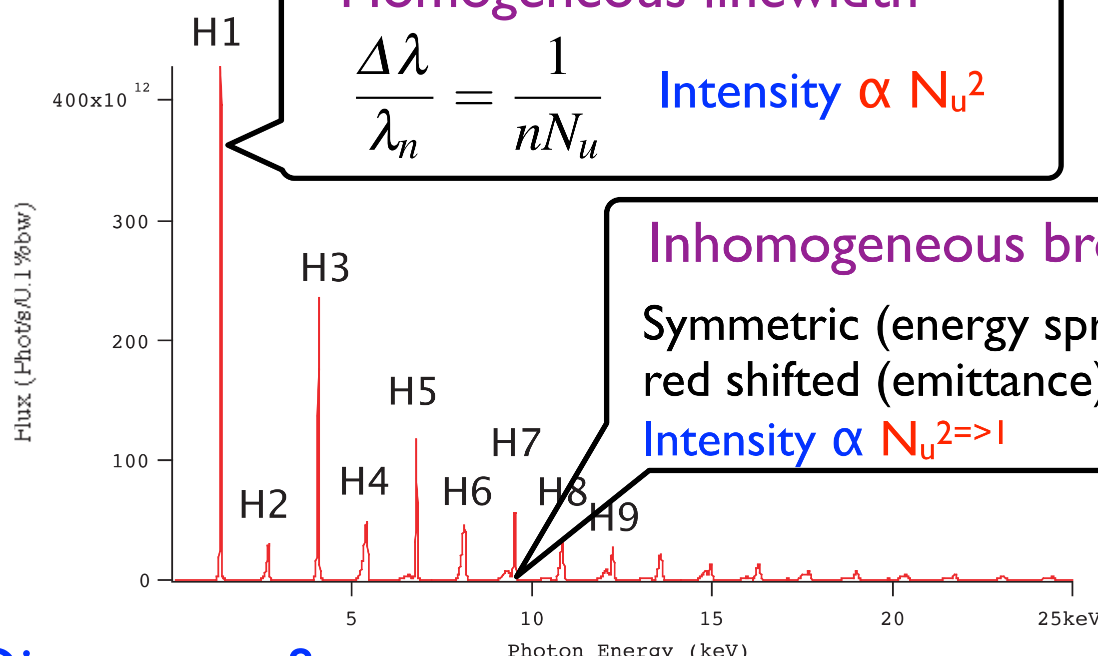
$$K_u = \frac{eB_u\lambda_u}{2\pi m_o c^2}$$ Deflection parameter

$$K_u = 0.934 B_u(T)\lambda_u(cm)$$

n harmonic number



Spectre de raies



Homogeneous linewidth

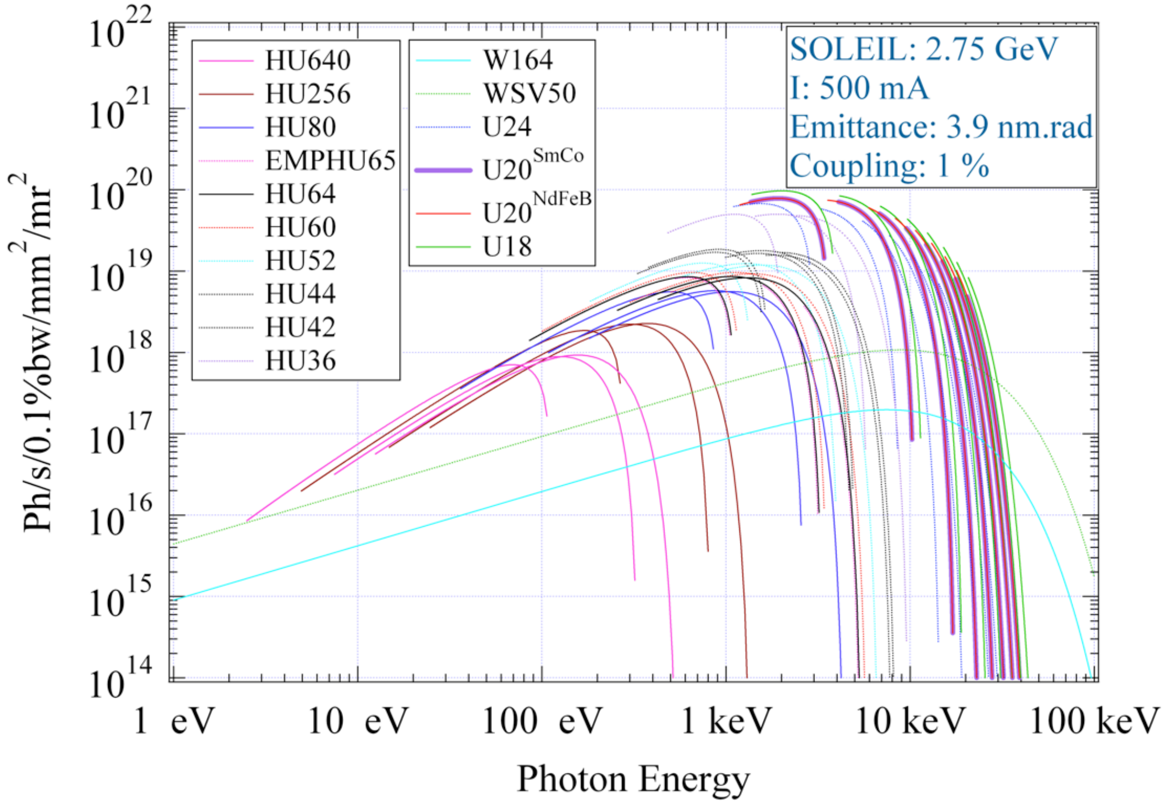
$$\frac{\Delta\lambda}{\lambda_n} = \frac{1}{nN_u}$$ Intensity α N_u^2

Inhomogeneous broadening

Symmetric (energy spread), red shifted (emittance)

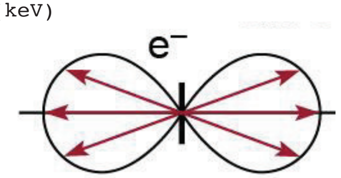
Intensity α $N_u^{2=>1}$

Tunable (E, B_u)



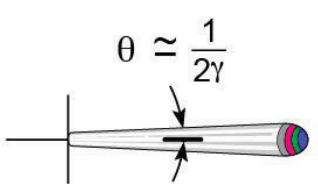
Divergence & taille faibles

electron frame



$\lambda' = \frac{\lambda_u}{\gamma}$

observer frame



$\lambda = \lambda' \gamma(1-\beta\cos\theta)$
$= \lambda_u (1-\beta\cos\theta)$

$$\sigma'_p = \sqrt{\lambda_r/4L_u} \qquad \sigma_p = \sqrt{\lambda_r L_u}/2\pi \qquad \epsilon_p = \sigma_p\sigma'_p = \lambda_r/4\pi \qquad Z_p = \sigma_p/\sigma'_p = L_u/\pi$$

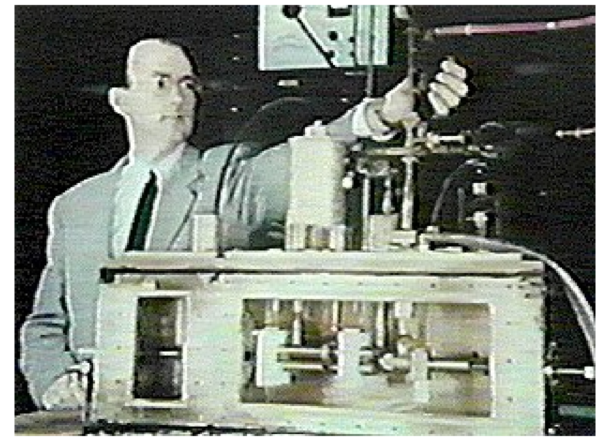
Les origines du LEL: l'invention du laser au XX^{ieme} siècle

A. Einstein (1879-1955)

1917: analyse du corps noir, prédiction de l' émission stimulée

A. Einstein, Physikalische Zeitschrift 18 (1917)

1954 : first MASER in the micro-waves (NH_3 molecule).



Columbia University

Source micro-onde «quantique» (C. Townes, N. G. Basov, A. M. Prokhorov): Molécule excitée placée à la place du faisceau d' e dans une cavité micro-onde résonante à la fréquence de transition de la molécule.

J.P. Gordon, H. J. Zeiger and C.H. Townes, Phys. Rev., 95 (1954) 282.
J. P. Gordon, H. J. Zeiger and C. H. Townes, Phys. Rev., 99 (1955) 1264.

Charles Townes (1905-2015)

Arthur Leonard Schawlow (1905-1999)

1958 : Laser concept (optical maser)

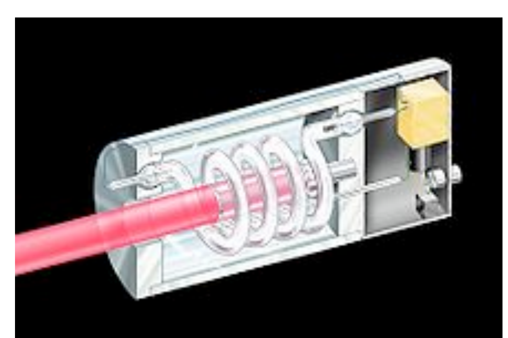
« Extension of maser techniques to the infrared and optical region :
For wavelengths much shorter than those of the ultraviolet region, maser-type amplification appears to be quite impractical. Single mode may be selected by making only the end walls highly reflecting, and defining a suitably small angular aperture. => extremely monochromatic and coherent light. »

A. L. Schawlow C. H. Townes, Infra-red and optical masers, Phys. Rev. Lett. 1940-1948 (1958)
Patent, Optical Masers and Communication, by Bell Labs.

1960 : First Ruby laser (Ion CR3+ in ruby)

Hughes Research Laboratories

T.H. Maiman, Nature, 187 Nature 187, 493-494 (1960)
T. H. Maiman, Hoskins, D'Haenens, Asawa and Evtuhov, Phys. Rev., 123 (1961) 1151.



Theodore Harold Maiman (1927-2007)

L'émergence du concept de LEL

«As one attempts to extend maser operation towards very short wavelengths, a number of new aspects and problems arise, which require a quantitative reorientation of theoretical discussions and considerable modification of the experimental techniques used.»
«These figures show that maser systems can be expected to operate successfully in the infrared, optical, and perhaps in the ultraviolet regions, but that, unless some radically new approach is found, they cannot be pushed to wavelengths much shorter than those in the ultraviolet region.»

A. L. Schawlow and C. Townes, Infra-red and Optical masers», Phys. Rev. 112 1940 (1958)

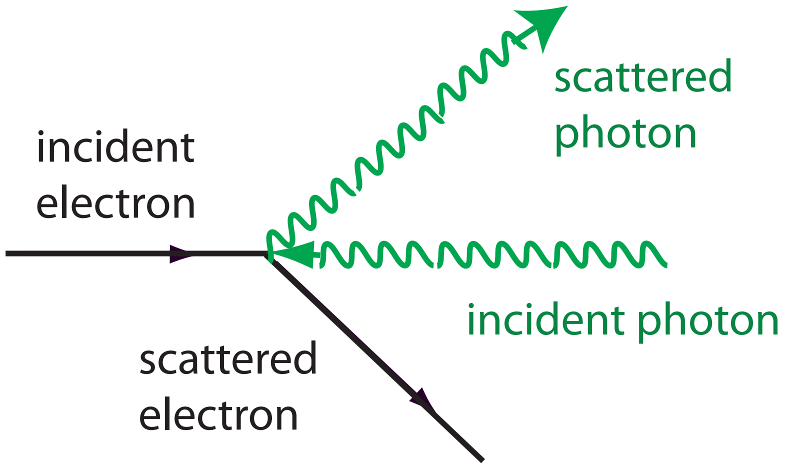

J. M. J. Madey (1943-2016)

«Schawlow and Townes' descriptions of masers and lasers coupled with the new understanding of the Gaussian eigenmodes of free space offered a new approach to high frequency operation that was not constrained by the established limits to the capabilities of electron tubes»
Was there a Free Electron Radiation Mechanism that Could Fulfill these Conditions?

J. M. J. Madey, Nobel Symposium, Sigtuna, Sweden, June 2015
J. M. J. Madey, Wilson Prize article: From vacuum tubes to lasers and back again, Phys. Rev. ST Accel. Beams 17, 074901 (2014)

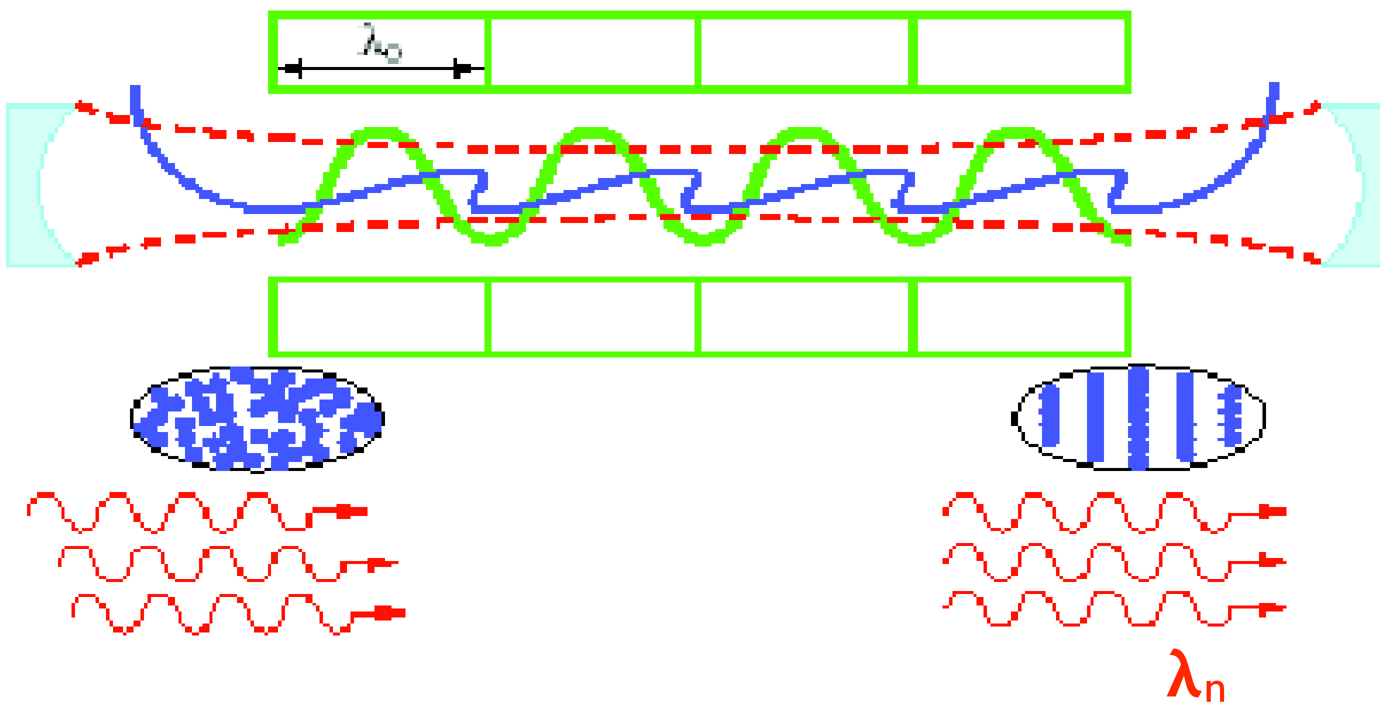
Emploi de faisceaux d'électrons relativistes:
- Compton Scattering
- Champ périodique intense : Onduleur => accordabilité
- Fort courant crête => source de faisceau d'électrons

=> Concept du LEL



J. M. J. Madey, Stimulated emission of Bremmstrahlung in a periodic magnetic field; J. Appl. Phys., 42, 1906–1913 (1971)

L' émergence du concept de LEL oscillateur



- interaction faisceau d'électrons-onde optique
- échange d'énergie entre l'onde optique et les électrons
- microbunching (separation par λ)
- émission cohérente and amplification de l'onde optique
- saturation (augmentation de dispersion en énergie, condition de résonance non satisfaite)

$$\lambda_n = \frac{\lambda_u}{2\gamma^2 n}\left(1 + \frac{K_u^2}{2}\right)$$

$$Gain \propto \frac{\rho_e L_{und}^3}{\gamma^3}$$

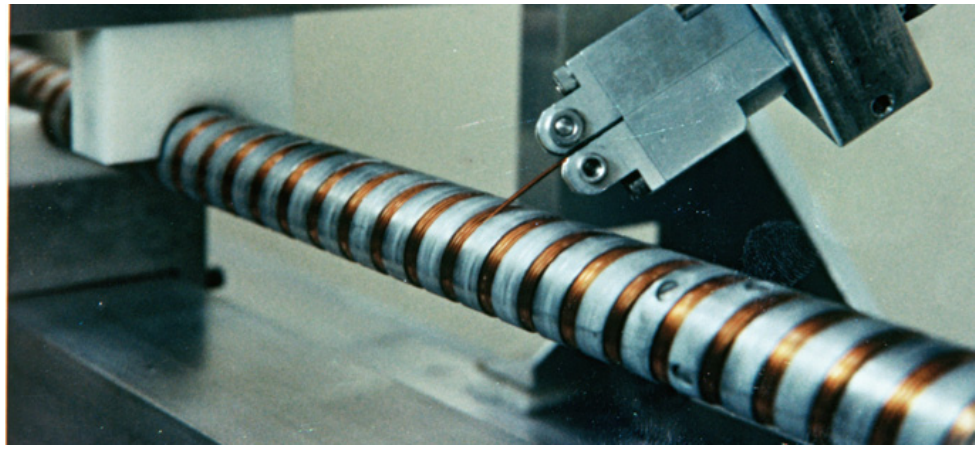
Courte longueur d'onde=> grande E=> haute qualité d'électrons
Début des LELs dans le domaine infra-rouge

J. M. J. Madey, Stimulated emission of Bremmstrahlung in a periodic magnetic field; J. Appl. Phys., 42, 1906–1913 (1971)

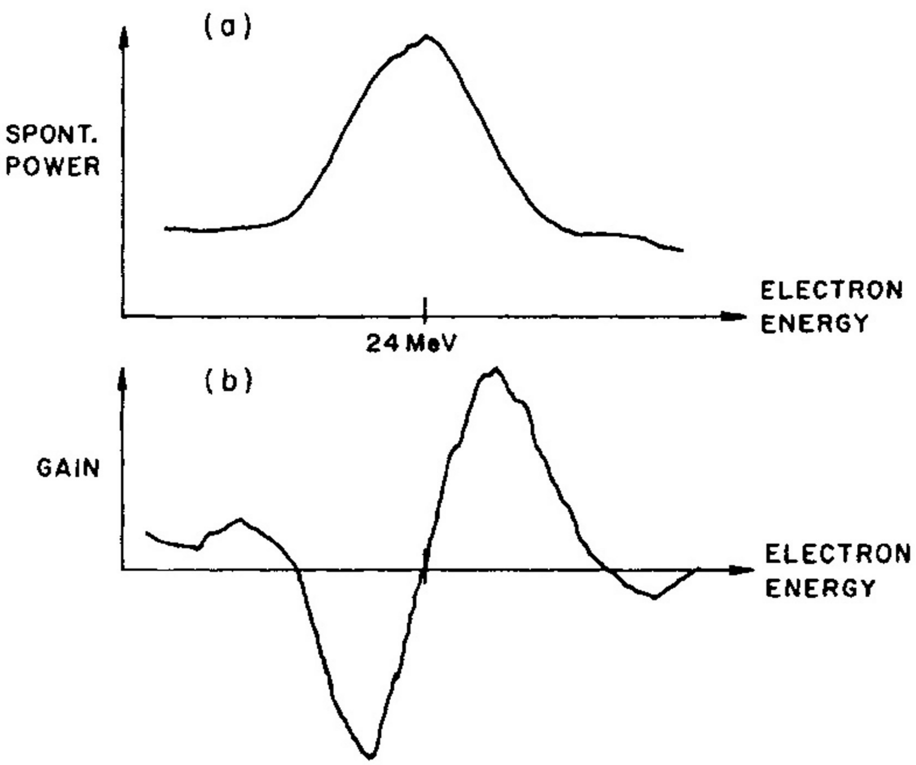
La première démonstration de LEL

Linac supra, Stanford, infra-red, J. M. J. Madey

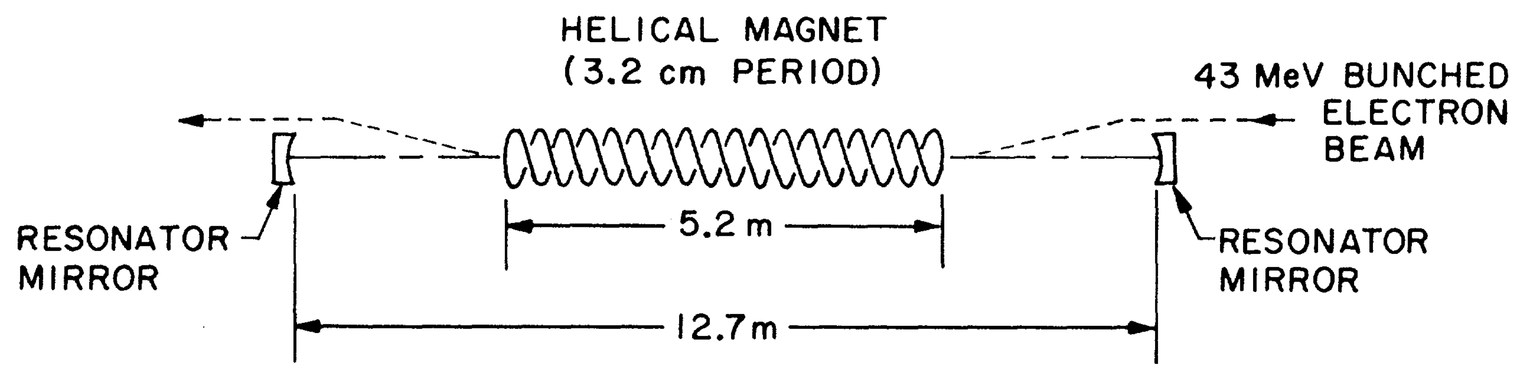
1976 : First FEL amplification

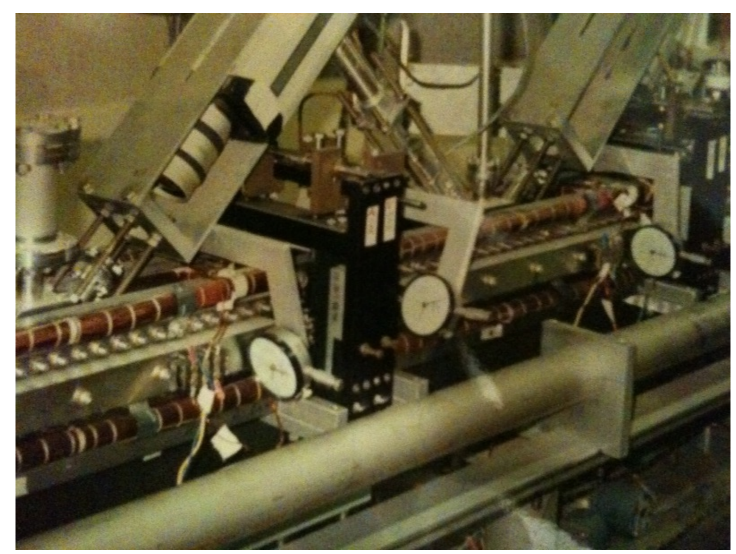


L. Elias et al., Observation of the stimulated emission of radiation by relativistic electrons in a spatially periodic transverse magnetic field, Phys. Rev. Lett. 36, 717-720 (1976)



1977 : First Free Electron Laser





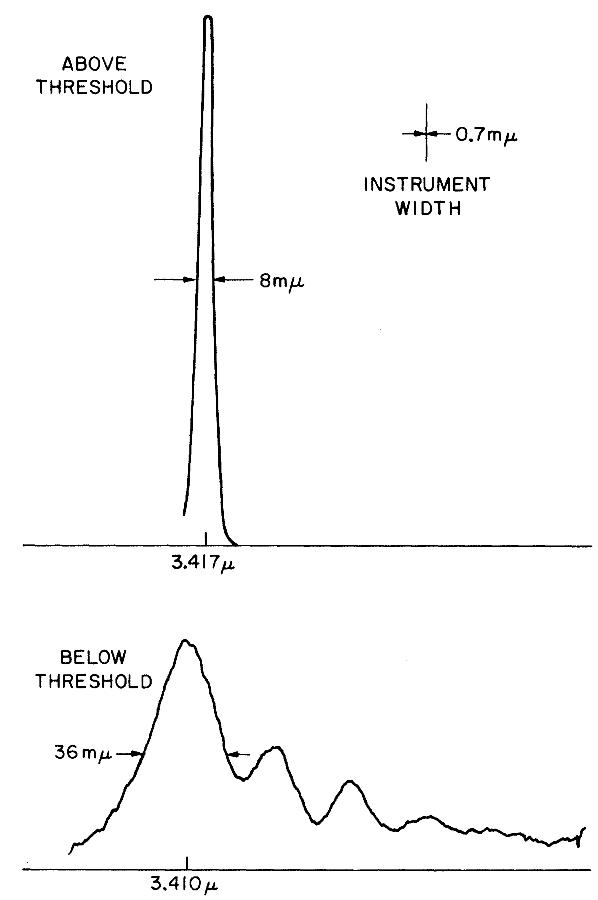


FIG. 2. Emission spectrum of the laser oscillator above threshold (top) and of the spontaneous radiation emitted by the electron beam (bottom).

D. A. G. Deacon et al, First Operation of a FEL. PRL 38, 16, 1977, 892

Saturation- Hope in storage ring FELs

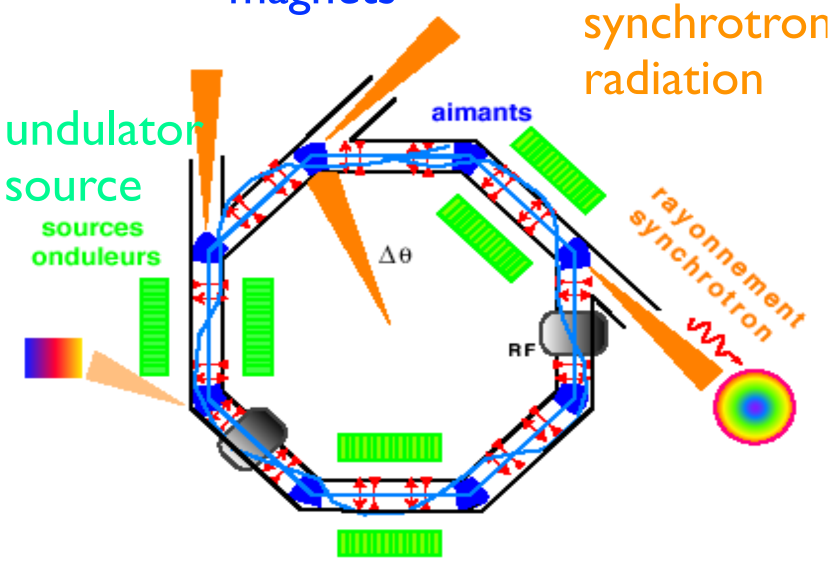
Use of a storage ring would be particularly attractive because the rf accelerating field for the ring would have to supply only the energy actually transformed to radiation in the periodic field. The overall efficiency of such a system thus would not be limited to the fraction of the electrons' energy convertible to radiation in a single pass through the interaction region. The feasibility of the idea hinges on the form of the electrons' phase-space distribution after passage through the periodic field, a subject currently under study.

L. Elias et al., Observation of the stimulated emission of radiation by relativistic electrons in a spatially periodic transverse magnetic field, Phys. Rev. Lett. 36, 717-720 (1976)

Collaboration avec l'équipe de J. M. J. Madey (Stanford) et celle d' ACO (France pour une demo LEL à Orsay

Yves Petroff

Yves Farge



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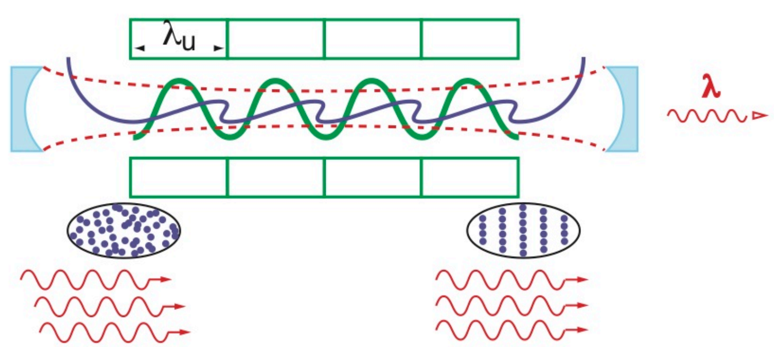

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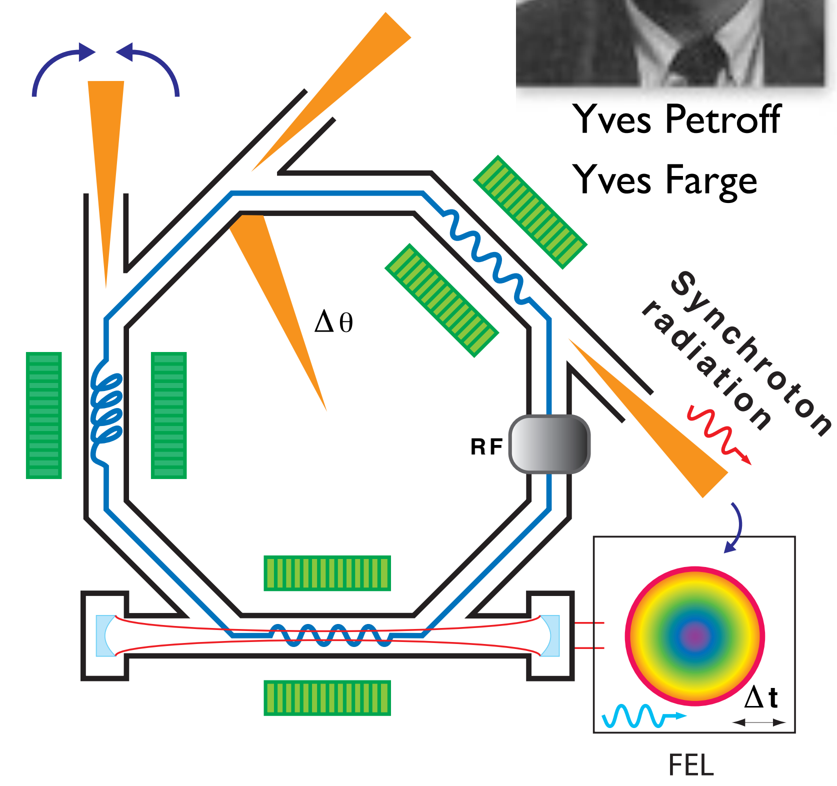
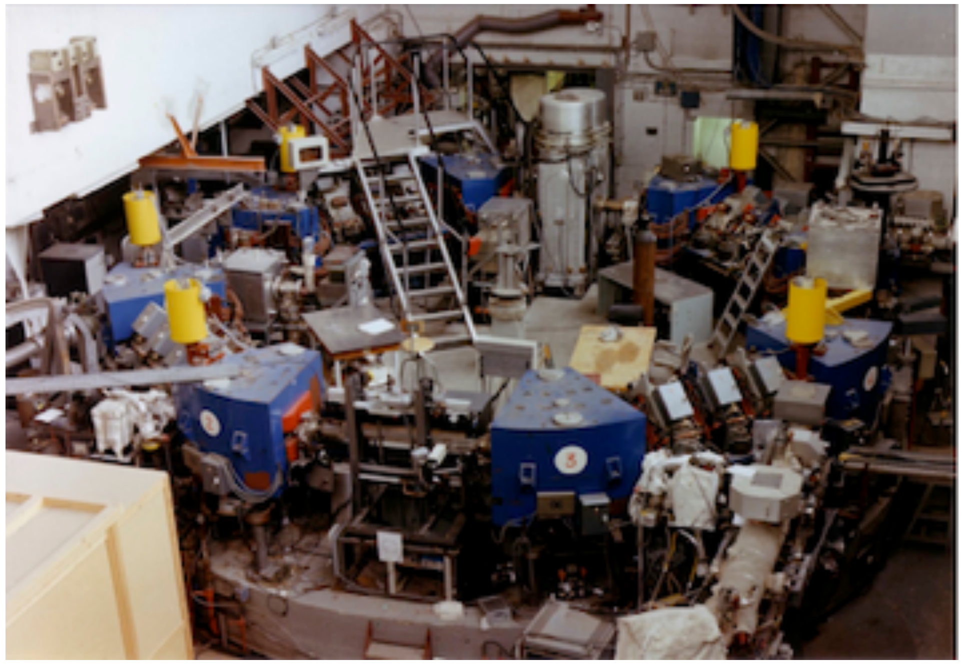
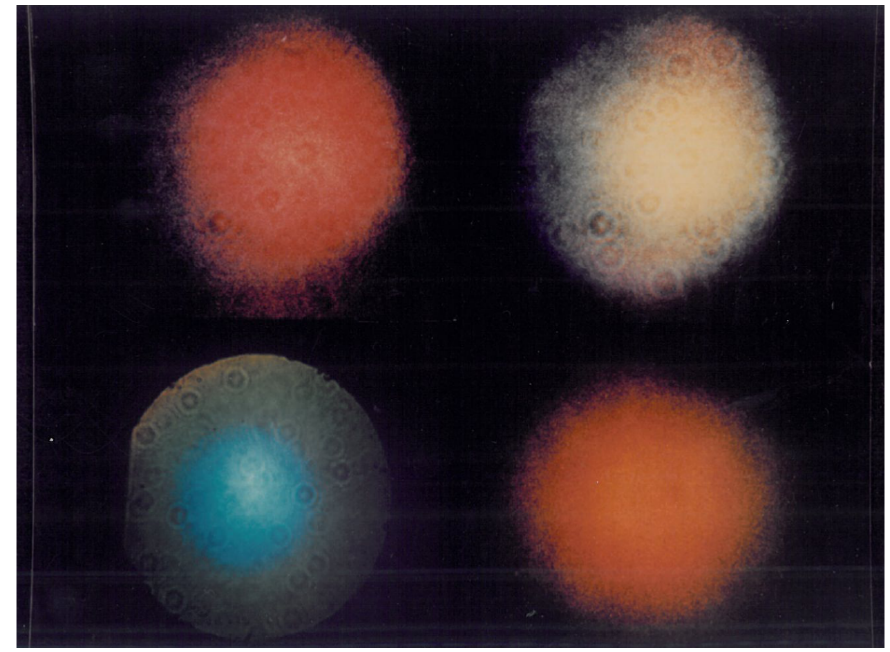


Renieri, A. (1979). Storage ring operation of the free-electron laser: The amplifier. Il Nuovo Cimento B Series 11, 53(1), 160-178.
Dattoli, G., & Renieri, A. (1980). Storage ring operation of the free-electron laser: the oscillator. Il Nuovo Cimento B Series 11, 59(1), 1-39.

Le second FEL en 1983, six ans après !

Sur l'anneau de stockage ACO (Orsay, France) dans le visible





M. Billardon et al., Phys. Rev. Lett. 51, 1652,(1983)

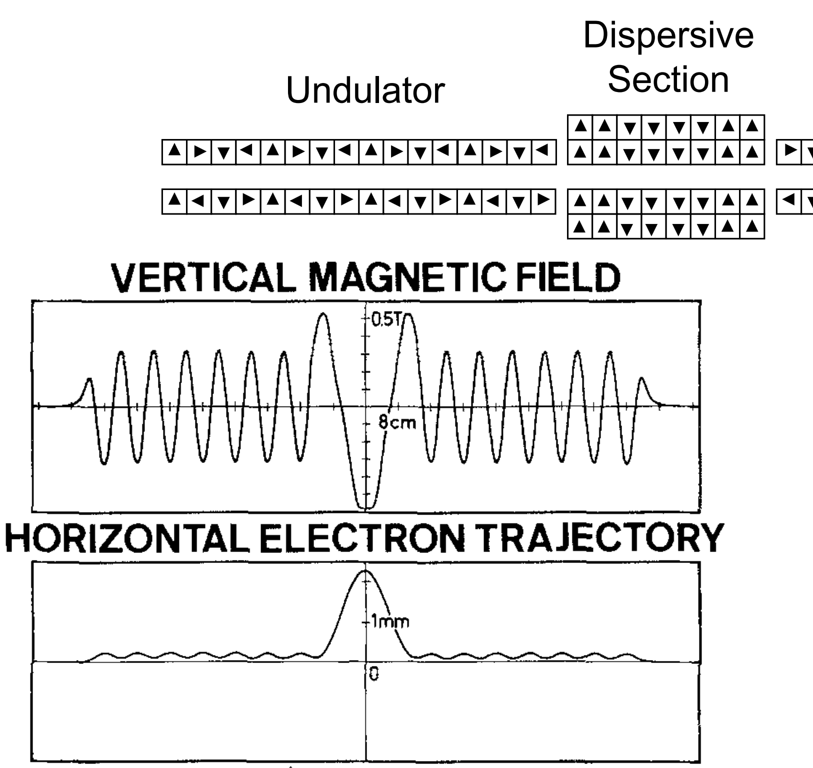


Fig. 1. Vertical magnetic field calculated for the Orsay optical klystron (gap: 33 mm) and the corresponding calculated horizontal electron trajectory at an energy of 240 MeV

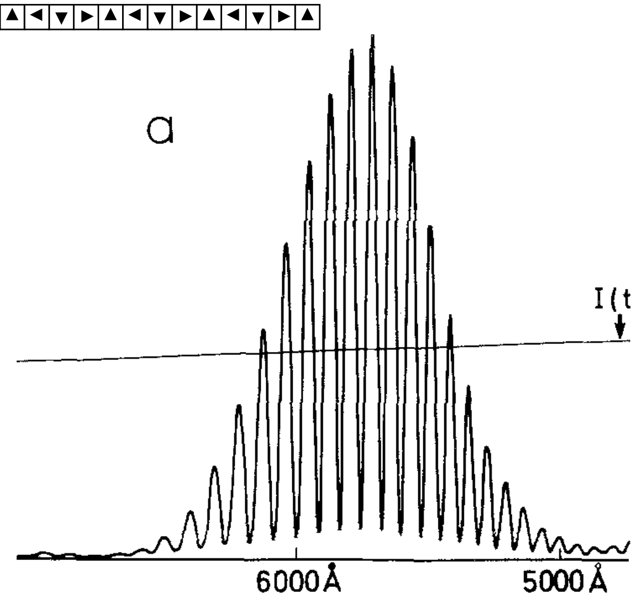


Fig. 3. Spontaneous emission spectrum $dI/d\lambda d\Omega$ measured for an electron energy of 238 MeV and a magnetic field parameter of $K = 2.09$ at low current where the modulation is almost total. The current decay $I(t)$ is superimposed

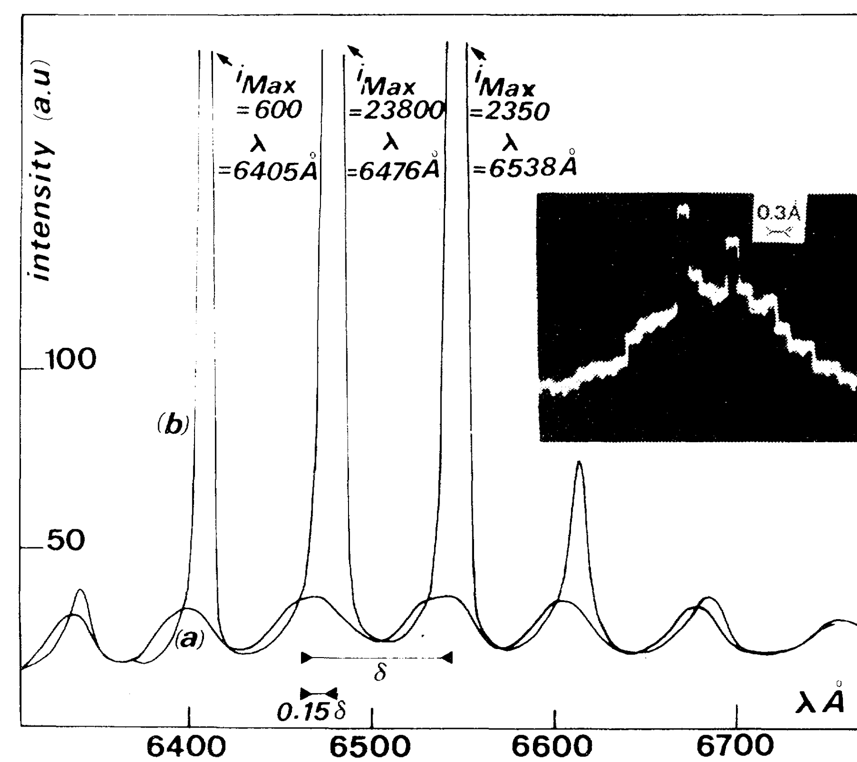
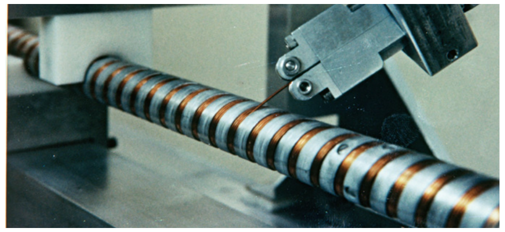


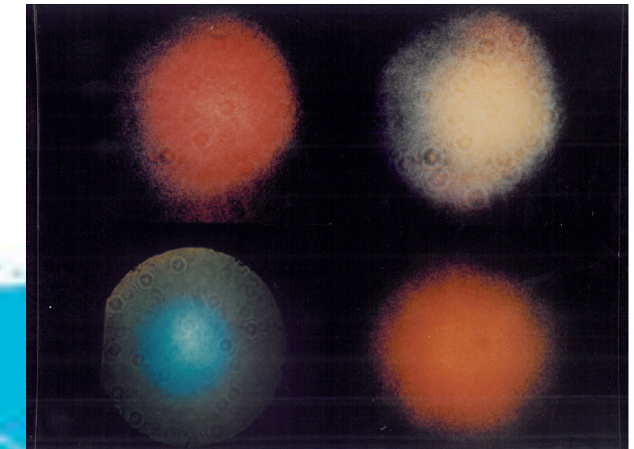
FIG. 4. Spectra of the cavity output radiation under two conditions: curve a, cavity detuned (no amplification) and curve b, cavity tuned (laser on).

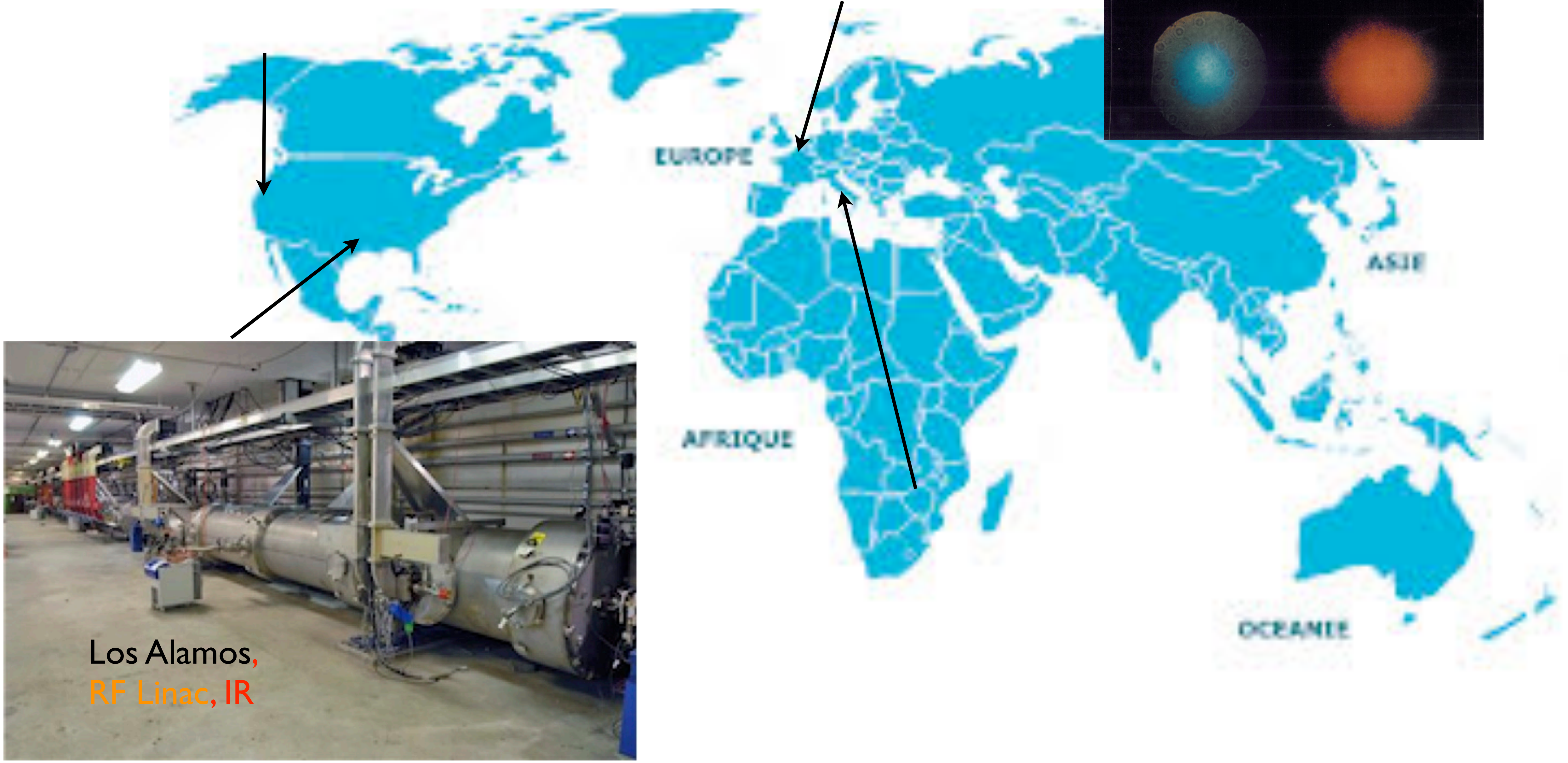
Les LEL oscillateurs suivants en 1983



Stanford,
Linear acc
IR

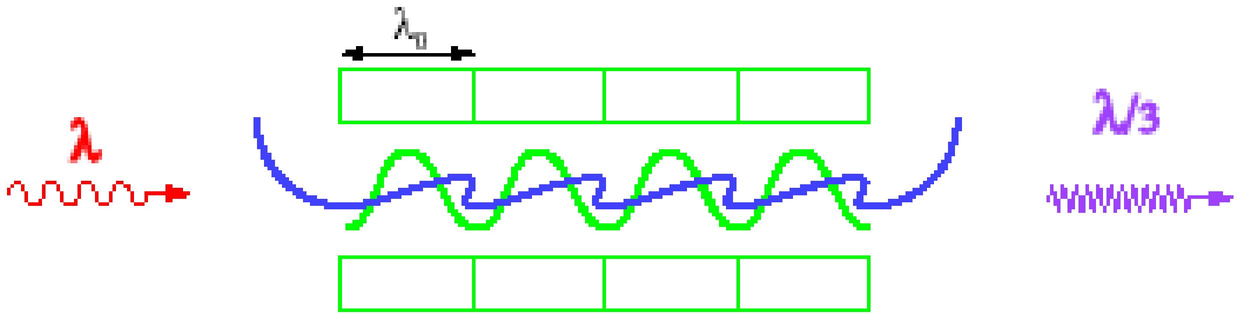
ACO, SR, vis, UV,VUV



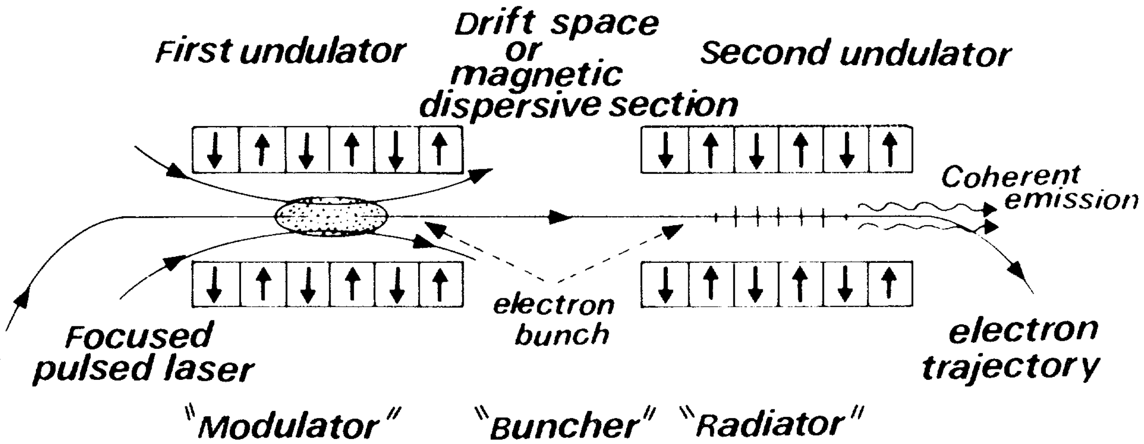


R.Warren et al., Society for Optical and Quantum Electronics, 425, 042016 (1983)

Génération d'Harmoniques Cohérentes sur ACO

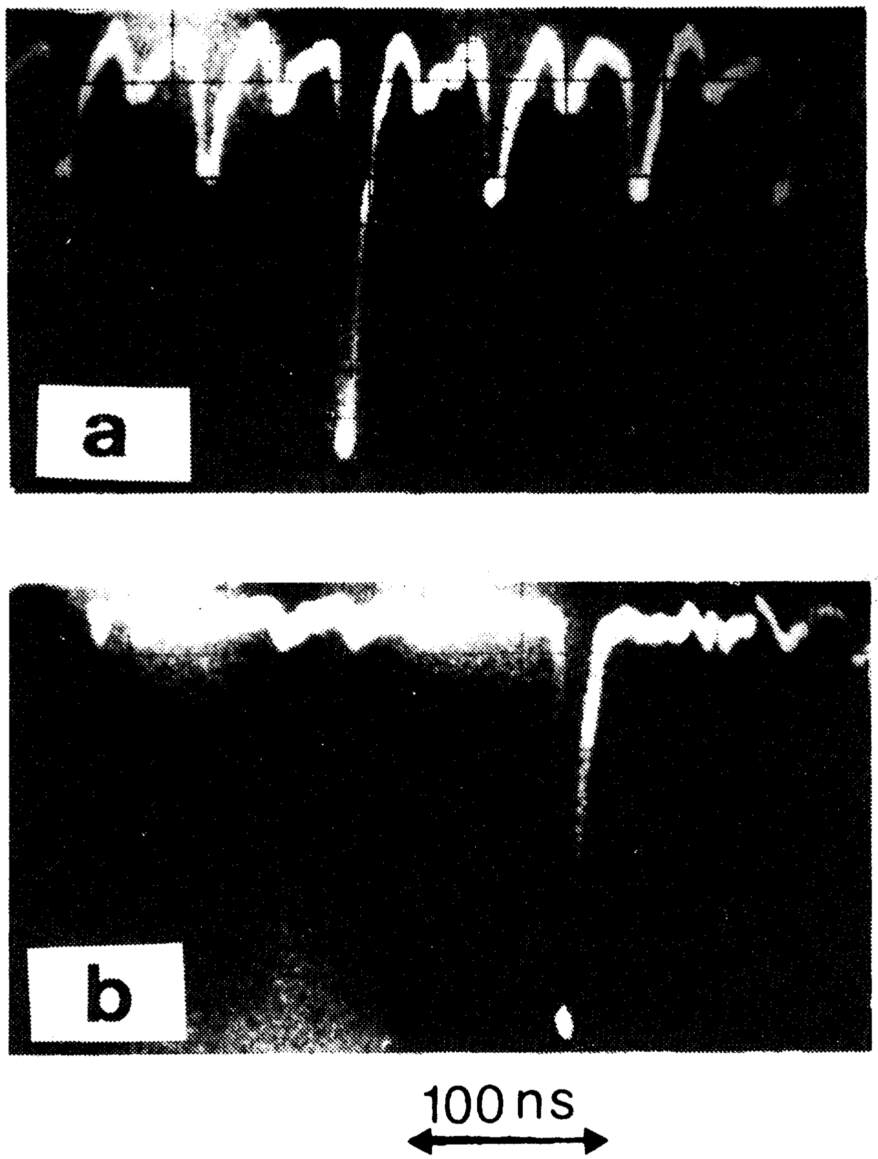


ACO (Orsay, France), 166 MeV
Nd-Yag at 1.06 µm, 20 Hz, 15 MW, 12 ns
=> CHG at 352 nm



352 nm
$R_3 = 3$

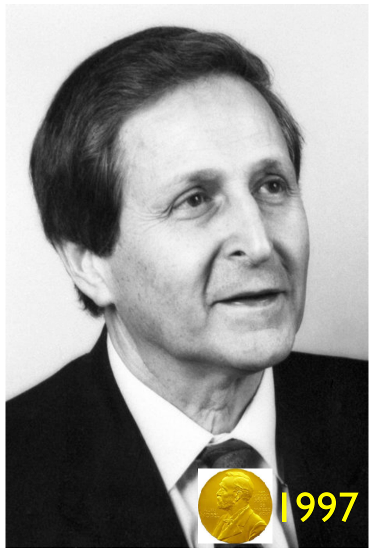
352 nm
$R_3 > 100$



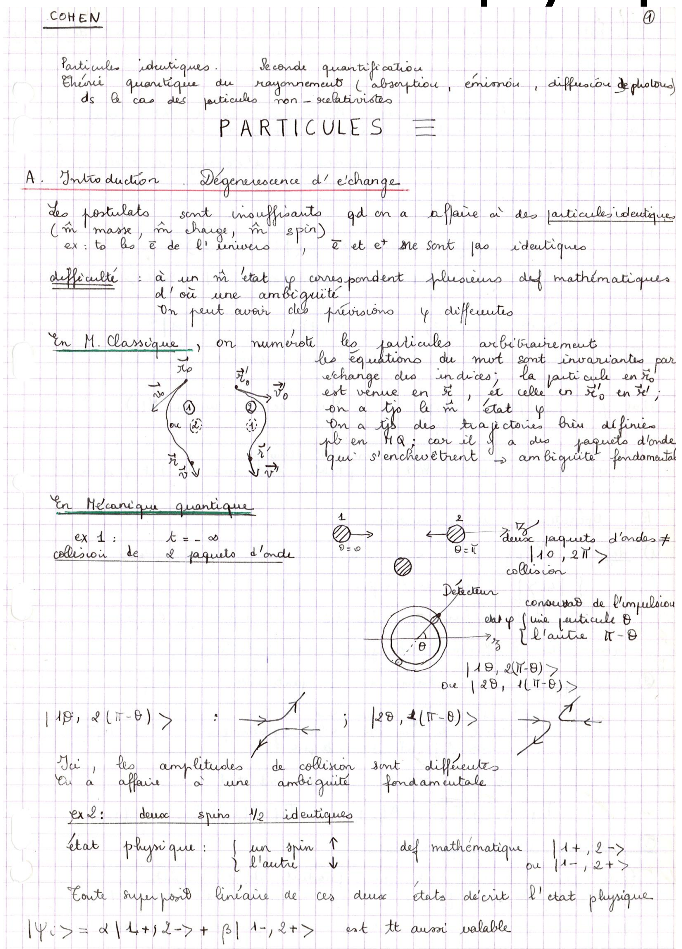
B. Girard, Y. Lapierre, J. M. Ortéga, C. Bazin, M. Billardon, P. Elleaume, M. Bergher, M. Velghe, Y. Petroff, Opitcal frequency multiplication by an optical klystron, Phys. Rev. Lett. 53 (25) 2405-2408 (1984)

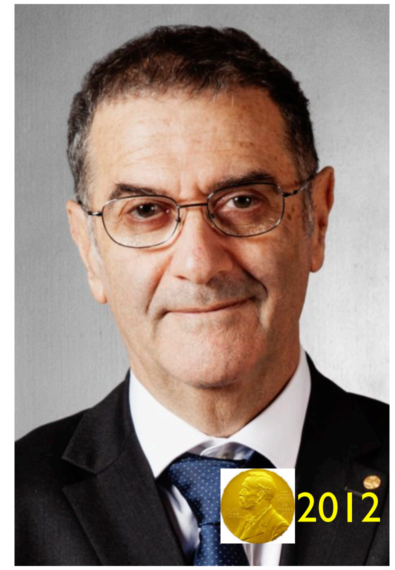
1985: Comment j'en suis venue au FEL…

1984-1985 M2 physique atomique et moléculaire à Paris VI, ENS

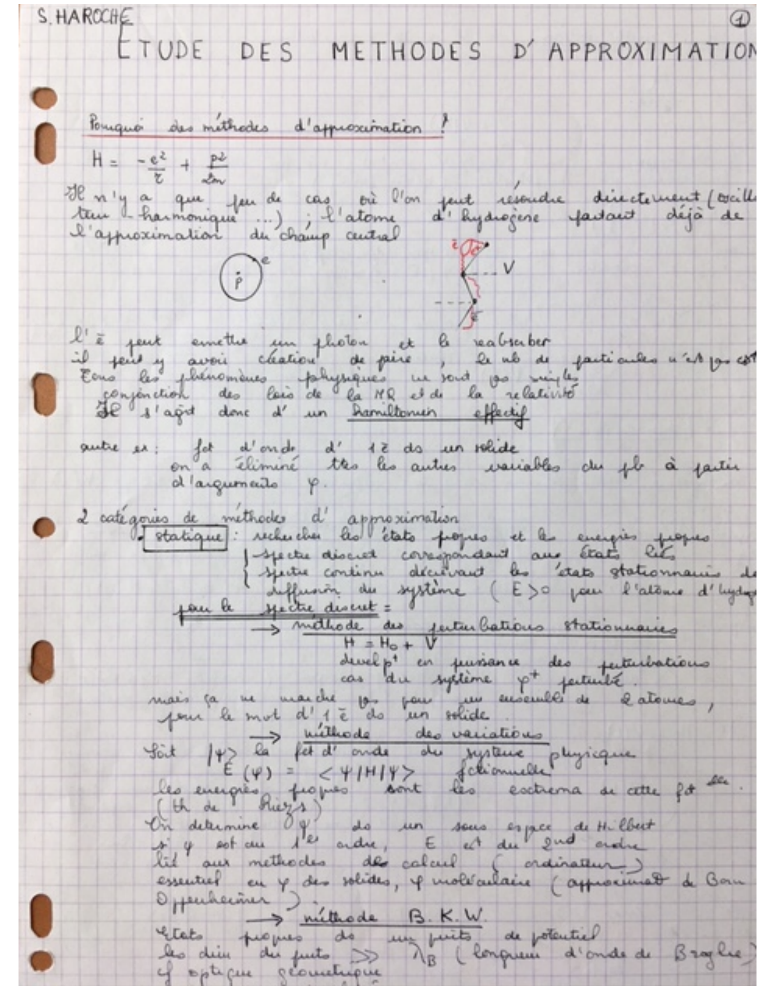


C. Cohen-Tannoudji





S. Haroche



Eduquée en mécanique quantique et en lasers, j'étais fascinée par la production de lumière avec des électrons relativistes dans un champ magnétique, ce nouveau type de milieu de gain.

LEL : multi-disciplinaire (accélérateur, laser, magnétisme, optics …),

LEL : nouveau type de laser, Domaine très exploratoire en 1985

Stage sur ACO en 1983 en physique des surfaces

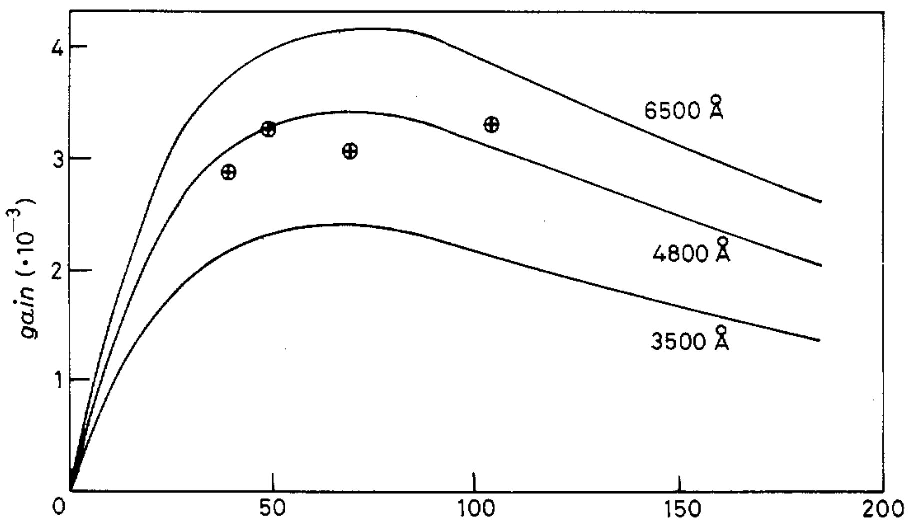
=> j'ai rejoint le groupe LEL d'ACO qui préparait aussi celui de Super-ACO

Pascal Elleaume (1956-2011)

Nouveaux résultats sur le LEL sur ACO

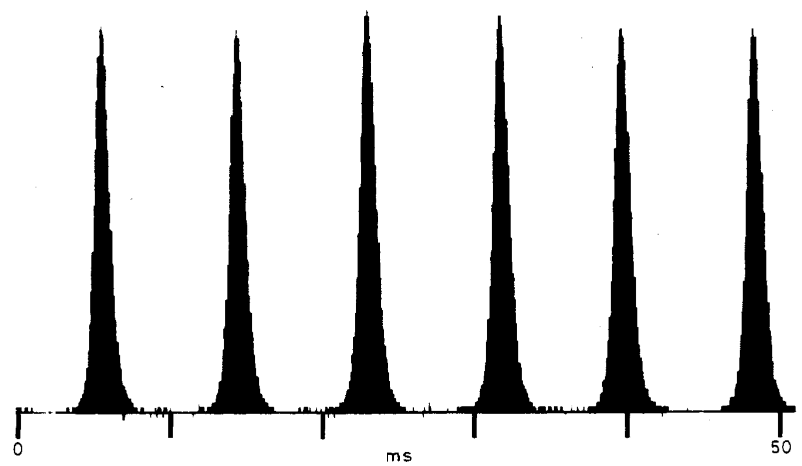
FEL oscillator

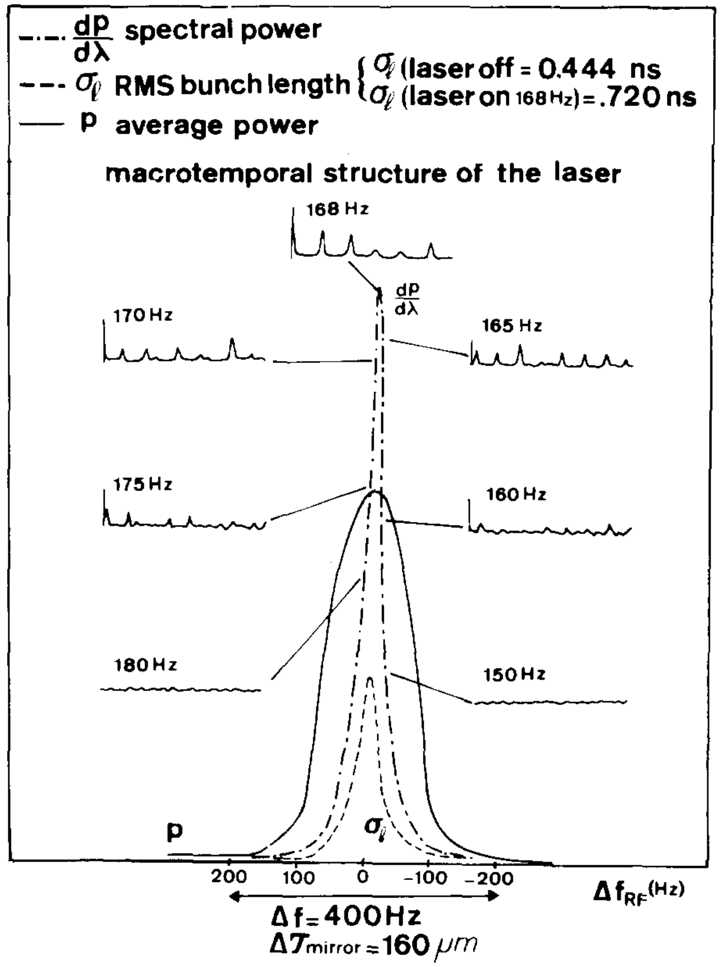
Gain



M. Billardon et al, Europhys. Lett., EPL 3 689 (1987)
M. E. Couprie et al. , NIMA A259, 77-82 (1987)

Structure macrotemporelle => Q-switch





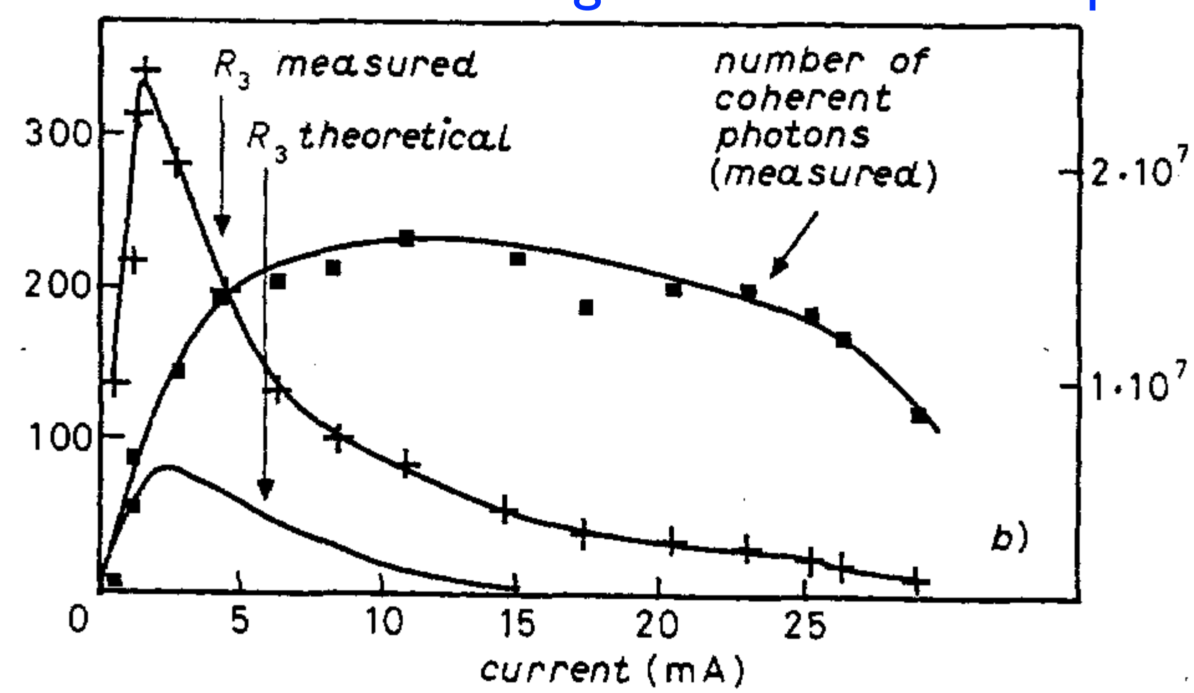
CHG à 355 nm, 177 et 106.4 nm

R. Prazeres et al., Nucl. Instr. Meth. A272 (1988), 68-72
R. Prazeres et al, Europhys. Lett., 4 (7), 817-822 (1987)

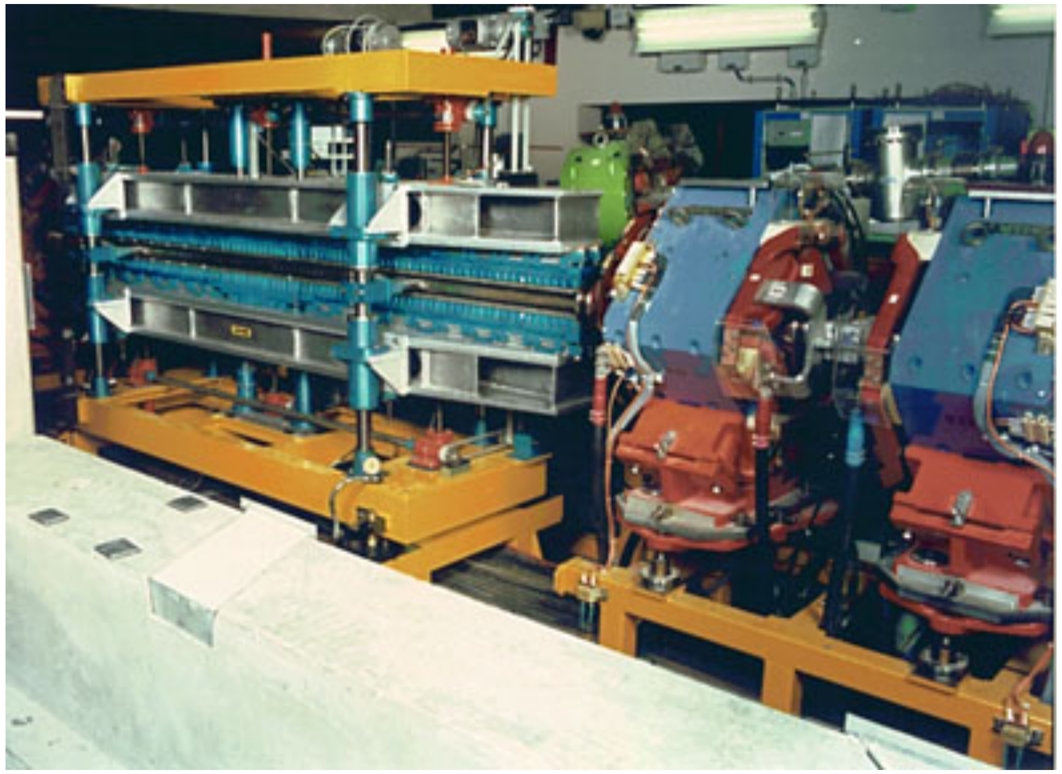
Experimental results on ACO (1987)

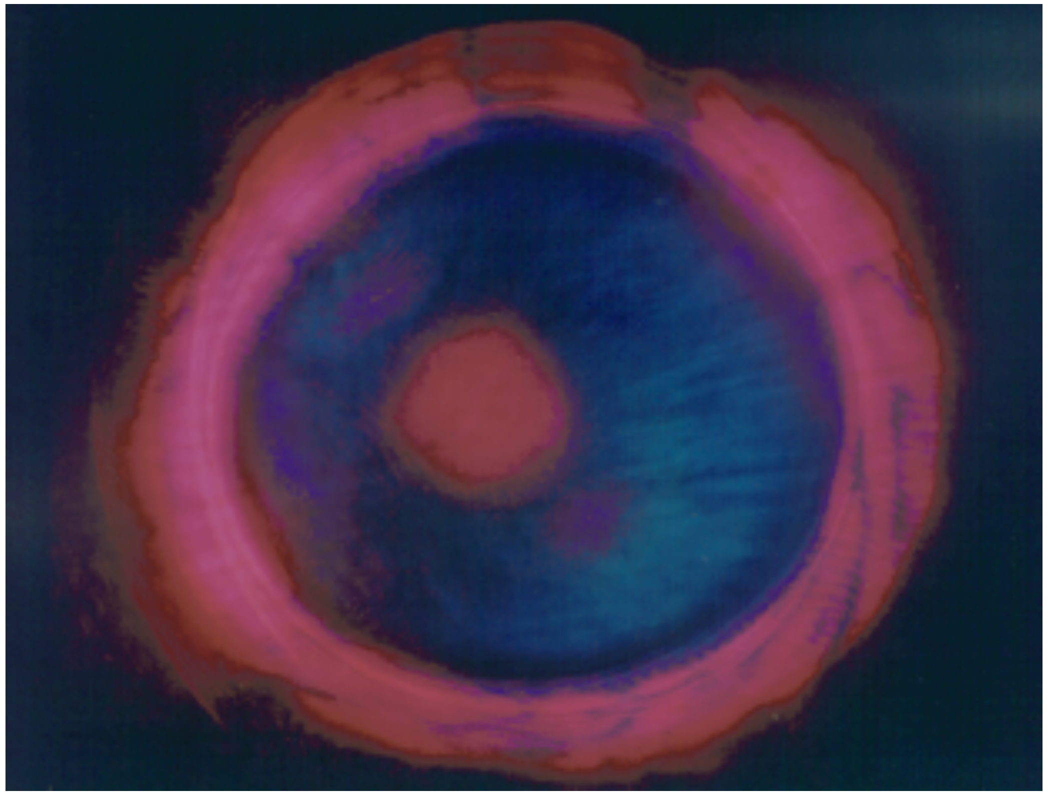
Observed harmonic	3	5
Corresponding wavelength [Å]	1773	1064
Integrated ratio R_n^{int}	350	3–4
monochromator bandwidth [Å]	2	2
monochromator angular aperture [mrad^2]	1.4	3
Spectral ratio $R_n(\lambda, \Omega)$	6000	100
Number of coherent photons/pulse	1.5×10^7	10^5
in spectral width [Å]	0.1	0.07
in angular aperture [mrad]	0 2	0.1

Aplatissement de la dist. longitudinale électronique



Super-ACO FEL developments (1989-2003)



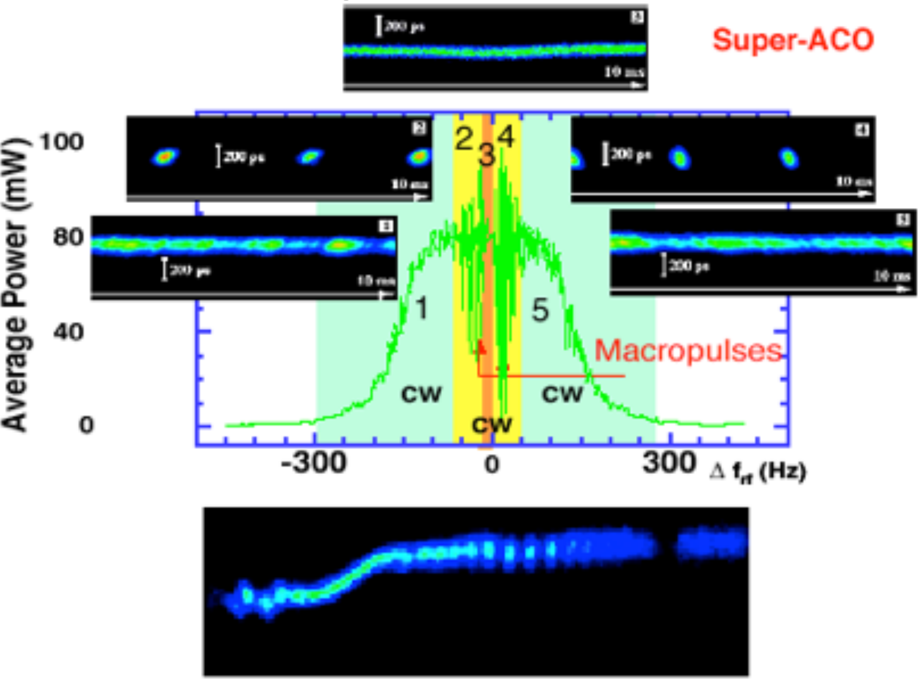


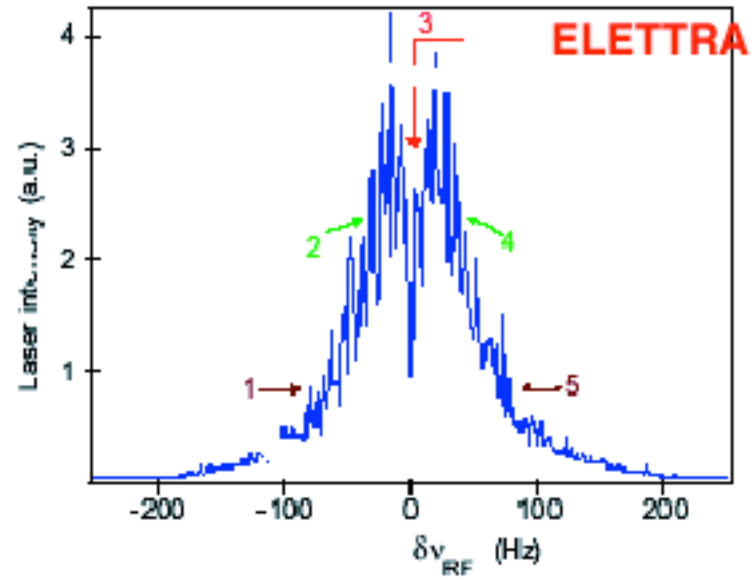
Construction du klystron optique
Etude de dégradation de miroirs
Fonctionnement à plus courte longueur d'onde et stabilité
Première expériences d'utilisation
Chaos
Compton scattering

Collaborations:
CLIO (France) : linac based FEL in the infrared
VEPP3 (URSS) : SRFEL, linewidth narrowing
UVSOR (Japon) : SRFEL, longitudinal dynamics, polarisation control, CHG
ELETTRA (Italie) : SRFEL, short wavelength operation

Dynamique d'un LEL sur anneau de stockage

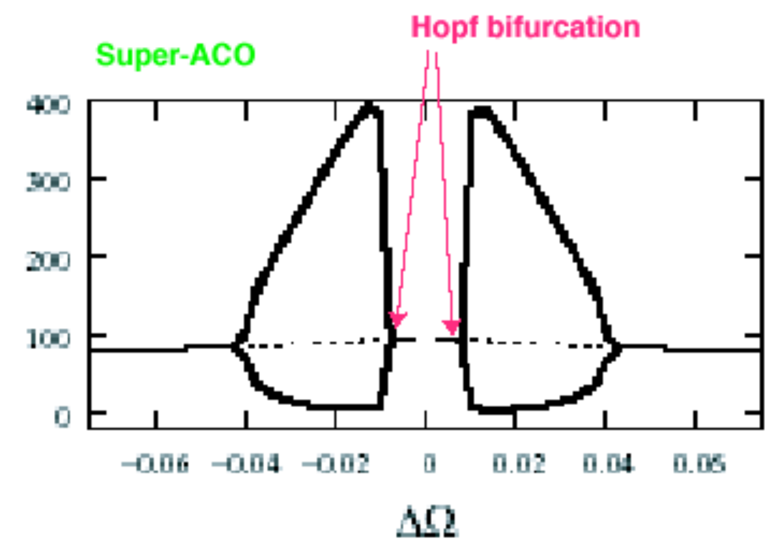
Detuning curve





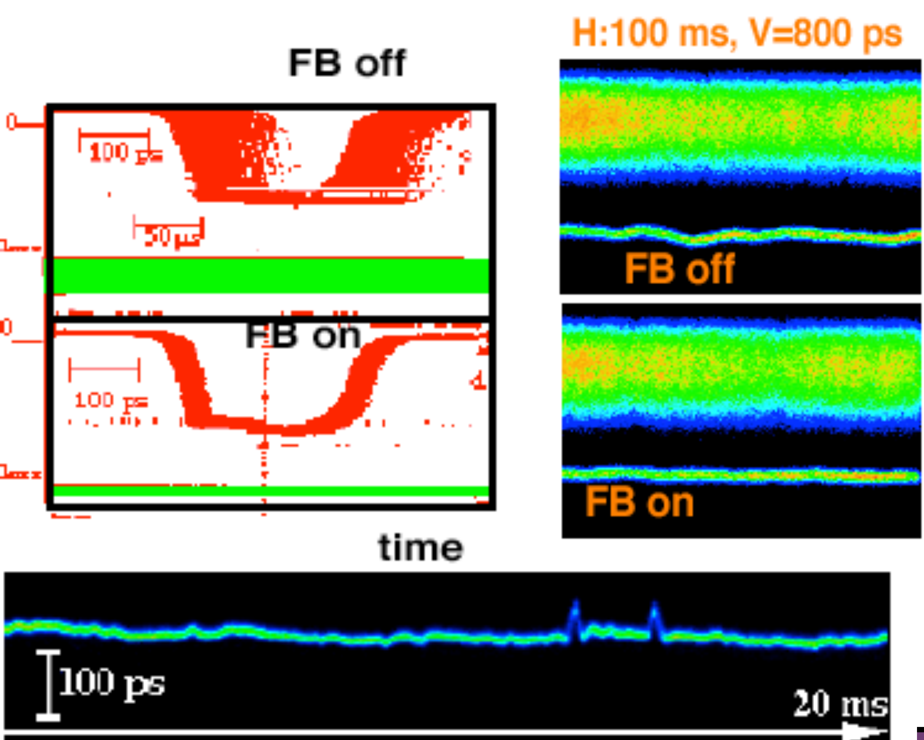
M. Billardon et al., Phys. Rev. A 44 (2), 15, 1301-1315 (1991)

Control of the pulsed regimes on Super-ACO

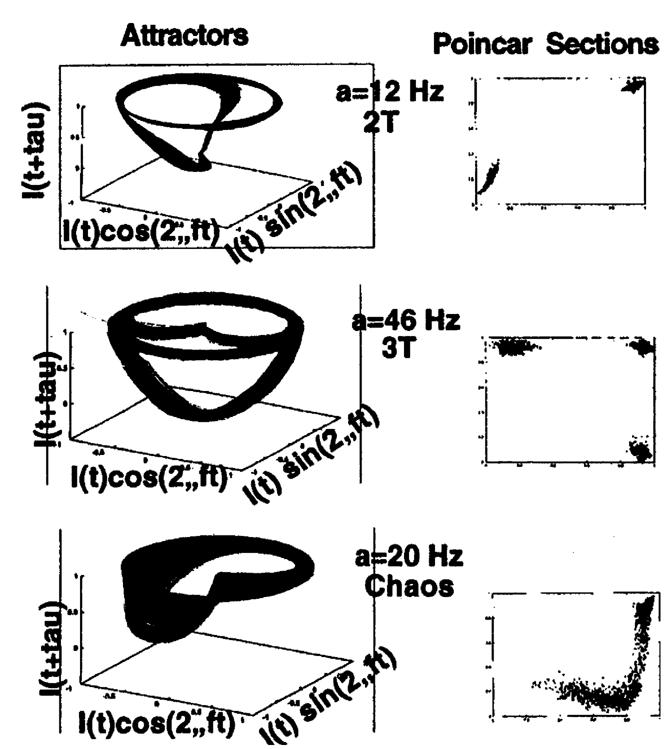


Longitudinal feedback for improved stability (Super-ACO)

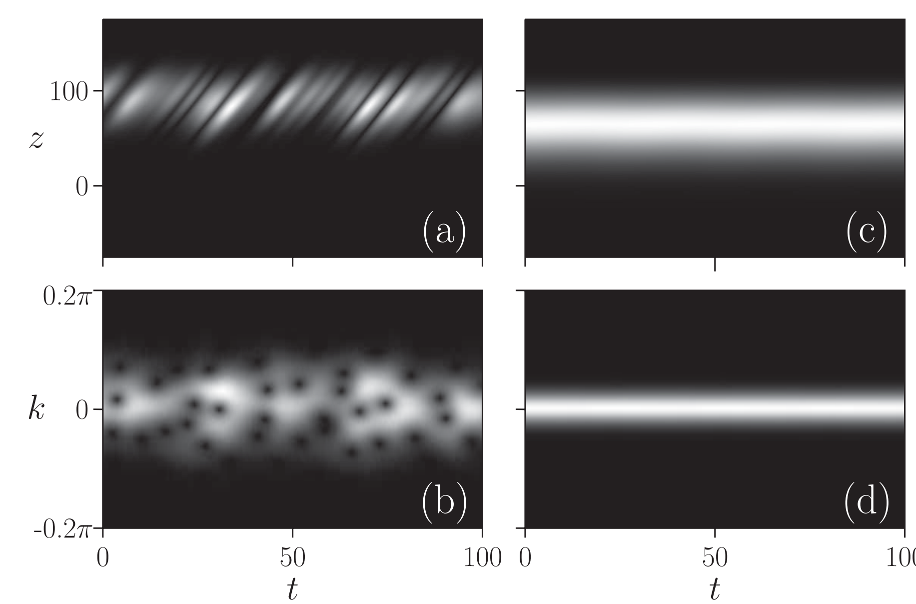
M. E. Couprie, NIMA A 358-374 (1995)



Chaos



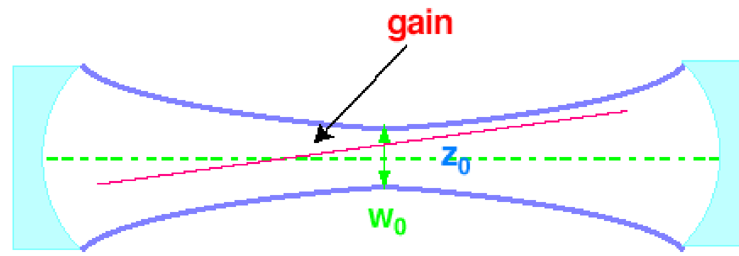
M. E. Couprie, NIMA A 483(1-2) 167-171 (2002)

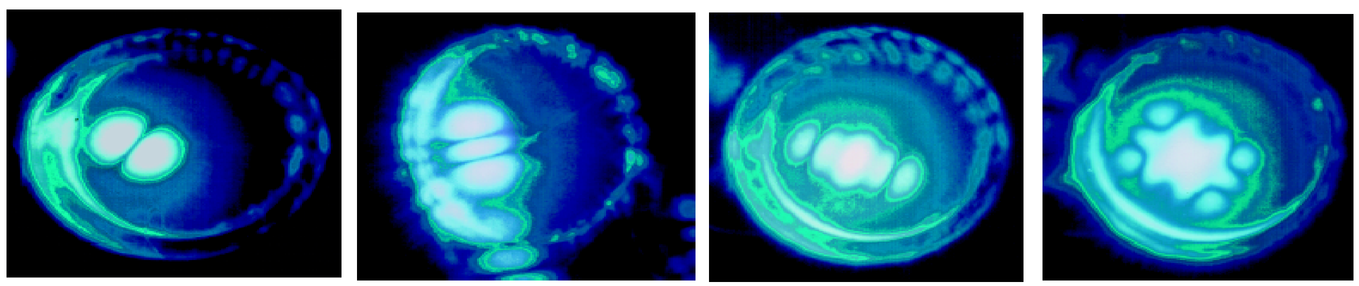


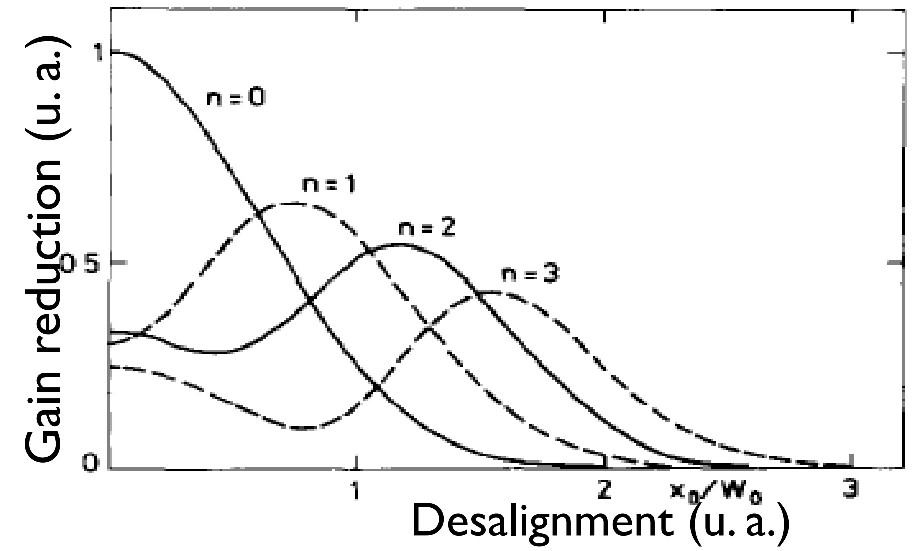
S. Bielawski et al., Phys. Rev. E 69, R045502 (2004)

Propriétés des LELs oscillateurs

Transverse modes

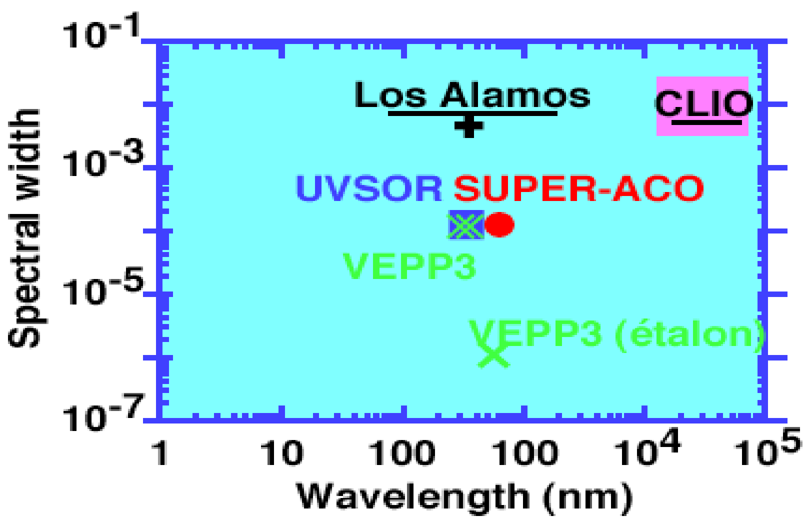


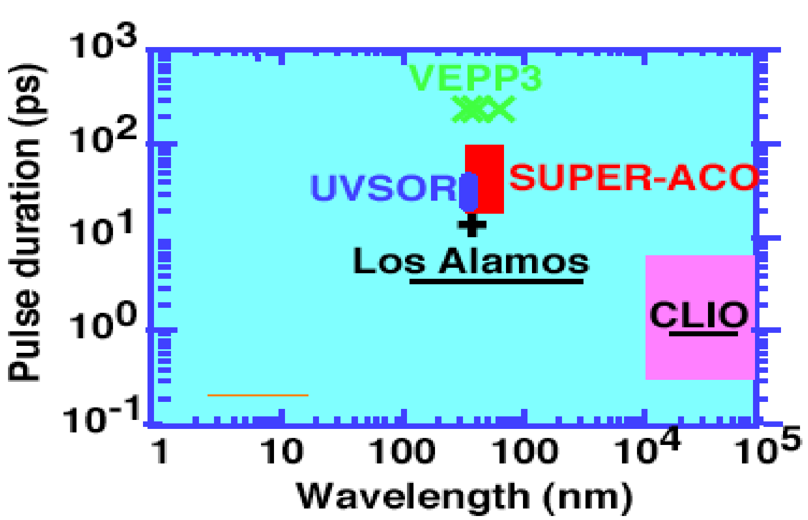




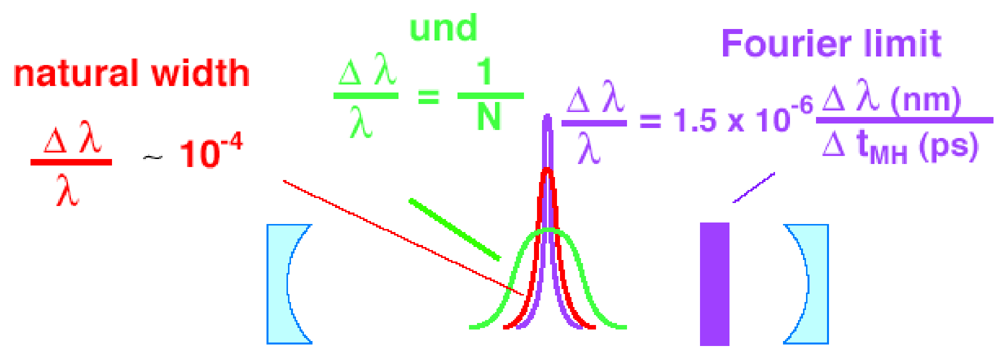
M.E. Couprie, D. Garzella, M. Billardon, Nucl. Inst. Meth. A 358, 382-386 (1995)

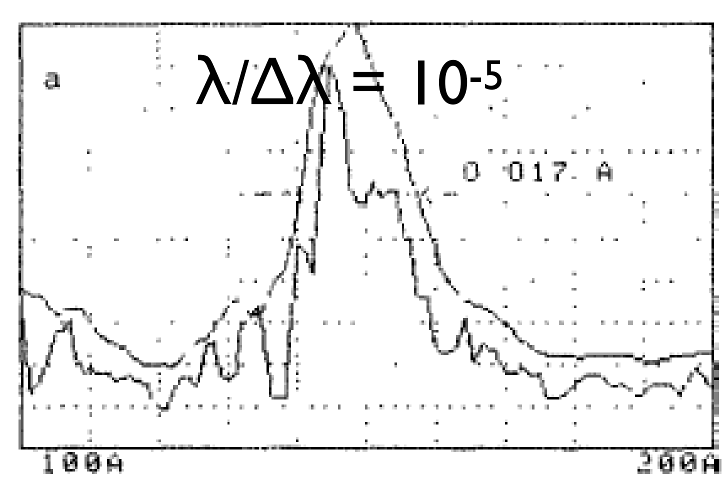
Temporal properties





M. E. Couprie, NIMA A393, 13-17 (1997)



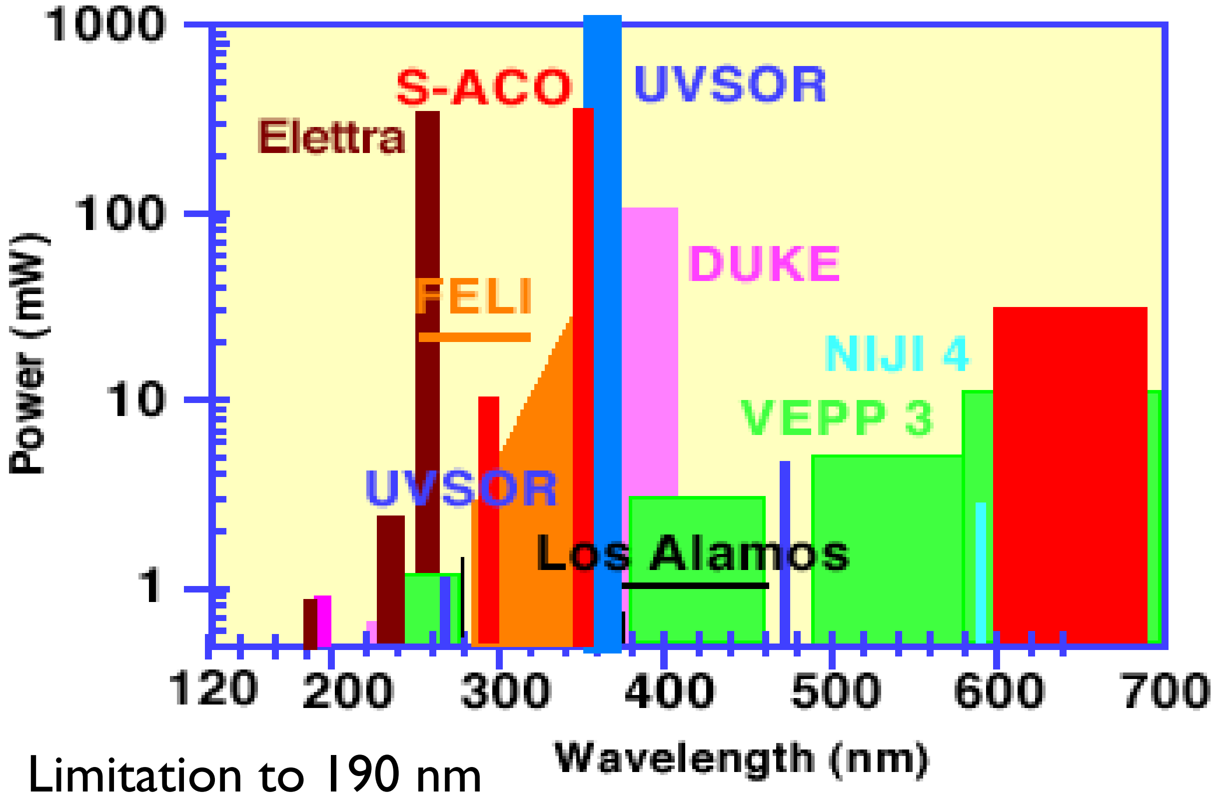


VEPP3 (Russia)

M. E. Couprie et al., NIMA 304 (1991) 47-52

Limite en longueur d'onde des LEL oscillateurs

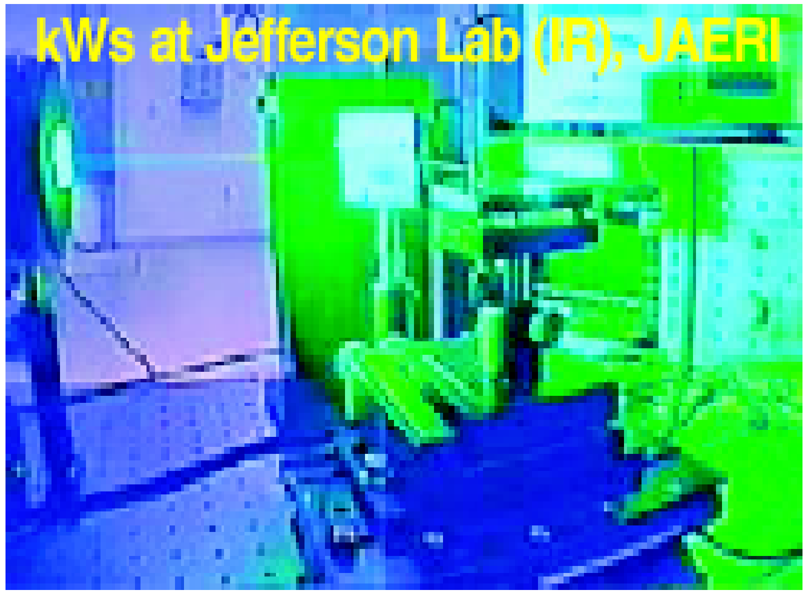
- anneau de stockage : longueur de section droite limitée
- onduleur plan : harmoniques élevées reçues par les miroirs => dégradation des optiques

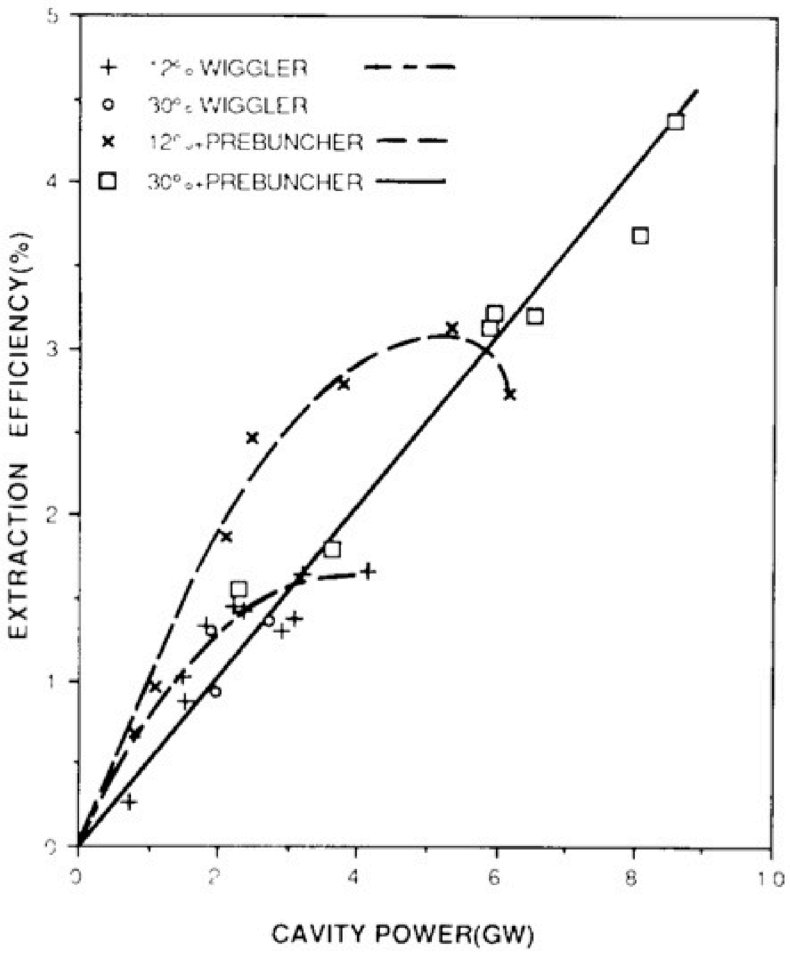


Limitation to 190 nm

M. Marsi, et al., 80 (16): 2851-2853 (2002).

- Linacs
- ERLs





Augmentation de l' efficacité par tapering d'onduleur sur LEL sur linac

$$r = \frac{1}{4N_u}$$

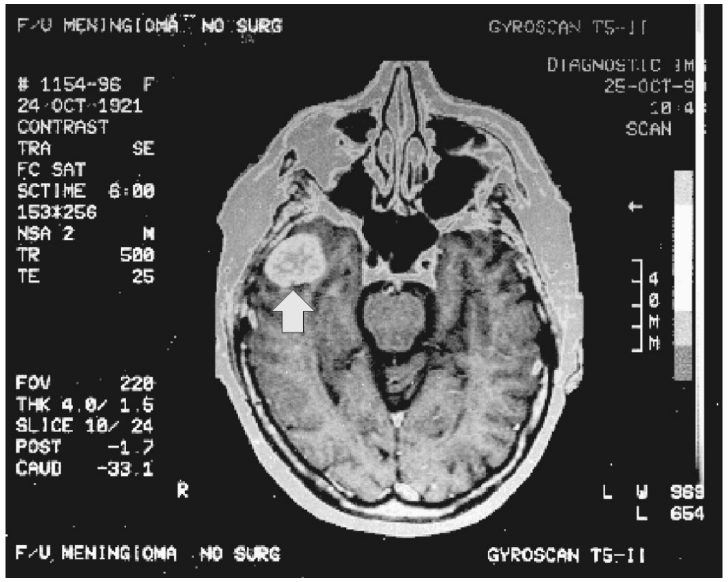
$$\lambda = \frac{\lambda_u}{2\gamma_s^2}\left[1 + \frac{1}{2}\left[\frac{eB_z(s)\lambda_u(s)}{2\pi m_o c^2}\right]^2\right]$$

$$n\lambda_n = \frac{\lambda_u}{2\gamma^2}(1 + \frac{K_u^2}{2} + \gamma^2\theta^2)$$

Livermore : 40 % efficiency, operated as amplifier

Warren, et al, IEEE Journal of Quantum Electronics,, 19(3), 391-401.

Premières utilisations des LELs oscillateurs



Human surgery

Vanderbuilt IR FEL

Edwards, G. et al.Review of scientific instruments, 74(7), 3207-3245 (2003)

Photon echo

Stanford IR FEL

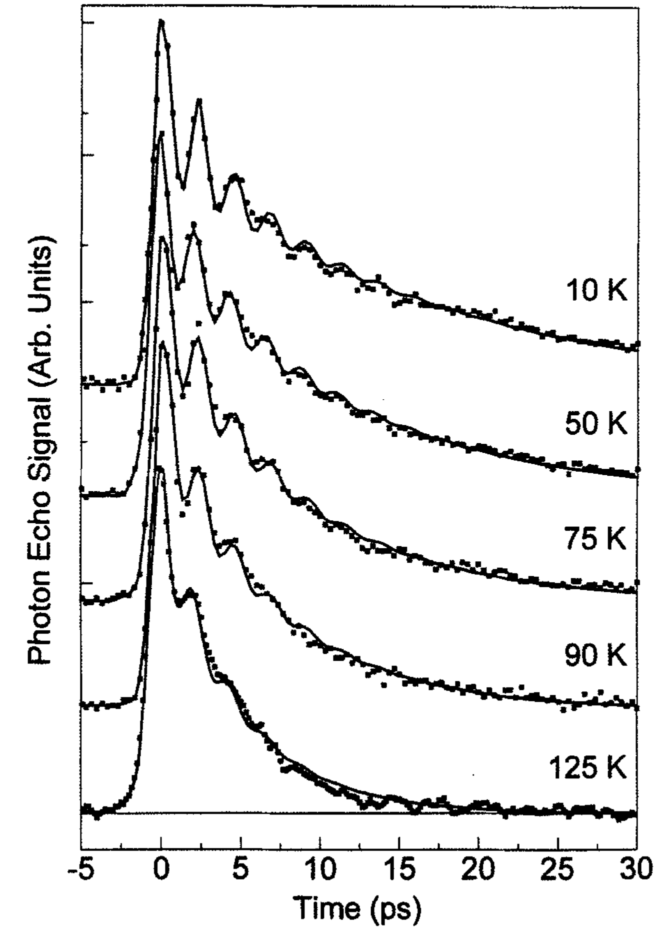
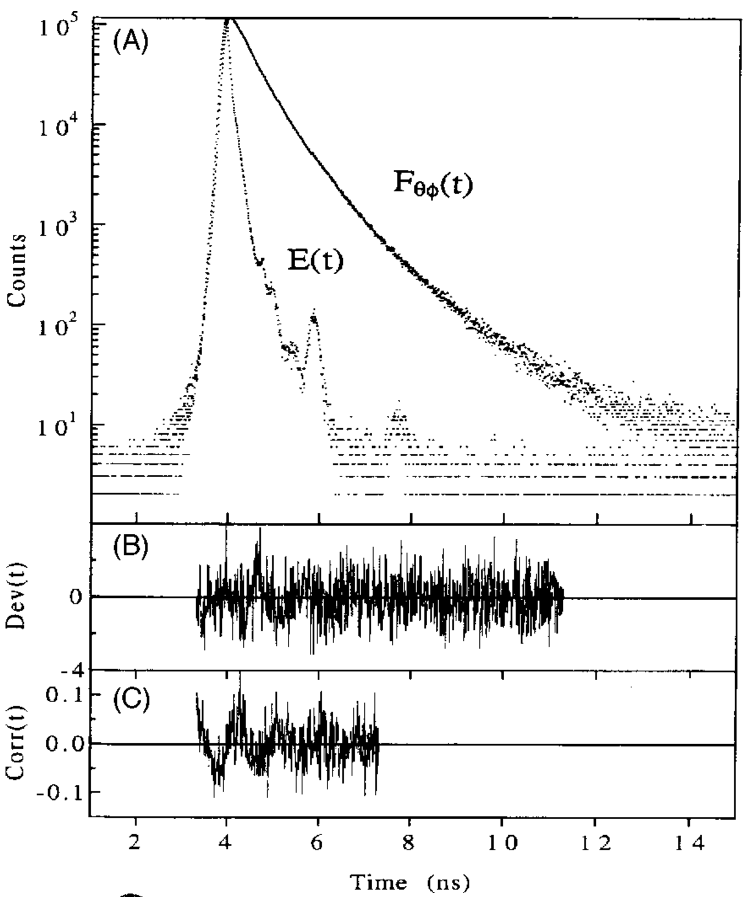
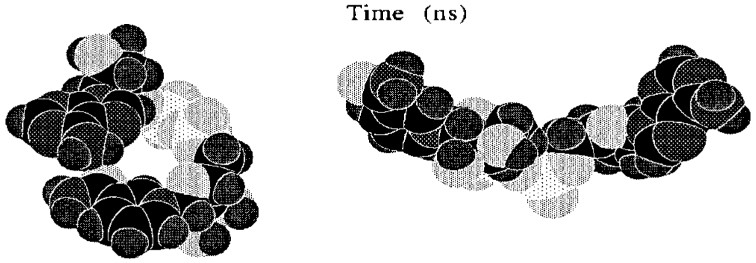


Figure 11. Beating evident in photon echo decays and fits for the asymmetric CO-stretching mode for $W(CO)_6$ in DBP as a function of temperature. Reprinted with permission from reference 37.





fluorescence résolue en temps:
Décroissance et dynamique rotationnelle du cofacteur enzymatique NADH

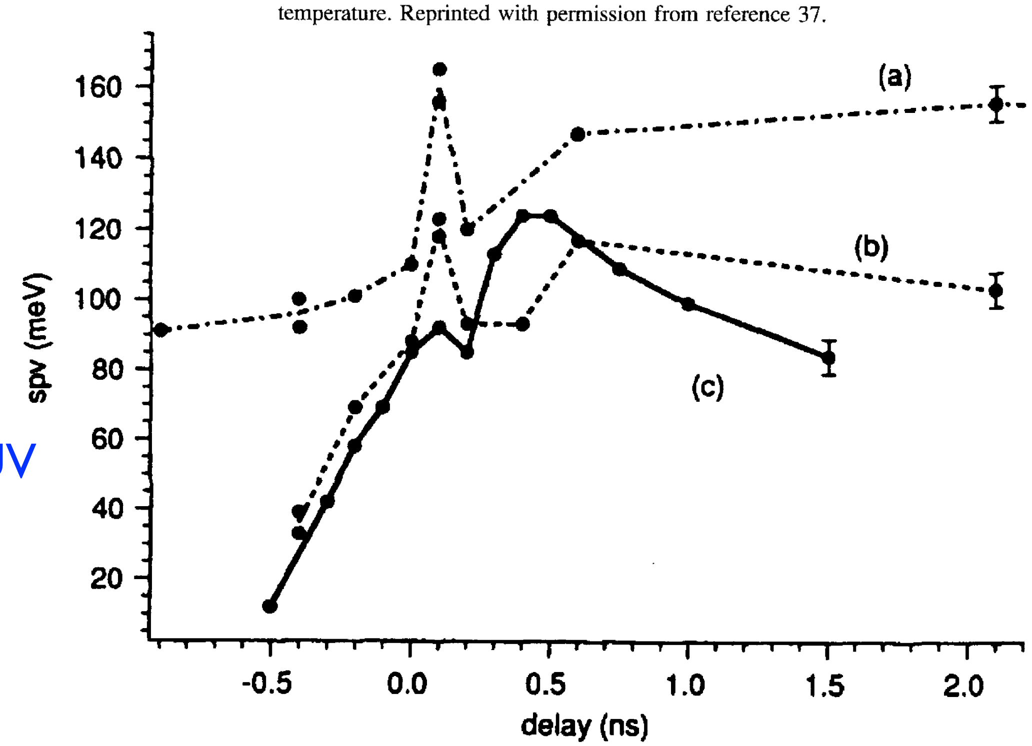
Super-ACO UV FEL

M. E. Couprie et al.Rev. of Scient. Inst., 65(5) May 1994, 1485-1495

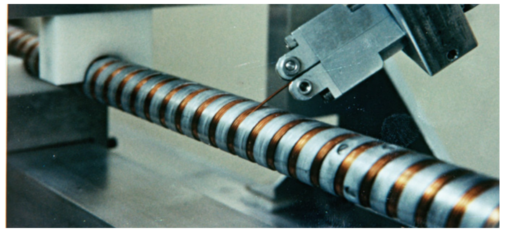
Effet de photovoltage de surface:
Si(111)2x1
pompe sonde LEL +
Rayonnement Synchrotron VUV

Super-ACO UV FEL

M. Marsi et al.,Appl. Phys. Lett. 70(7) (1997) 895-897



Panorama des LEL oscillateurs

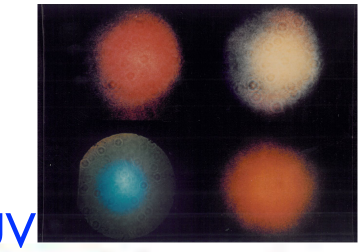


Stanford,
Linear acc
IR

Jefferson Lab., ERL,
IR-UV

Van der Vilt, Linac, IR

Los Alamos,
RF Linac, IR



ACO, SR, vis, UV,VUV
Super-ACO, SR, vis, UV,VUV

CLIO, Linac, IR
DELTA, SR, vis, UV
FHI, Berlin, Linac, IR
FELIX, Linac, IR

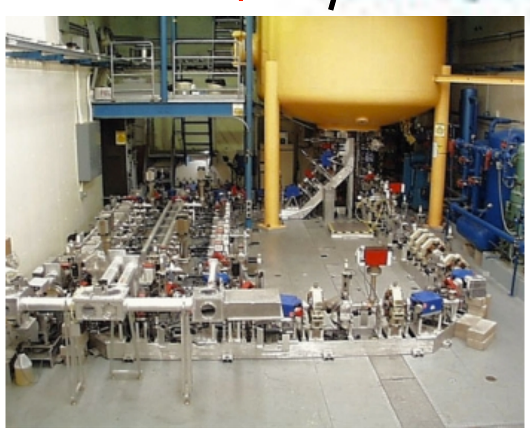
DUKE, SR, vis, UV,VUV
MARK III, Linac, IR

TERAS, SR, vis, UV
UVSOR, SR, vis, UV,VUV
NIJI- IV, SR, vis
FELI, Linac, IR, vis, UV

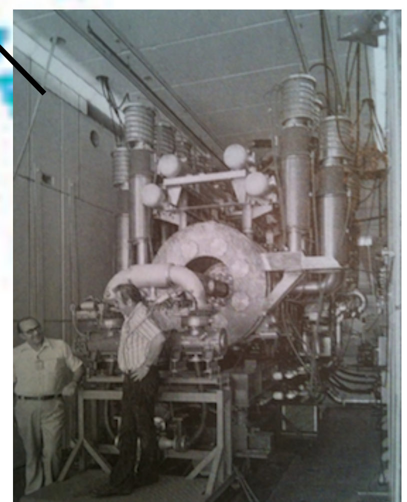
VEPP 3, SR, vis, UV
Novosibirsk, ERL, IR

ELETTRA, SR, vis, UV,VUV

Santa-Barbara,
Van der Graaf,
2.5 mm to 63 μm

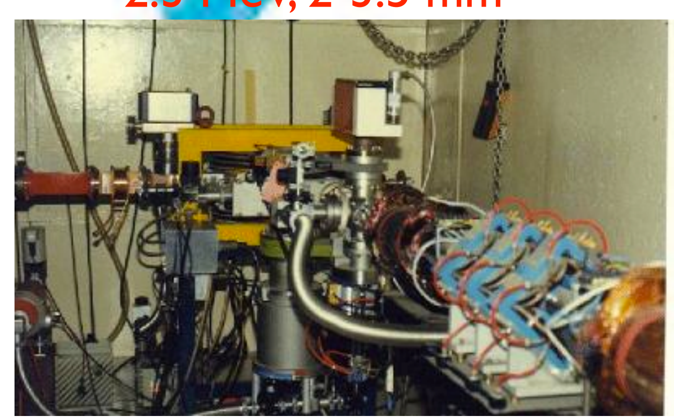


1985



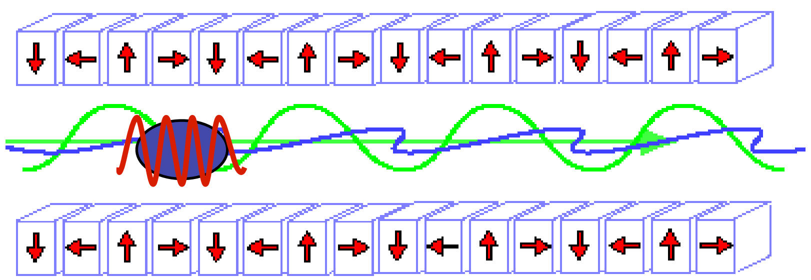
ETA, Lawrence
Livermore Nat. Lab.
induction linac
3.5 MeV, 9 mm

ENEA Frascati, microtron,
2.3 MeV, 2-3.5 mm



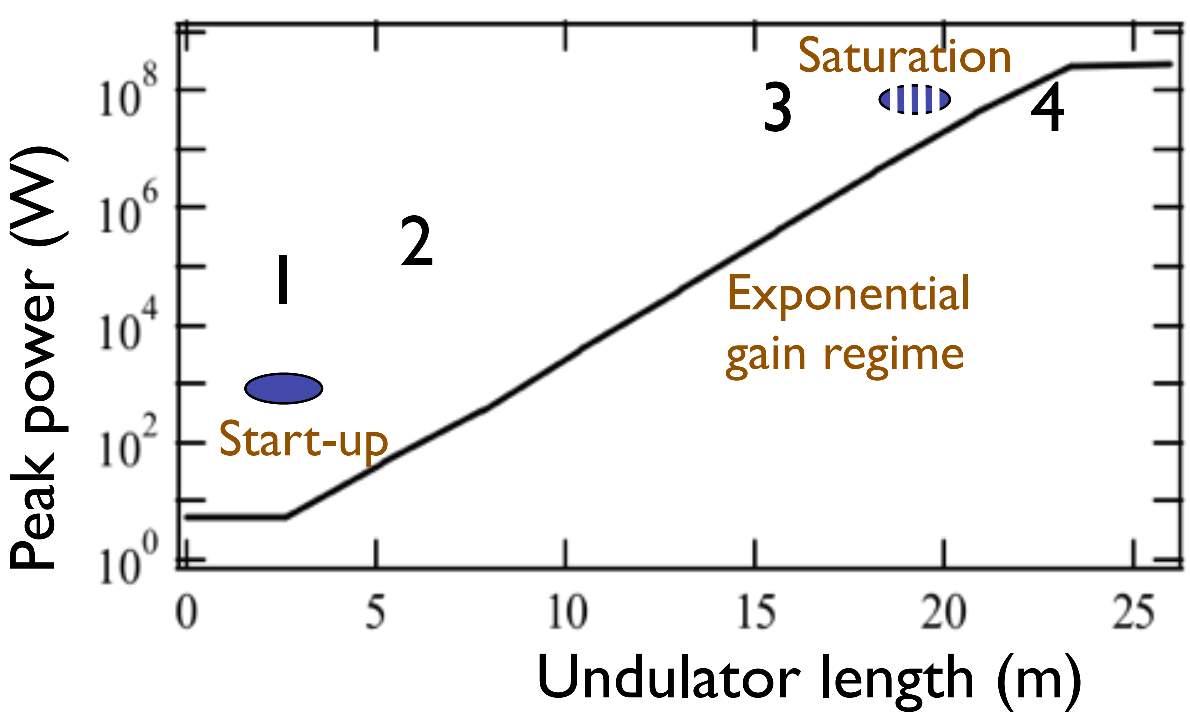
in operation
shut down

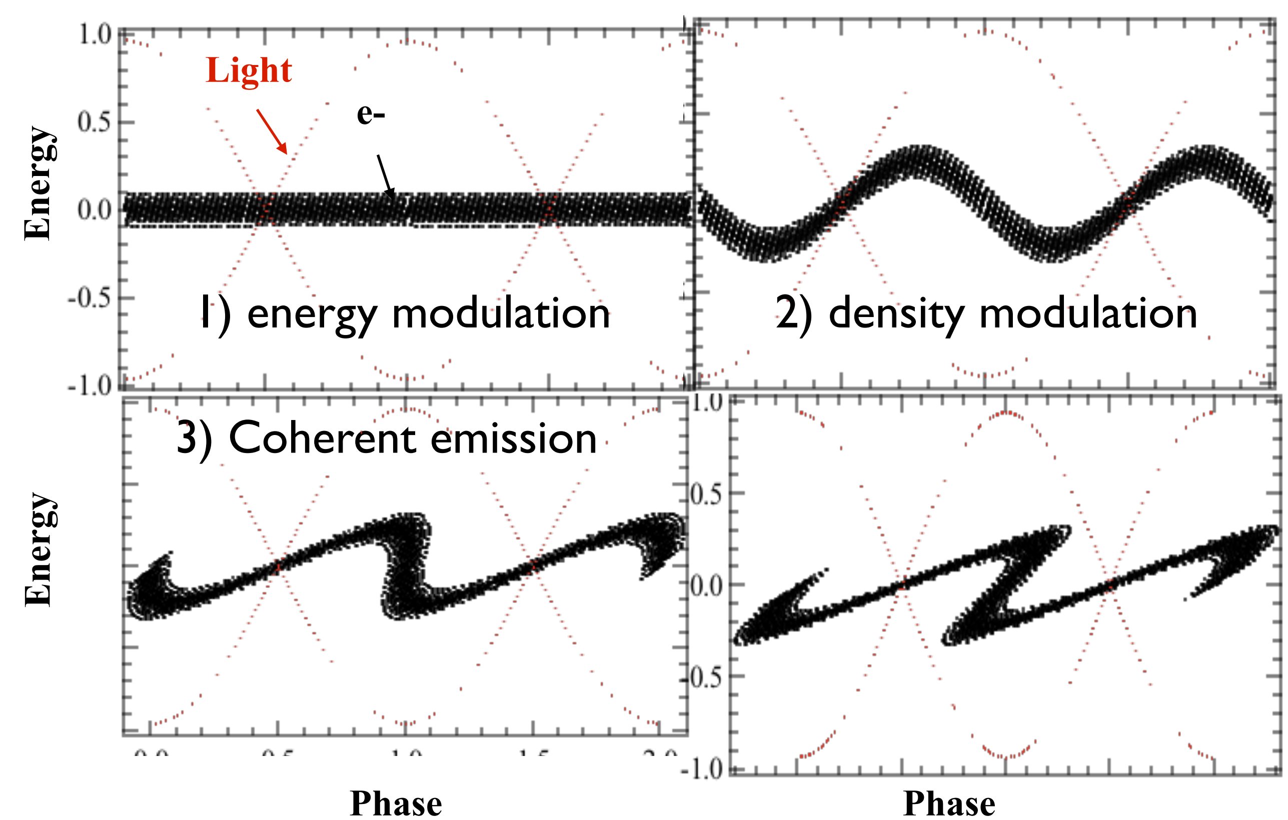
Self Amplified Spontaneous Emission (SASE)



Démarrage à partir du bruit de l'émission spontanée auto-organisation via le rayonnement et le champ de charge d'espace => électrons «self bunch» à l'échelle de la longueur d'onde rayonnée.
Emission collective des électrons ayant une phase similaire de rayonnement synchrotron cohérent.
Croissance exponentielle due à l'instabilité collective (régime de fort gain)
Optical guiding
Saturation : échange d'énergie cyclique entre les électrons et le champ rayonné.

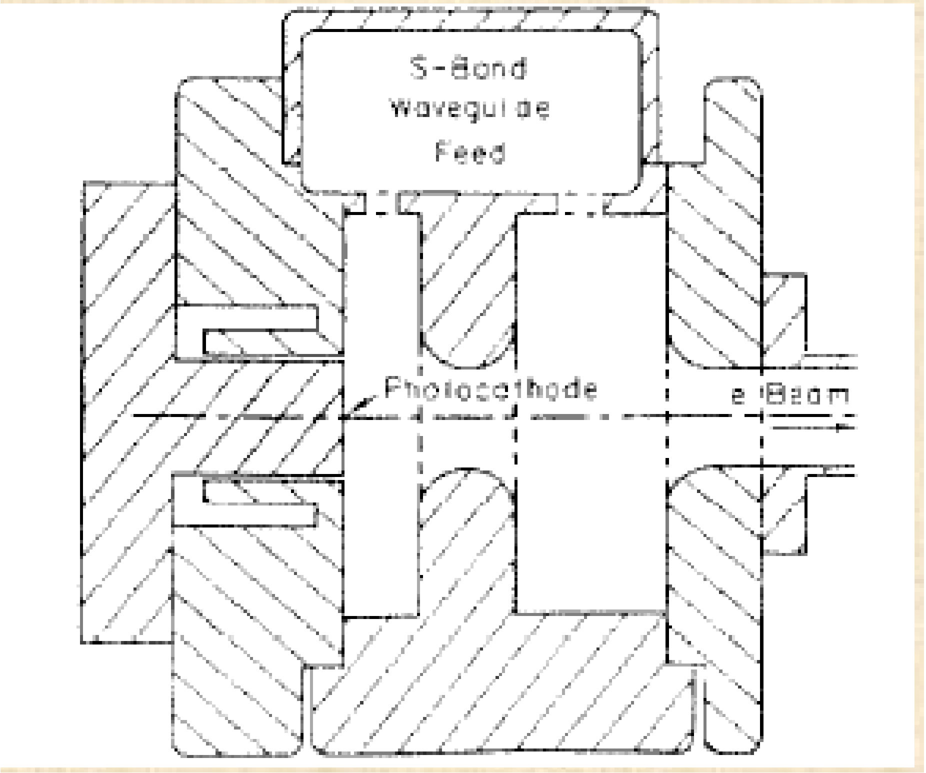
$$\rho_{FEL} = \left[\frac{K_u[JJ]\omega_p}{4\omega_u}\right]^{2/3} = \frac{1}{2\gamma k_u}\left(\frac{\mu_o e^2 K_u^2 [JJ]^2 k_u n_e}{4 m_o}\right)^{1/3} \qquad \Gamma = 2k_u\rho_{FEL} \qquad L_{go} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{FEL}} \qquad \frac{\Delta\lambda}{\lambda} = \rho_{FEL} \qquad P_{sat} = \rho_{FEL} E I_p$$





A.M. Kondratenko et al, Sou Phys. Dokl. 24 (12), 989 (1979)
Y.S. Derbenev, A.M. Kondratenko, E.L. Saldin: NIMA 193, 415–421 (1982)
Kondratenko A.M., Saldin E.L.: Part. Accelerators 10, 207–216 (1986)
K. J. Kim et al, PRL57, 1871 (1986)
C. Pelligrini et al, NIMA475, 1 (2001)

Basculement des anneaux vers les linacs



Limites de l'emploi des anneaux de stockage

J. B. Murphy and C. Pellegrini, J. Opt. Soc. Am. B, 2 (1985)

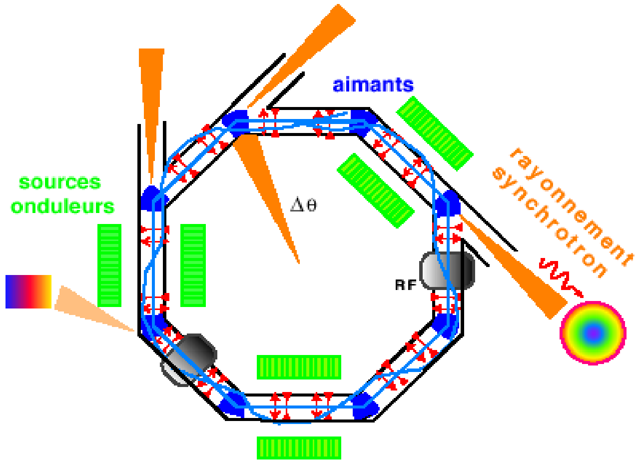
Développements des photo-injecteurs

Fraser, J.S. and R.L. Sheffield. 1987. IEEE J. Quantum Electron. QE-23: 1489-1496.
Batchelor, K., H. Kirk, K. McDonald, J. Sheehan and M. Woodle. 1988. Proc. of the 1988 European Particle Accelerator Conf., Rome, pp. 54–958.

with a linac and a photoinjector it is possible to reach the nm region at a beam energy of 1 GeV, with about 6 mJ/pulse starting from noise in an 11 m long undulator

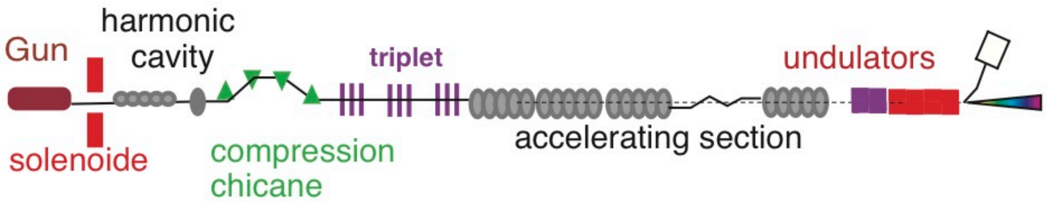
C. Pellegrini Nuclear Instruments and Methods A272, 364-367 (1988).

Emittance et dispersion en énergie => La communauté se tourne davantage vers les Linacs



10–30ps, $\varepsilon \alpha E^2$

Energy spread : 0.1 %

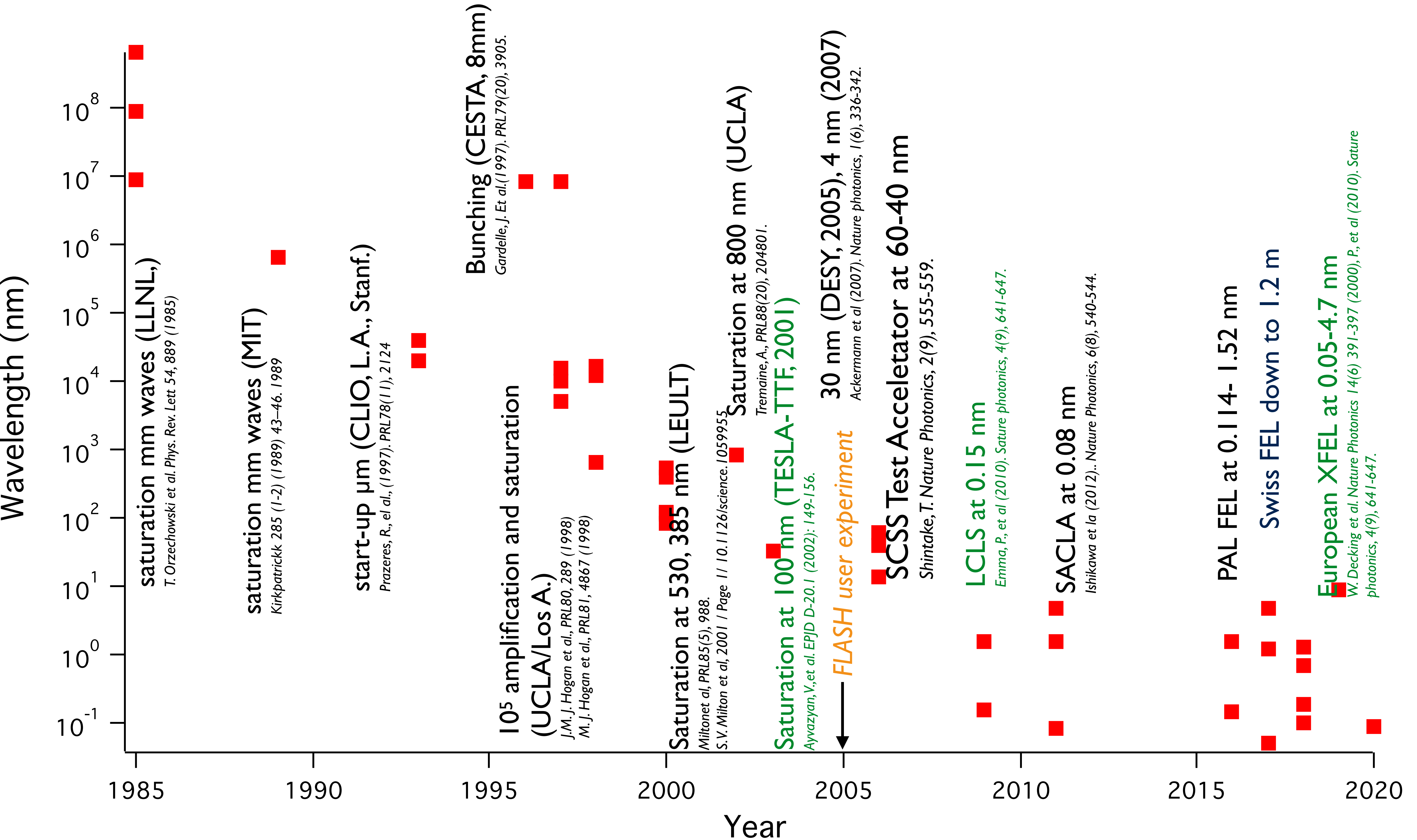


10 fs–10 ps, $\varepsilon \alpha 1/E$

Energy spread : 0.01 %

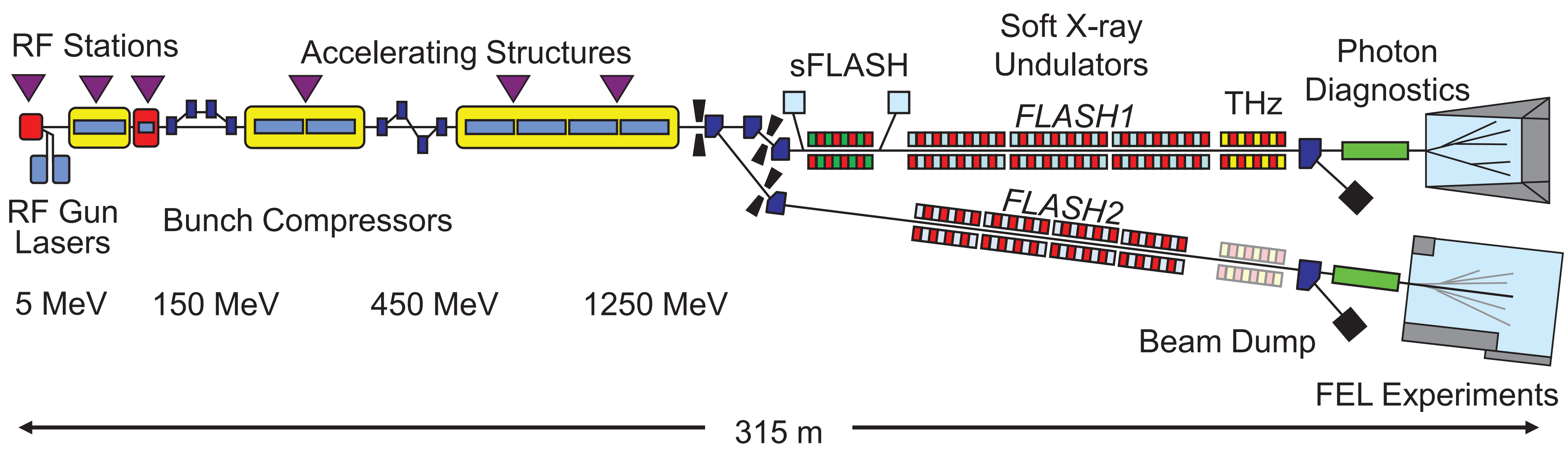
Repetition rate : depending on the linac (room temperature or superconducting)

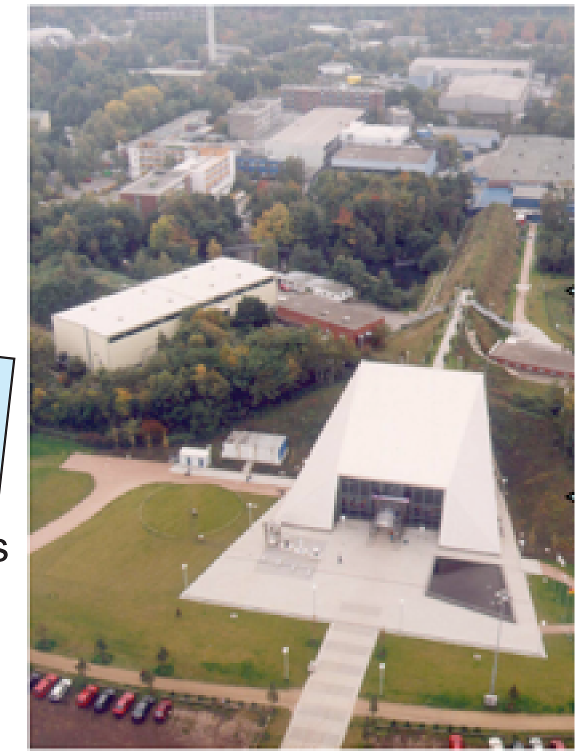
Observations du SASE

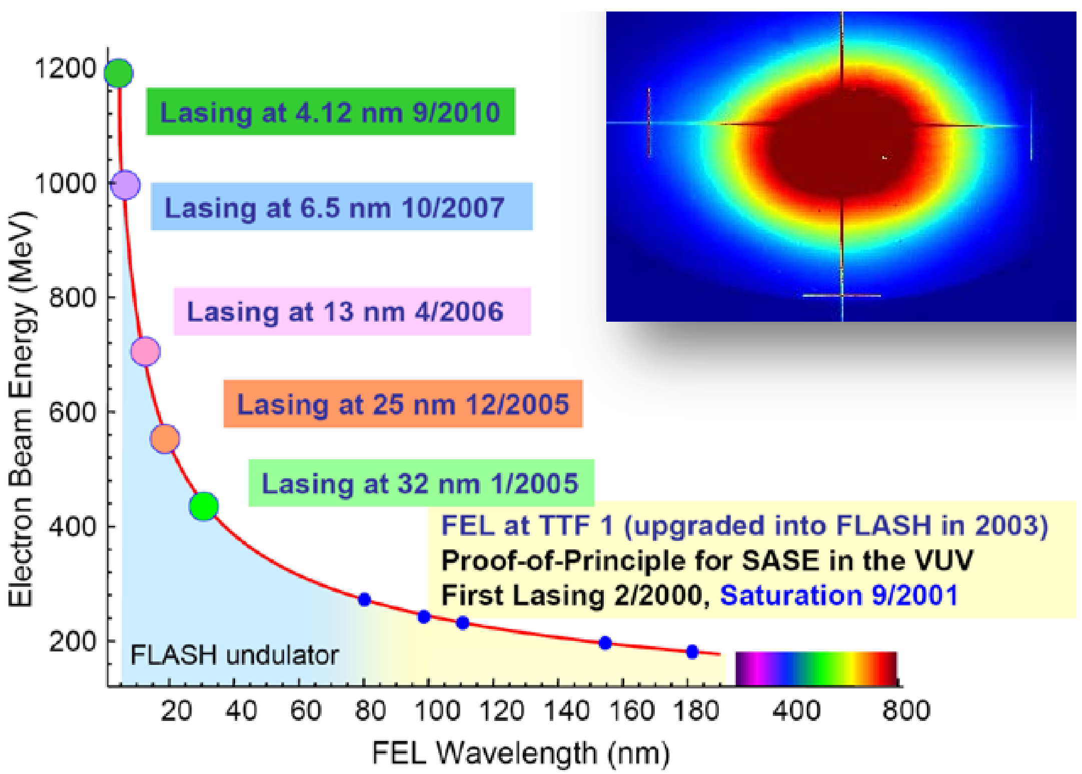


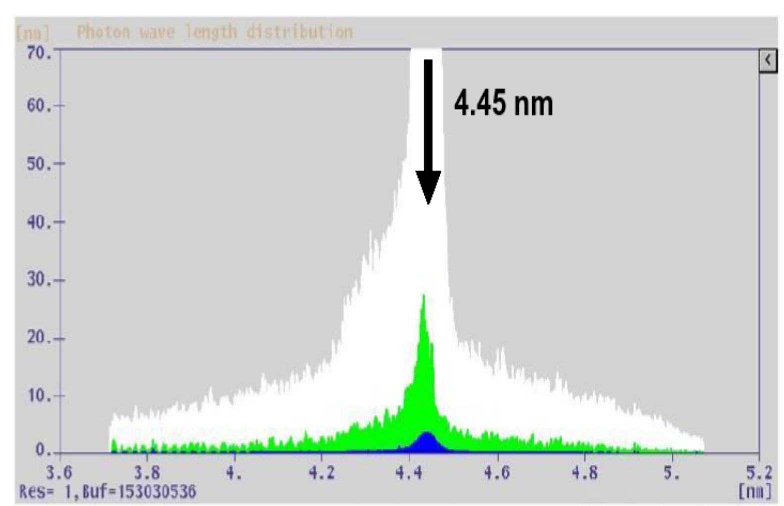
SASE FEL (soft X-ray) : FLASH centre utilisateurs

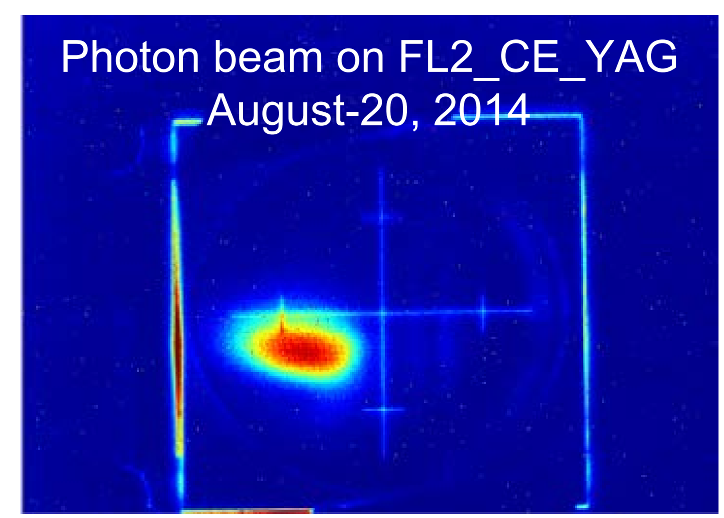
FLASH, DESY, Allemagne : 4-45 nm, 50-200 fs, 1-3 GW; FLASH-II : 40 and 20 nm









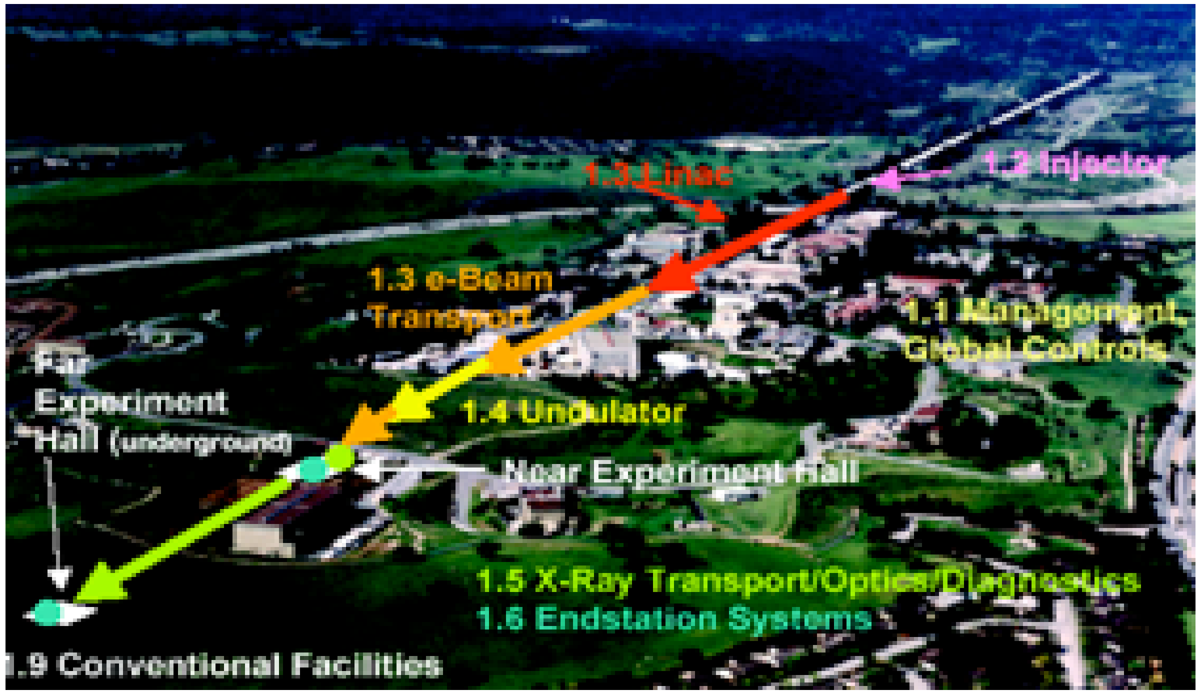


First lasing of FLASH II, 2014, Aug. 20,

K. Honkavaara et al., Proceed. FEL conf, Basel, Aug. 24_29

SASE FEL (hard X-ray) : LCLS centre utilisateurs

LCLS (Stanford, USA), 2 mJ, 1.4 Å , 1.5 Å saturation at 65 m (of 112 m), now 6 mJ, 4-50 fs, GW power, average flux 10^{12} ph/s, 2.10^{33} (10^{24}) ph/s/mm^2/mrad^2, 96.7 % availability, 120 pulses/s

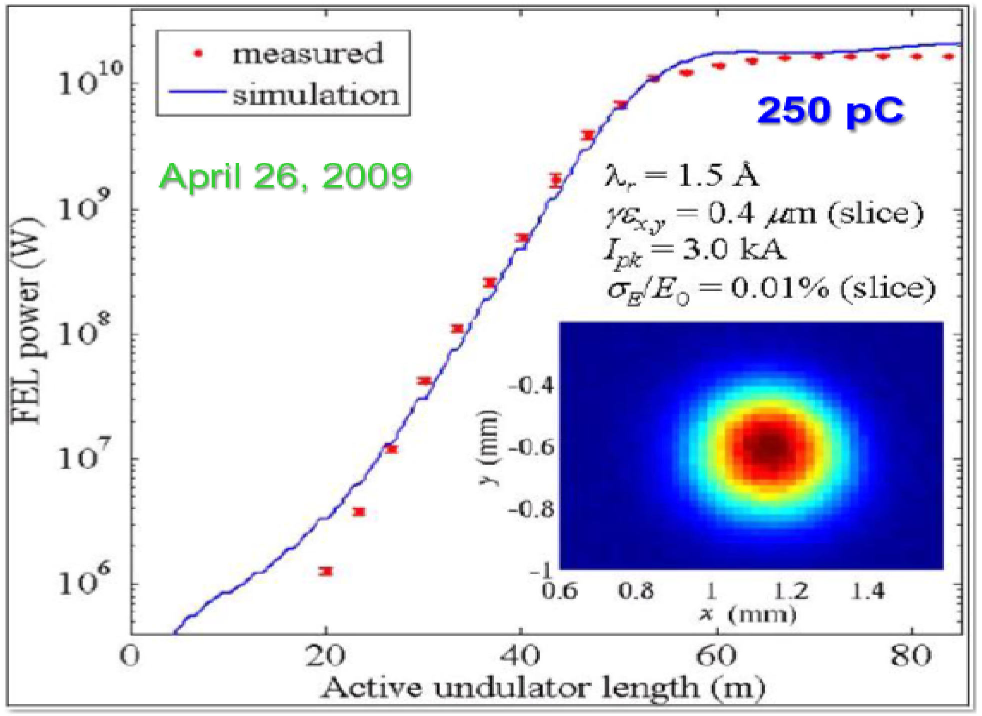


Stanford, USA

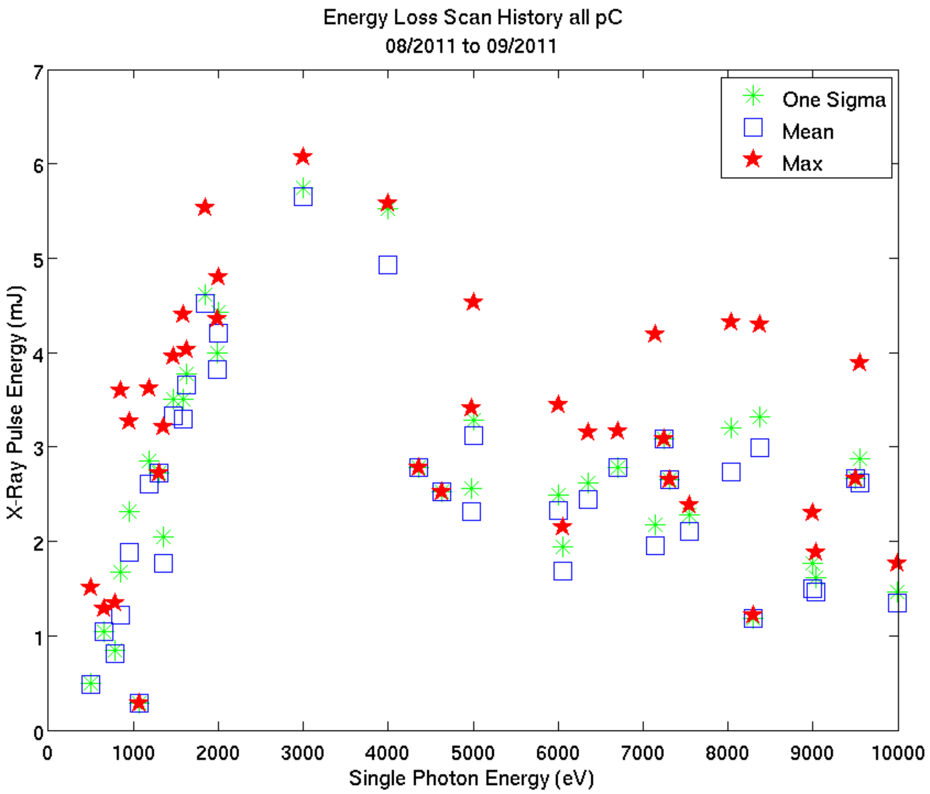
http://www-ssrl.slac.stanford.edu/lcls/

P. Emma et al., Nature Photonics, 2010,.176

32 années après le premier LEL,
50 ans après la découverte du laser



2 mJ, 1.4 Å
1.5 Å saturation at 65 m (of 112 m)
now 6 mJ
96.7 % availability



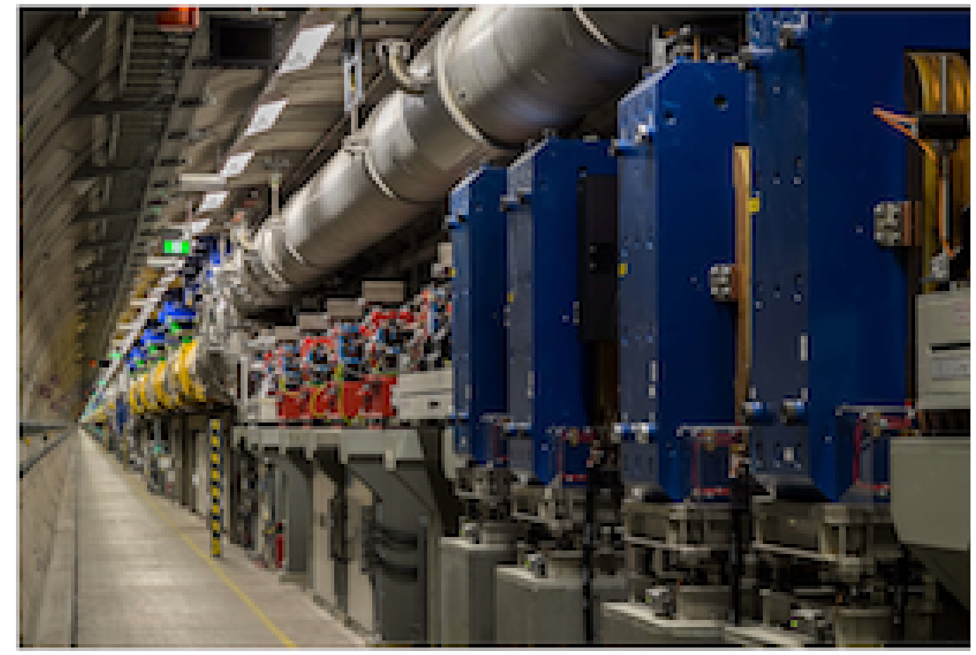
SASE FEL (hard X-ray) : European XFEL centre utilisateurs à haute cadence (MHz)

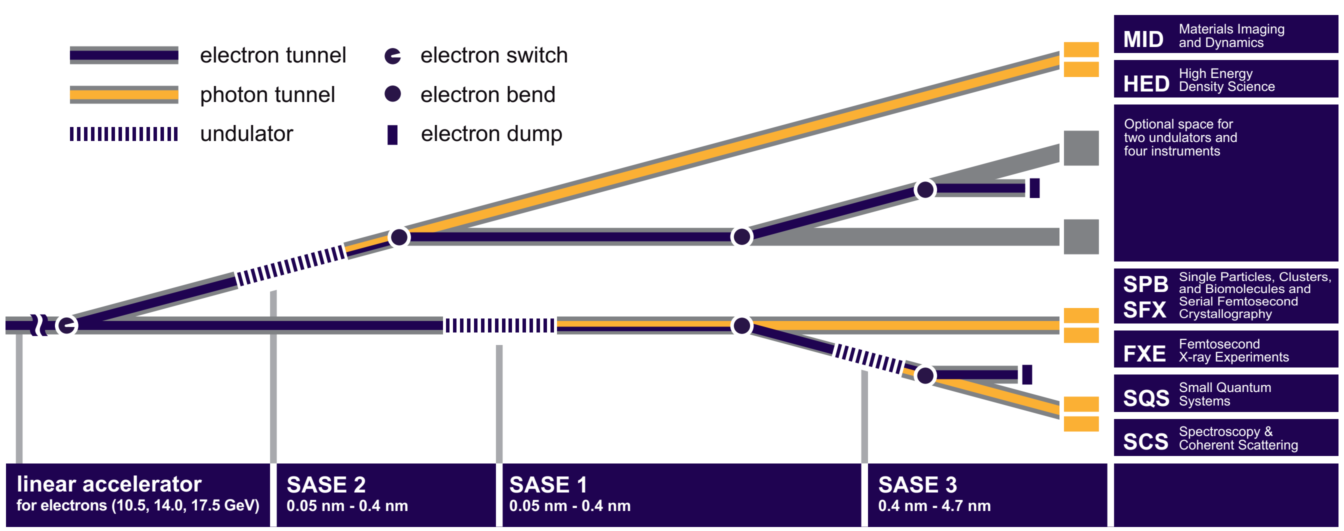
2017: Eu XFEL, 8-17.5 GeV, 0.05-0.2 nm,

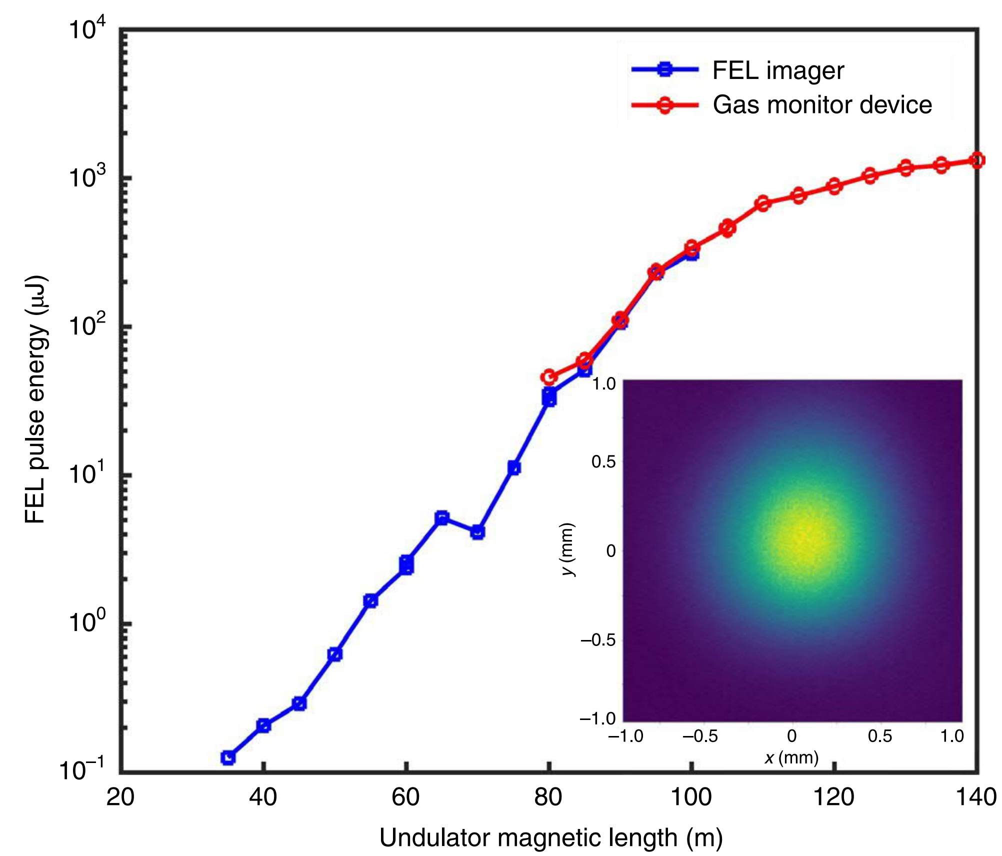
SC Linac, 2 km, 0.5 nC , 5 kA, $\varepsilon_n = 0.4\pi$ mm.mrad,

up to 5000 electron bunches/s

6 W average power





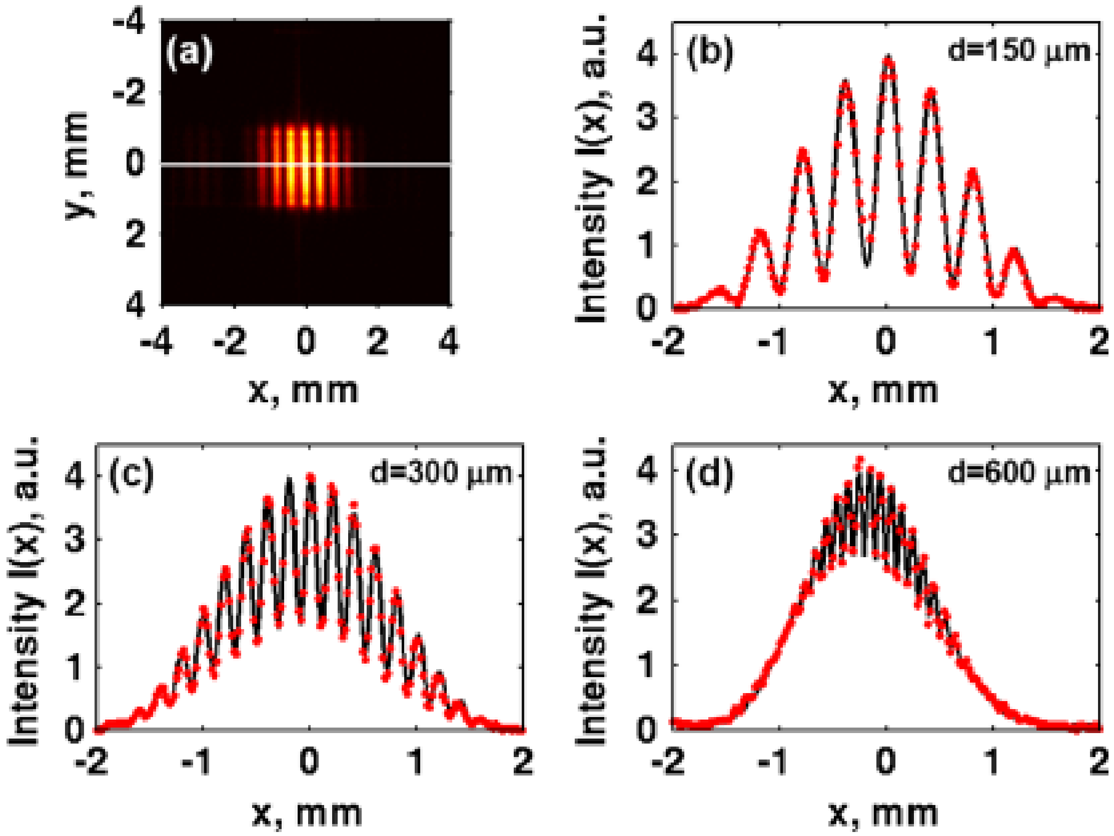


W. Decking et al., Nature Photonics, 14(6), 391-397 (2020)

And coming LCLS II (USA), SHINE (China)

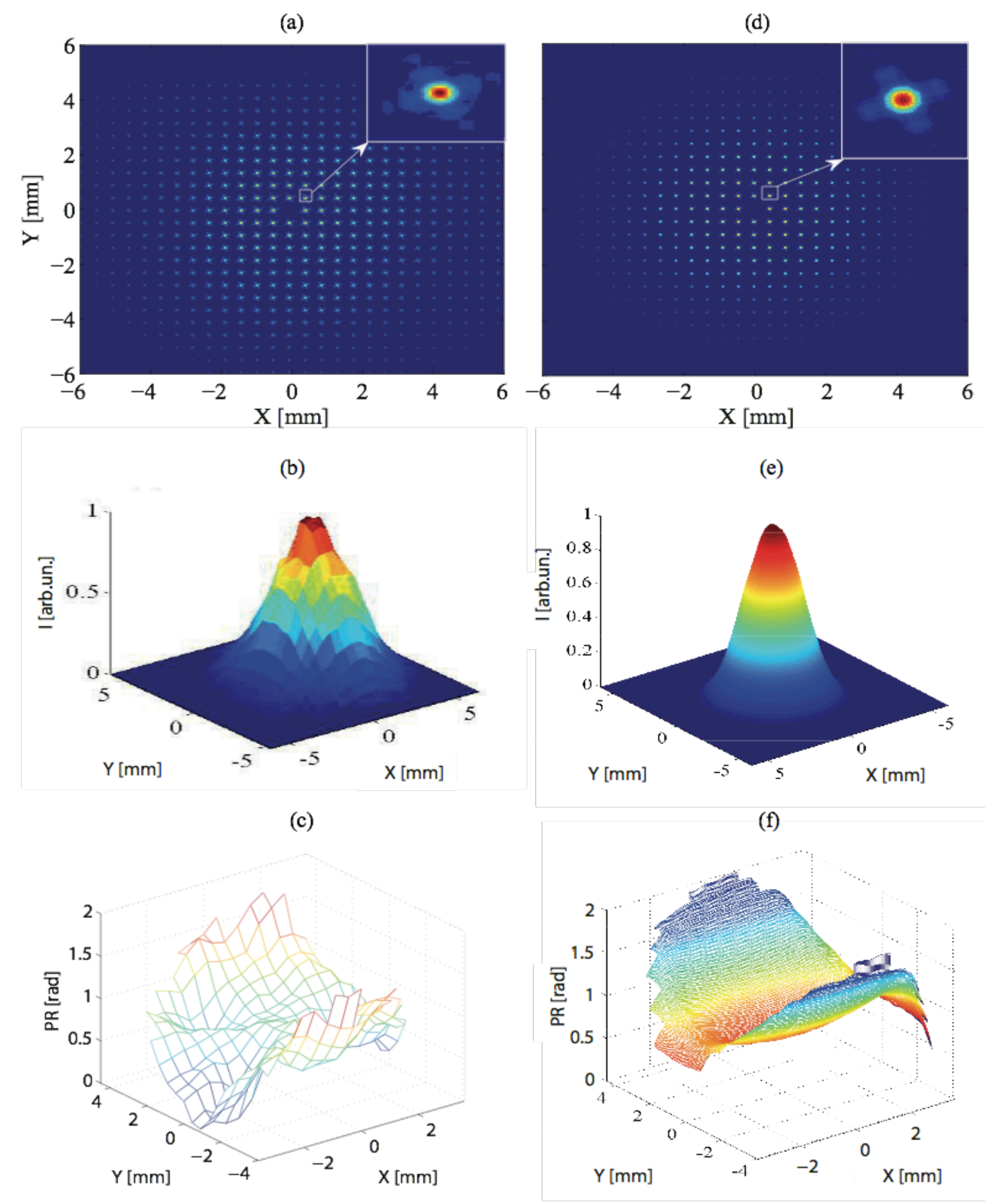
Propriétés du SASE

FLASH



M. Kuhlmann et al, FEL06
P. Mercère et al, , Optics Letters, 28 (17), 1534-1536 (2003)
A. Singer et al. PRL 101, 254801 (2008)

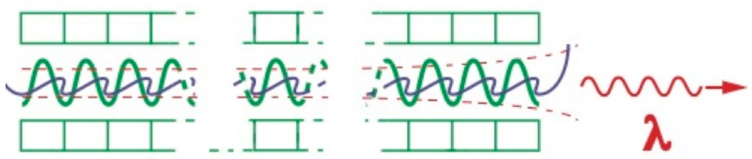
SCSS Test Accelerator : 60-40 nm



R. Bachelard et al., Phys. Rev. Lett. 106 (23), 234801 (2011)

Wavefront quality : ability to properly focus

Propriétés du SASE

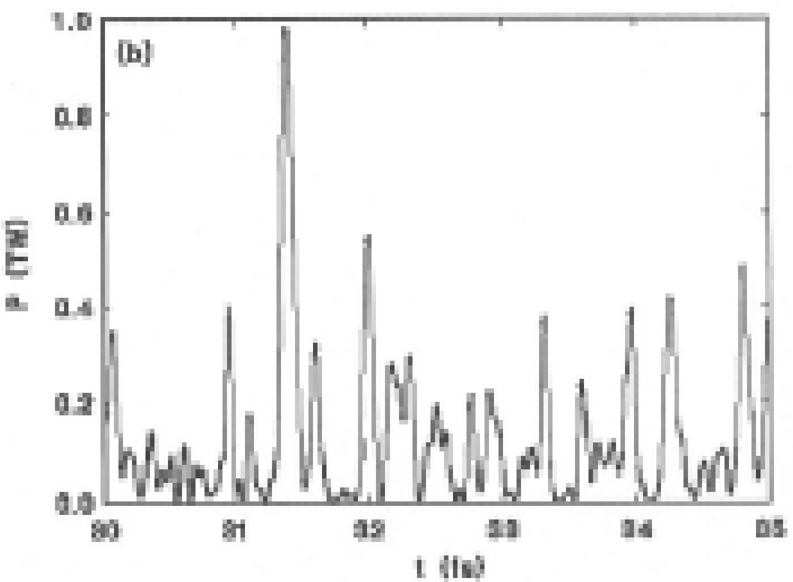


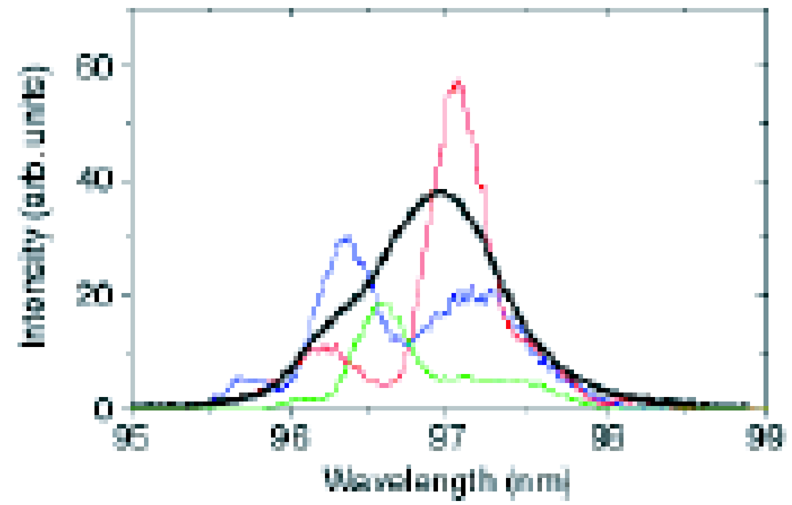
Cohérence temporelle limitée: démarrage à partir du bruit, bunching sur different trains du paquet => “spikes” dans les distributions spectrales et temporelles

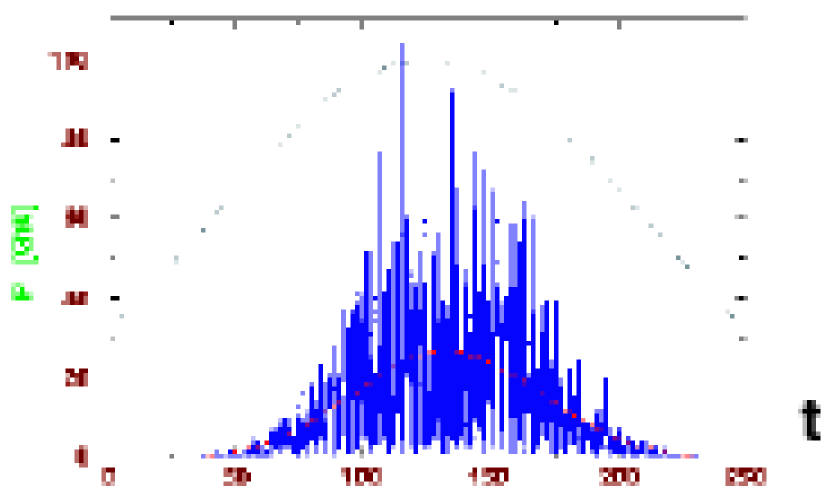
Longueur de coopération length : slippage sur une longueur de gain

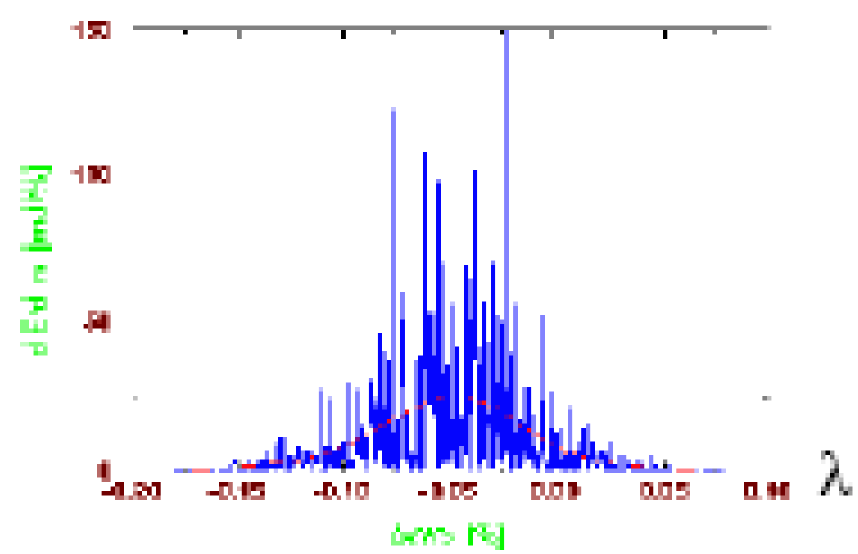
Nber of spikes = longueur de paquet / longueur de coopération

$$L_{coop} = \frac{\lambda}{4\pi\rho_{FEL}}$$







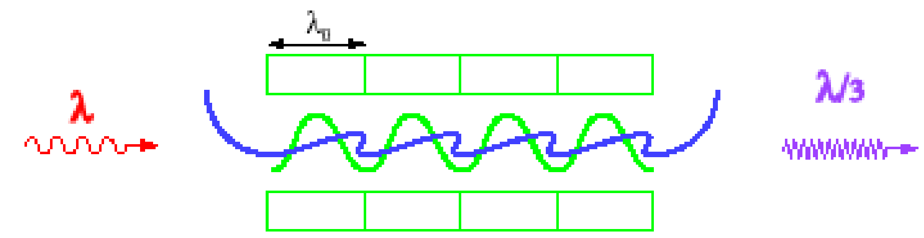


S. Reiche et al., NIMA 593 (2008) 45-48
L. Giannessi et al., Phys. Rev. Lett. 106, 144801 (2011)

- jitter d’une impulsion à l’autre

Manipulation :
single spike
taper
seeding / self seeding

Seeding



Seeding : une interaction laser-électron

- Cohérence temporelle apportée par la seed laser externe (suppression de spikes, réduction de la largeur de raie)
- Meilleure stabilité (intensité, fluctuations spectrales, jitter)
- Reduction of the saturation length
- Bonne transverse coherence

- Seed : laser, HHG (160, 60, 30 nm)
- up-frequency multiplication (260 nm -> 4 nm at FERMI)

Interaction électron/ laser dans l'onduleur :

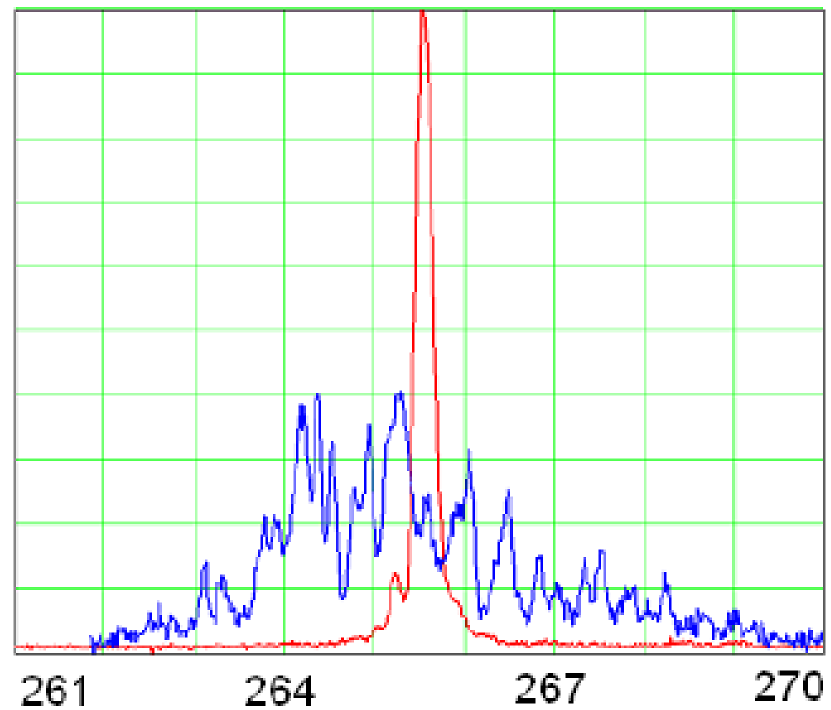
Modulateur: modulation en énergie imprimée par la seed à λ_{seed}

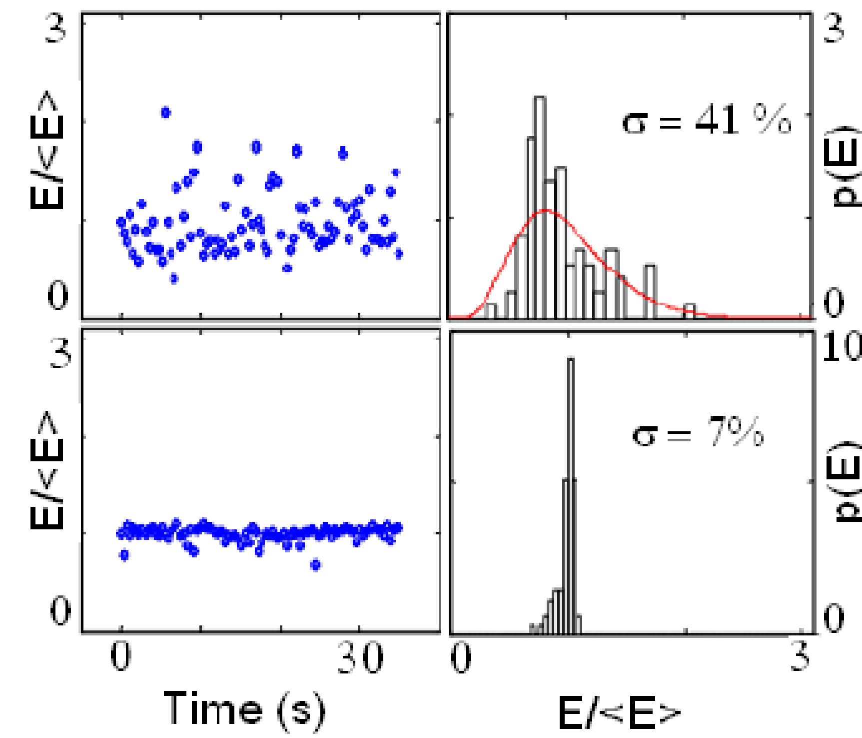
Chicane : modulation en densité, composantes de Fourier à λ_{seed}/n

Radiateur : émission de rayonnement cohérent

Modulation en énergie required ΔE pour un bunching suffisant à l'harmonique n harmonic ~ n $\sigma\Upsilon$

Détérioration du gain pour n_{max} ~15





L. H. Yu et al, PRL91 2003, 074801

L. H. Yu et al, Science 289, 2000, 932

High Gain Harmonic Generation

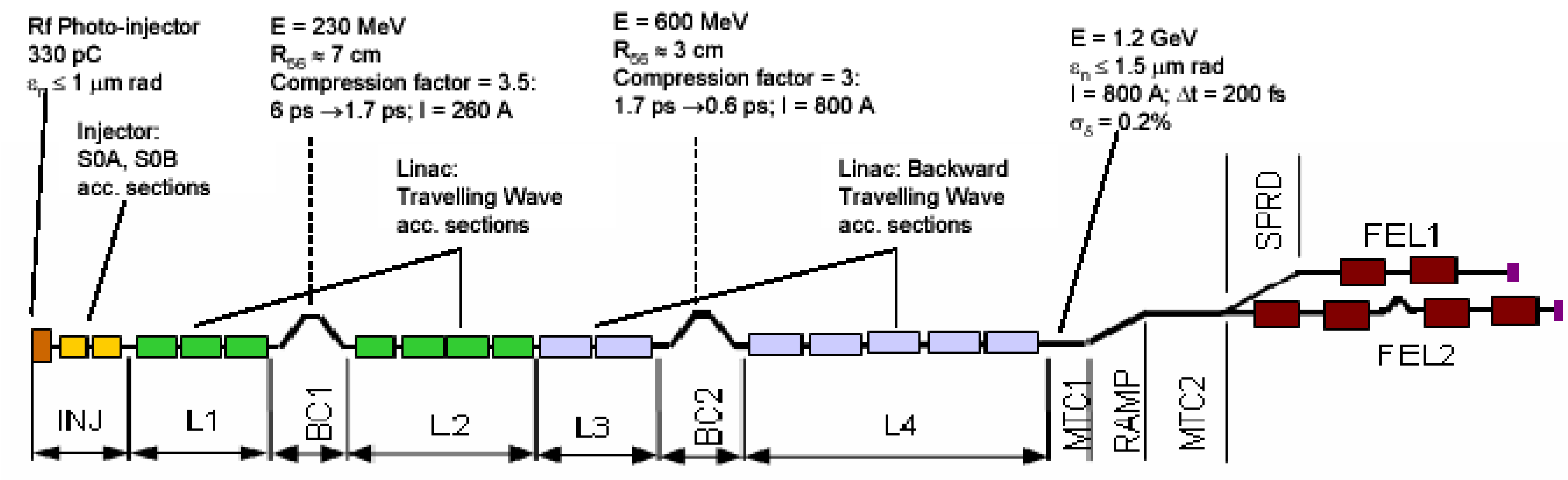
HGHG in cascade

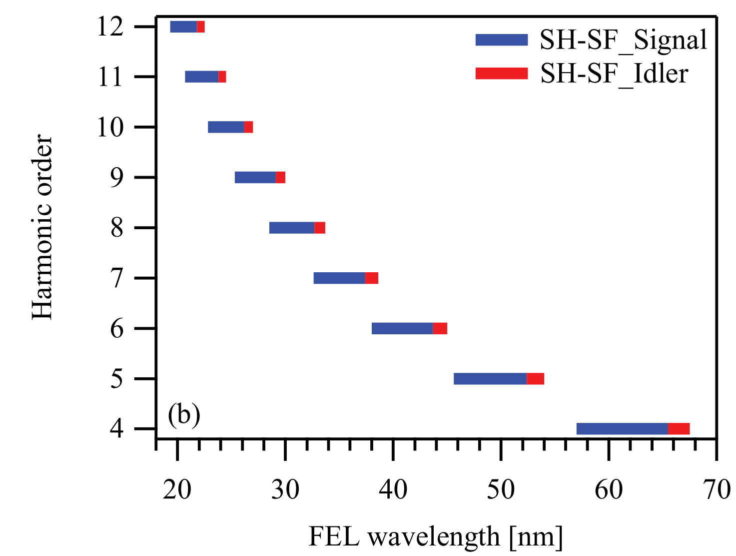
Fresh bunch technique. $\lambda_{seed}/n1n2$

Max n ~60-70

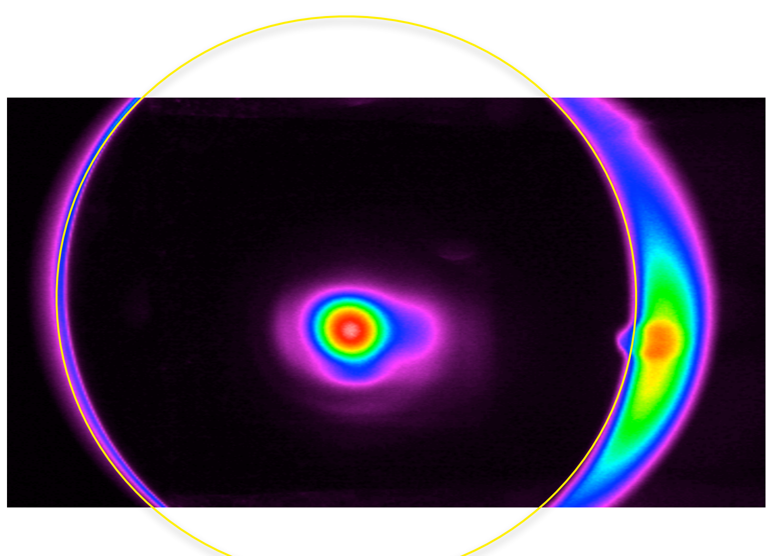
LEL injecté (soft X-ray) : FERMI, premier centre serveur

FERMI : 4-60 nm, sub-ps to 10 fs, ~0.3 GW, polarisation variable, centaine de μJ / impulsion





E. Allaria et al. New J. Phys. . 145, 112009, 2012



Allaria E et al 2012 Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet Nature Photon. 6 699–704

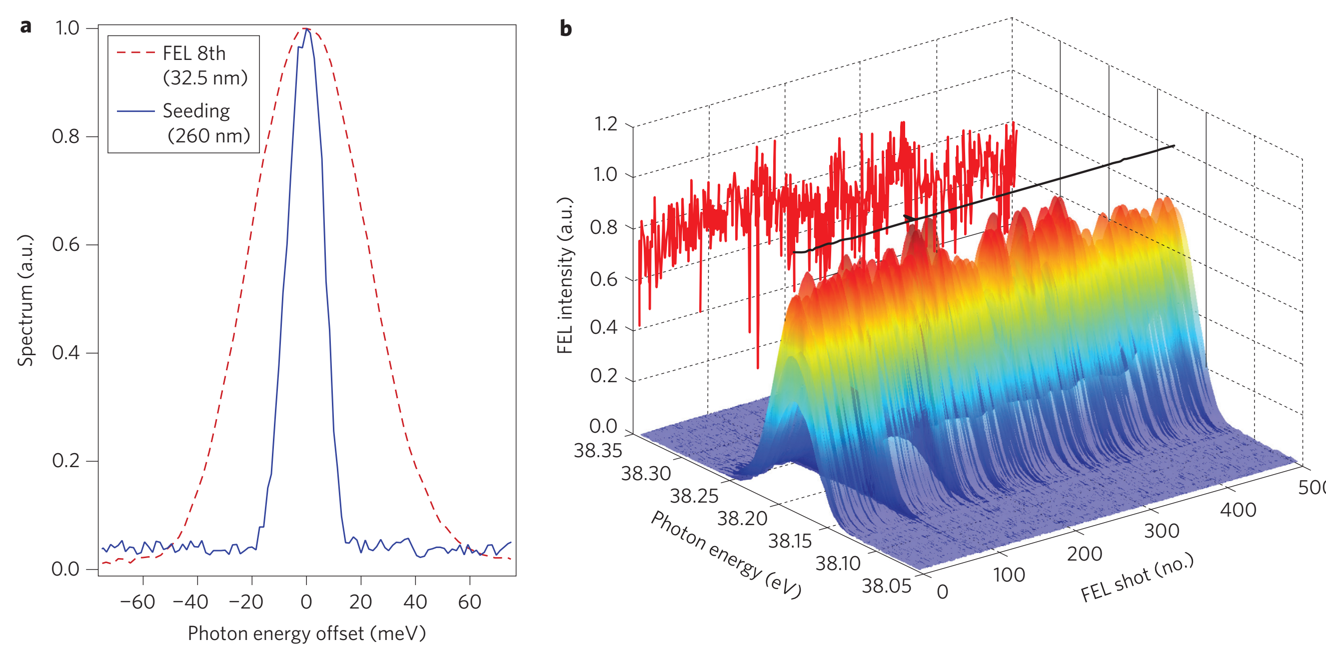
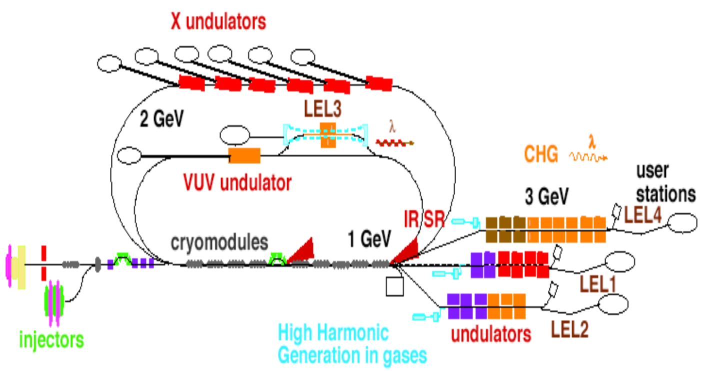


Figure 4 | Single-shot and multi-shot spectra at 32.5 nm. a, Measured FEL and seed laser spectrum (dashed red and continuous blue lines respectively). **b**, Acquisition of 500 consecutive FEL spectra.

Progrès en injection directe de LEL

Avec une seed HHG

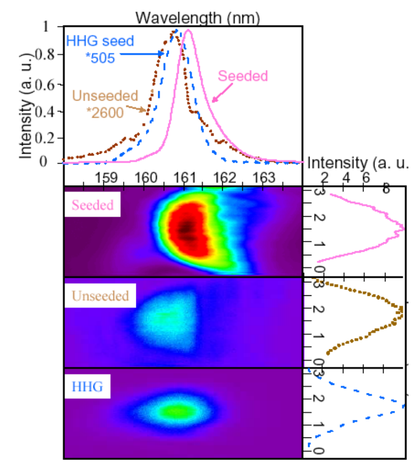
Concept



ARC-EN-CIEL
Accelerator Radiation Complex for ENhanced Coherent Intense Extended Light

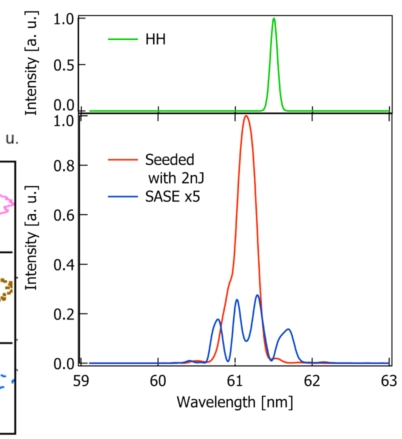
D. Garzella et al., Nucl. Inst. Meth. A 528, 502 (2004)

HHG 160 nm seeding, SCSS Test Acc, up to H7



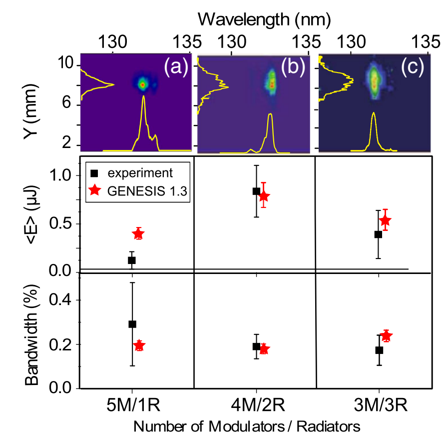
G. Lambert et al., Nature Physics Highlight, (2008) 296-300

HHG 60 nm seeding, SCSS Test Acc



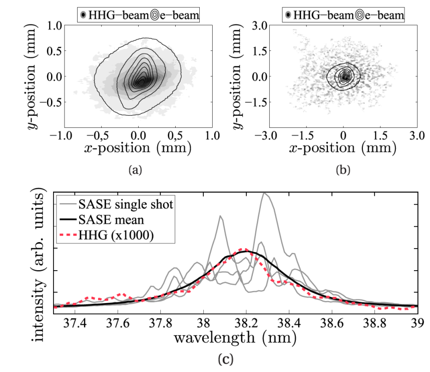
T. Togashi et al., Optics Express, 1, 2011, 317-324

HHG 160 nm seeding, SPARC



M. Labat, et al., Phys. Rev. Lett. 107, 224801 (2011)

HHG 38 (19)nm seeding, SFLASH

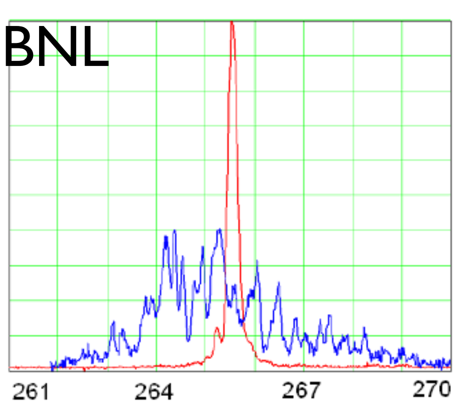


S. Achkermann et al, PRL 111, 114801 (2013)

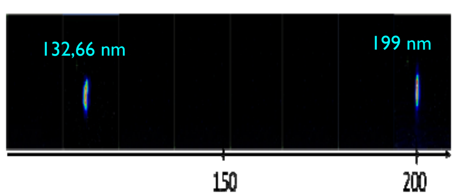
2000 2002 2004 2006 2008 2010 2012 2014 2016 2018

Avec une seed laser

BNL

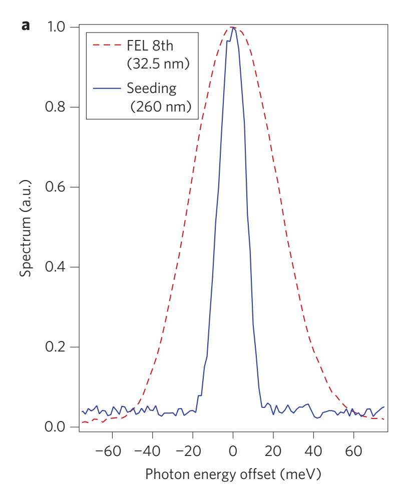


L. H. Yu et al, Science 289, 2000, 932



L. Giannessi et al., FEL 2010, Malmo, Sweden

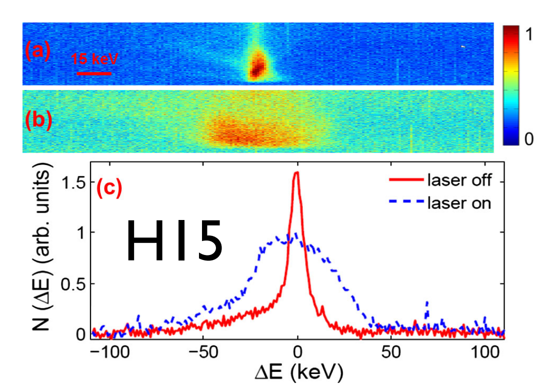
FERMI FEL 1 H3-13
FERMI FEL 2 H65



Allaria E et al 2012 Nature Photon. 6 699–704

H192

L. Giannessi, FEL prize talk, FEL conf, Basel, Aug. 2014, Switzerland

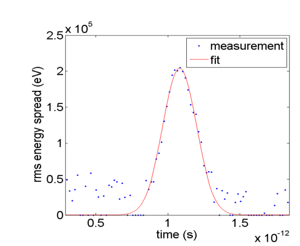


D. Xiang et al., Phys. Rev. ST Accel. Beams 16, 110701 (2013)

sFLASH, H8

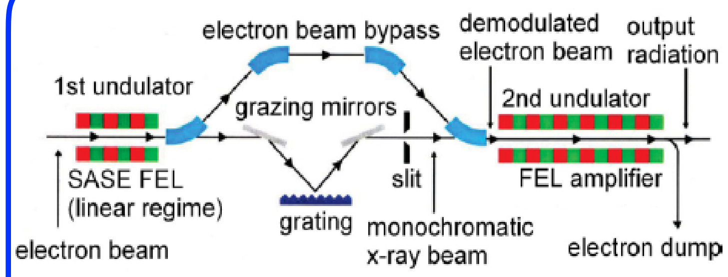
Dalian FEL 50-188 nm

SXFEL 50-188 nm

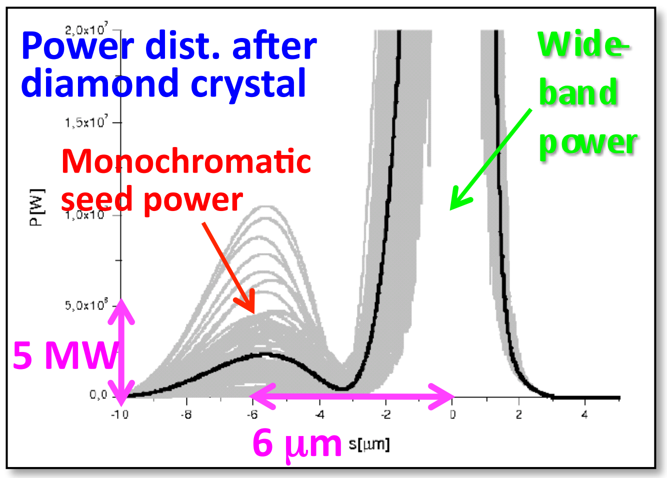


Self seeding

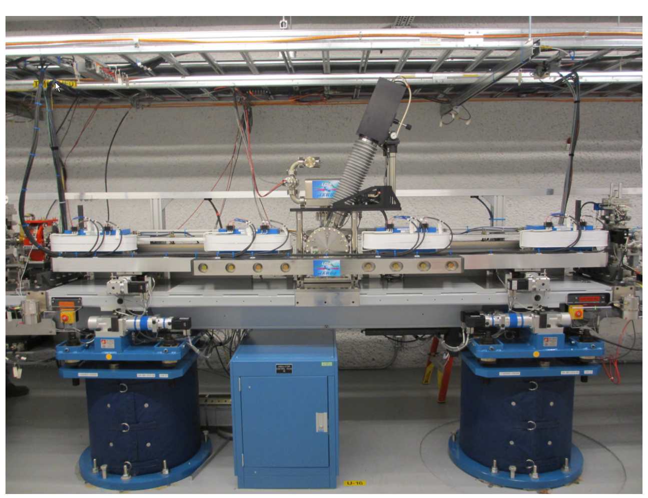
Concept



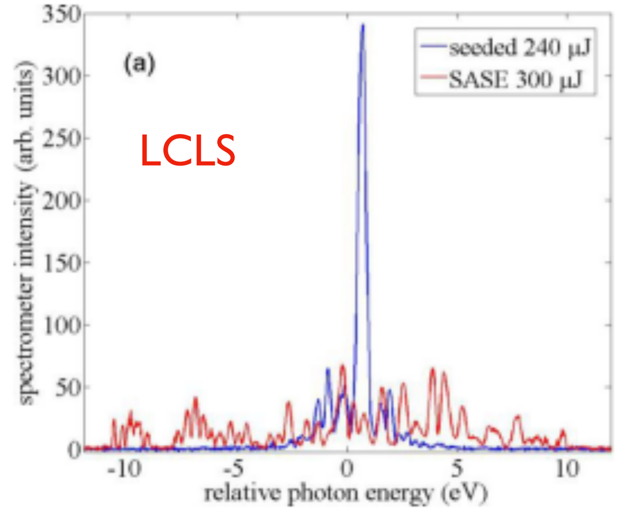
Feldhaus et al., Opt. Comm 140 (1997) 341

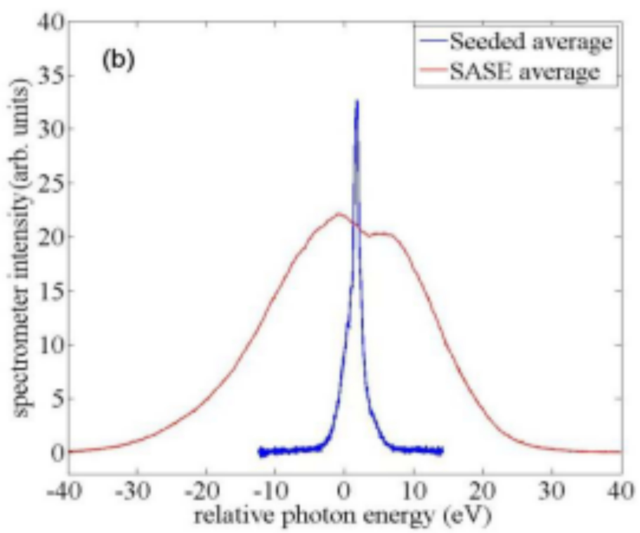


Geloni, Journal. Modern Optics, 58, 16, 2011



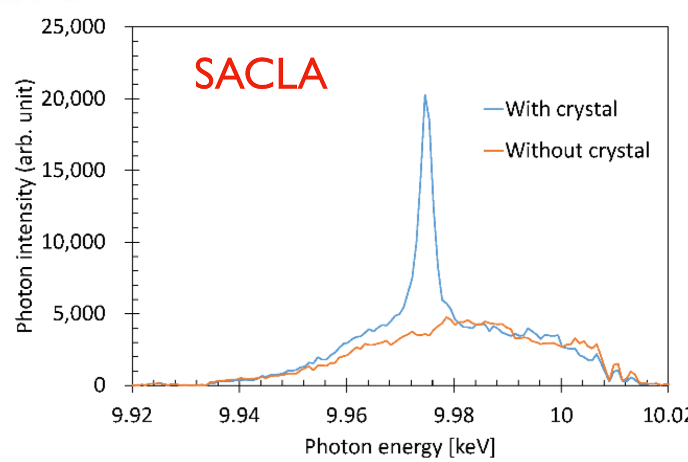
Demo hard X-ray (crystal)



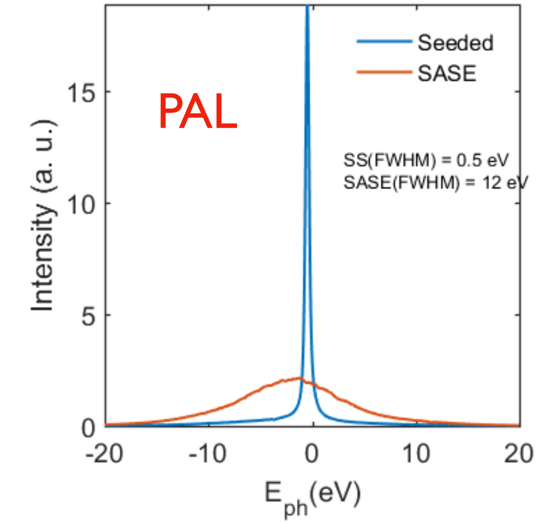


J. Amann et al., Nature Photonics 6, 693–698 (2012)

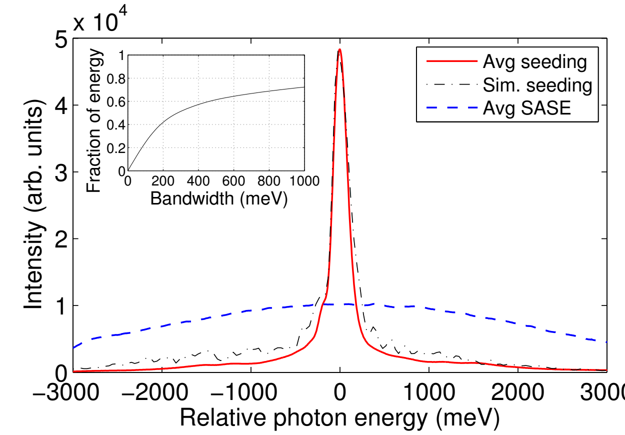
T. Inagaki, et al Proceedings of IPAC2014, 15-20.



C. K. Min, FEL 2019

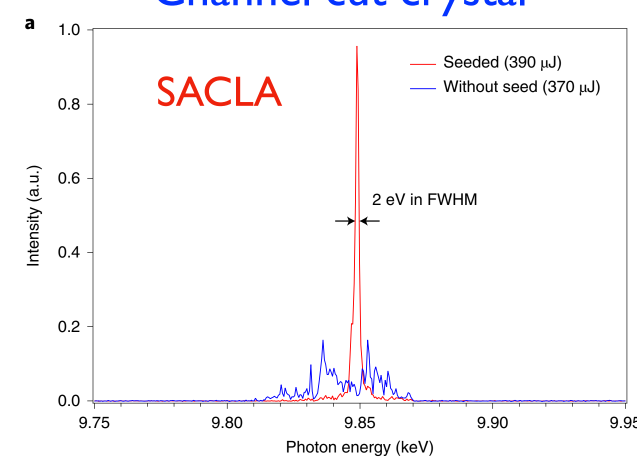


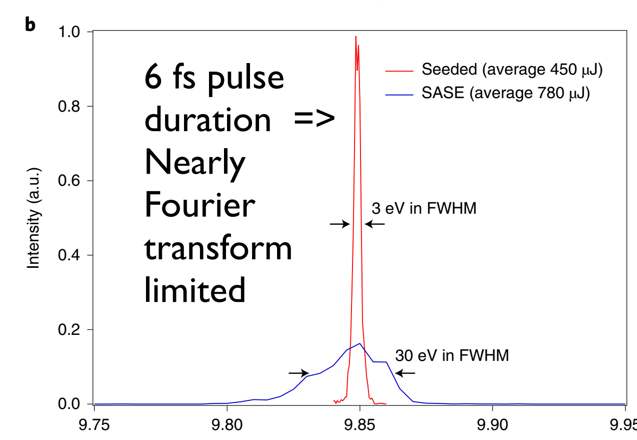
Demo soft X-ray Grating



D. Ratner et al., Phys. Rev. Lett., 114 (5), 054801, 2015.

Demo hard X-ray Channel cut crystal

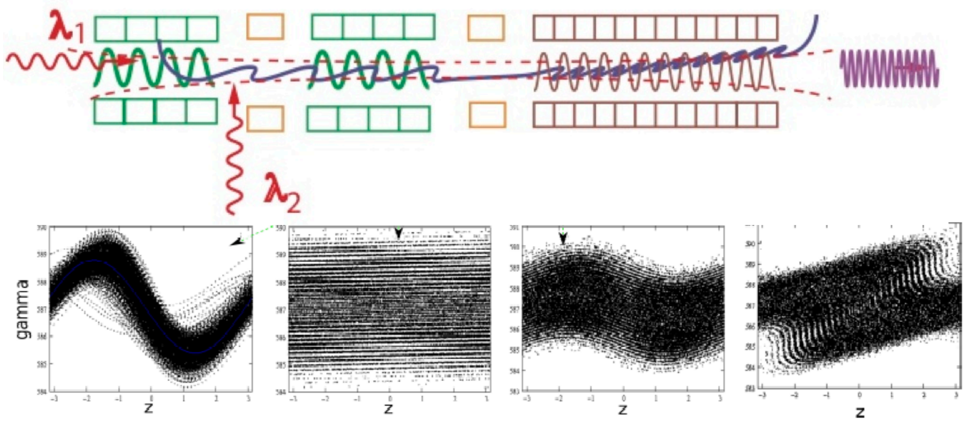




I. Inoue et al., Nature Photonics 13, 319-322 (2019)

2000 2010 2012 2014 2016 2018

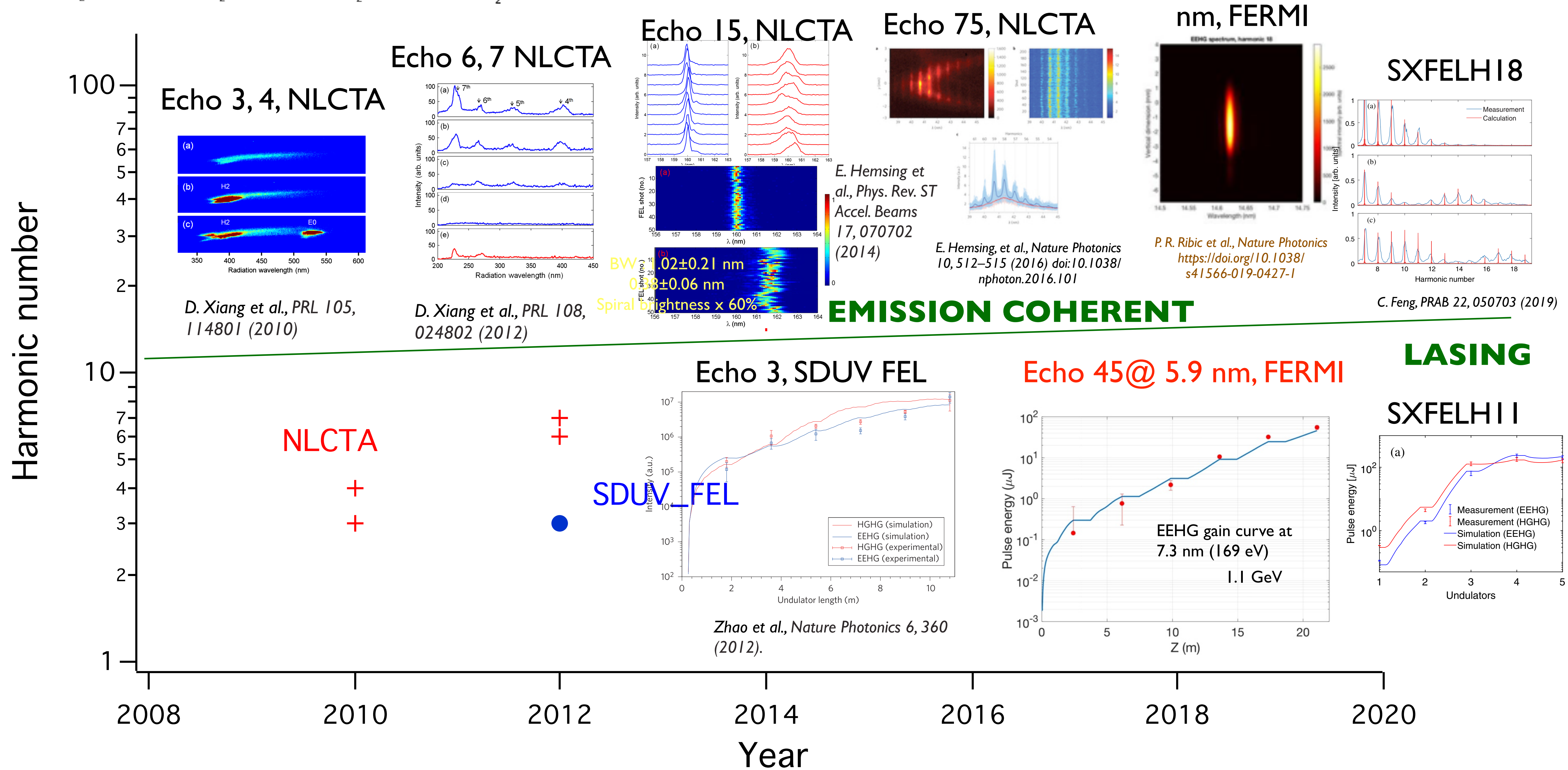
Echo Enabled Harmonic Generation



$$\frac{1}{\lambda_{echo}} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$$

Harmoniques d'ordre élevé atteinte de façon compacte

G. Stupakov., PRL 102, 074801 (2009)



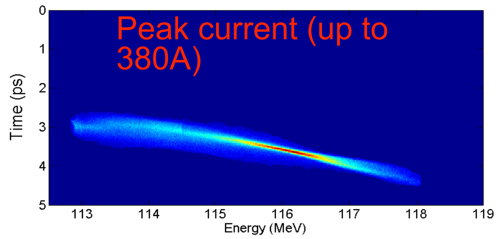
Vers une impulsion attoseconde unique

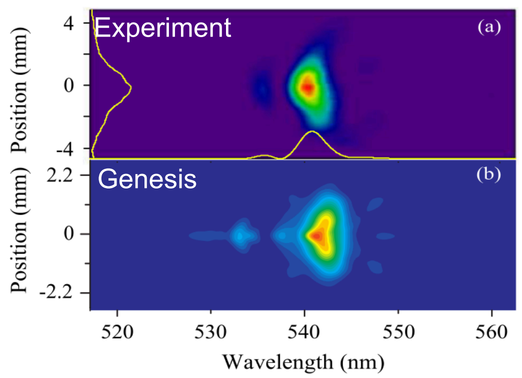
Energy chirp+ undulator taper

Spike duration :

$$l_c = \lambda \frac{L_g}{\lambda_u}$$

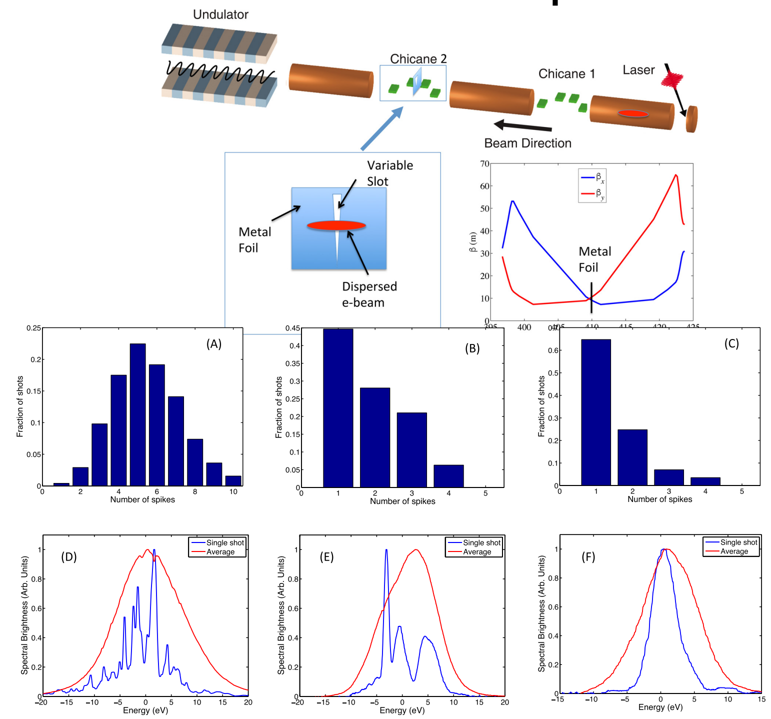
R. Bonifacio et al., Phys. Rev. Lett. 73(1),(1994)





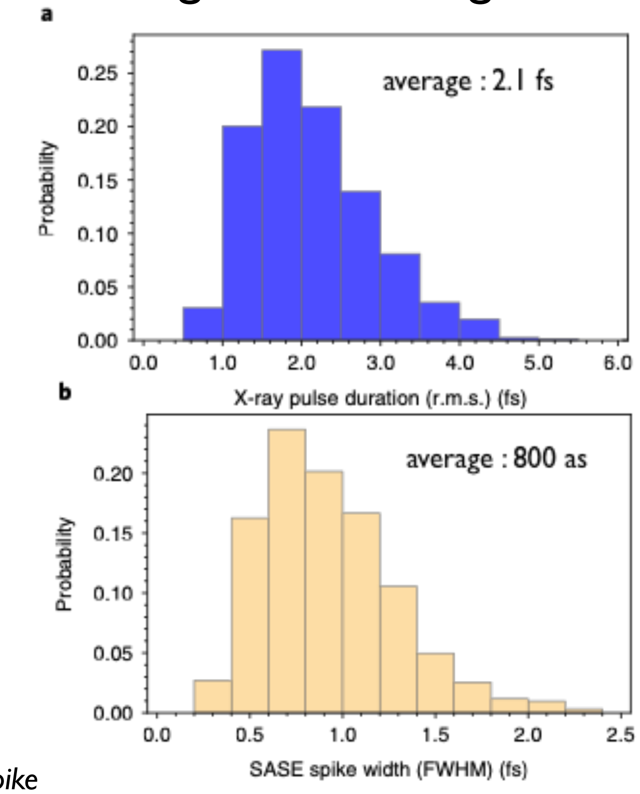
L. Giannessi et al., Phys. Rev. Lett. 106, 144801 (2011)

Slotted emittance spoiler



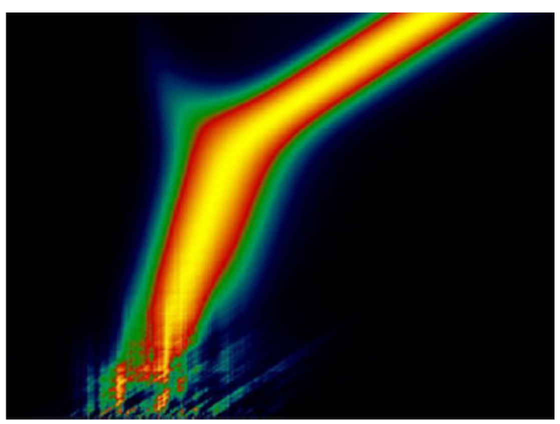
A. Marinelli et al., Experimental demonstration of a single- spike hard-X-ray free-electron laser starting from noise, Appl. Phys. Lett. 111, 151101 (2017)

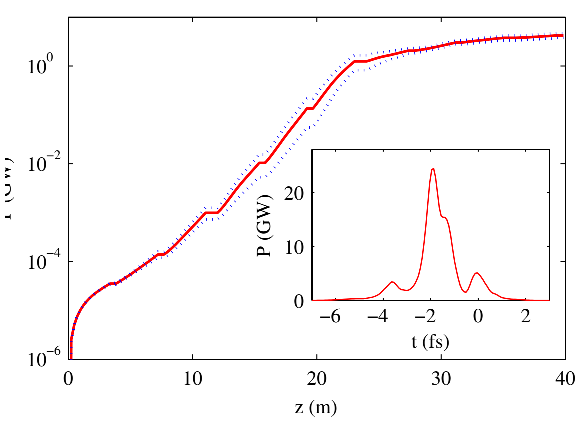
Angular streaking



N. Hartmann et al., Attosecond time-energy structure of X-ray free-electron laser pulses, Nature Photonics 12, 215-220 (2018)

2008 2010 2012 2014 2016 2018 2020



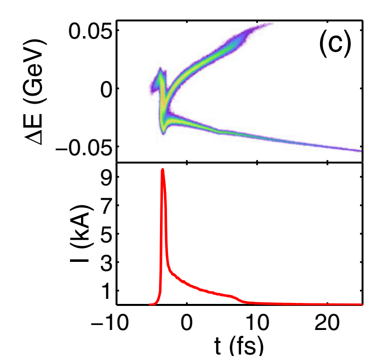


S. Reiche et al., NIMA 593 (2008) 45-48

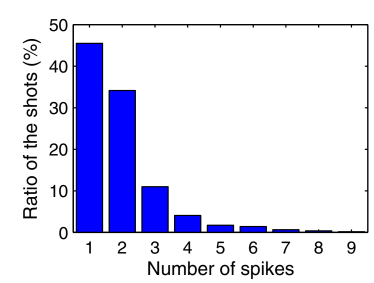
Y Ding et al., PRL 102, 254801 (2009)

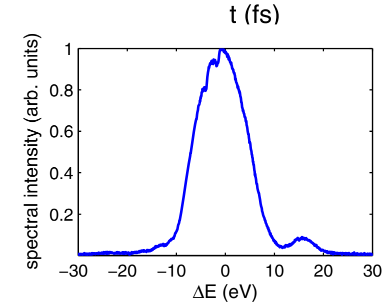
Low charge short electron bunch

Non linear bunch compression (X band linac section)
Longitudinal space charge



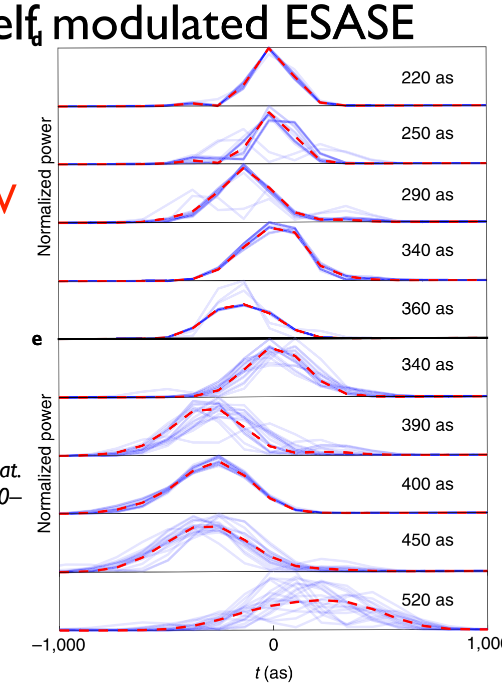
220 as, >100 GW





S. Huang et al., PRL 119, 154801 (2017)

Self modulated ESASE



J. Duris et al., Nat. Photonics 14, 30–36 (2020)

Fonctionnement multi-couleurs

ACO (optical kystron)

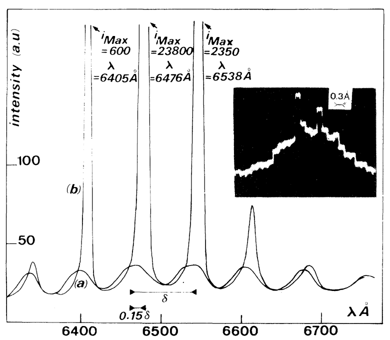
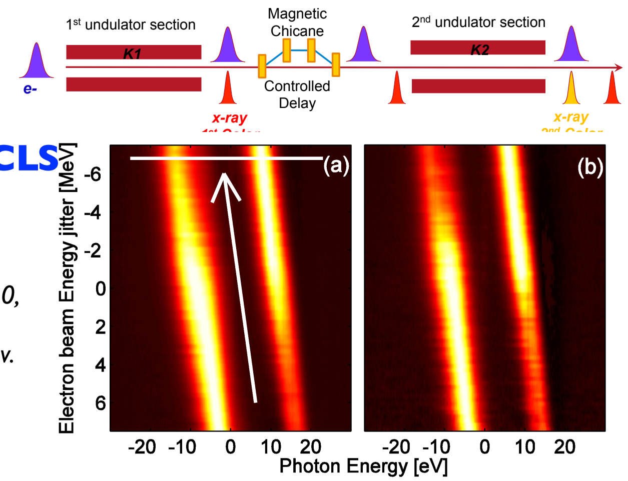


FIG. 4. Spectra of the cavity output radiation under two conditions: curve *a*, cavity detuned (no amplification) and curve *b*, cavity tuned (laser on).

M. Billardon et al., Phys. Rev. Lett. 51, 1652,(1983)

Delay (chicane) and different K_u

LCLS

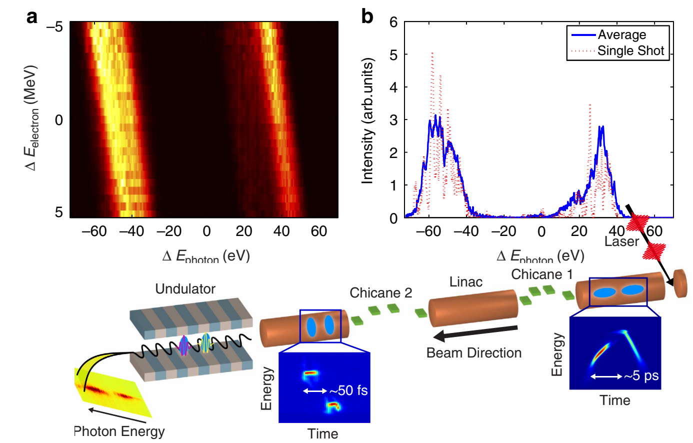


E_b = 5800 MeV and E_γ = 1.5 keV

A.A. Lutman et al., PRL 110, 134801 (2013)
A. Marinelli et al., Phys. Rev. Lett. 111, 134801 (2013)

Twin bunches

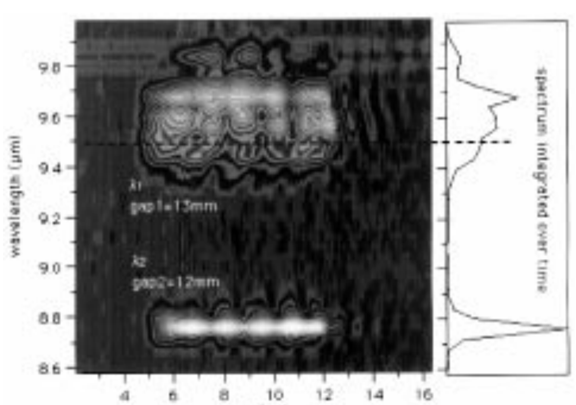
LCLS

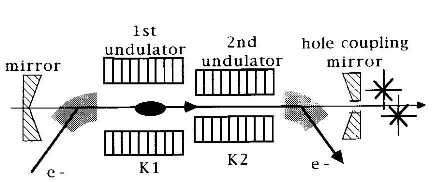


1983 // 2000 2012 2014 2016 2018

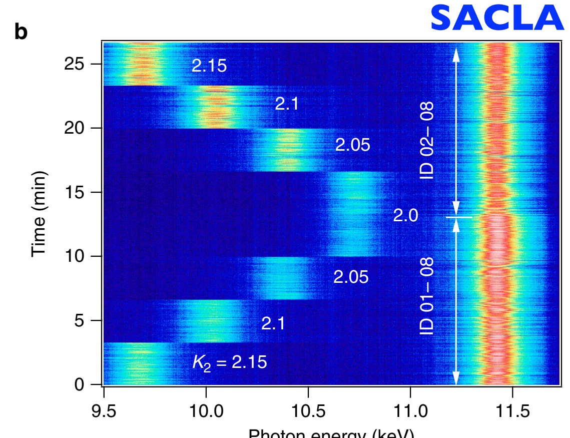
CLIO

R.Prazeres, et al., Eur. Phys. J. D3, 87 (1998)



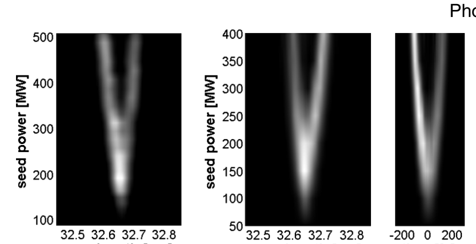


SACLA



T. Hara et al., Nature Communications, 4, 2919, 2013

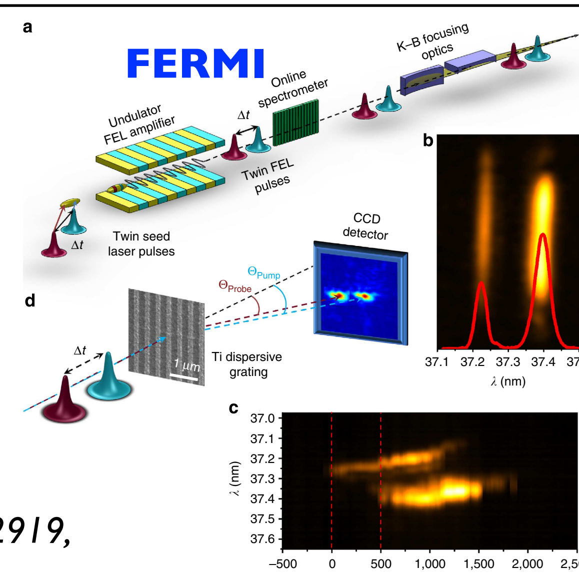
Seeded pulsed splitting FERMI



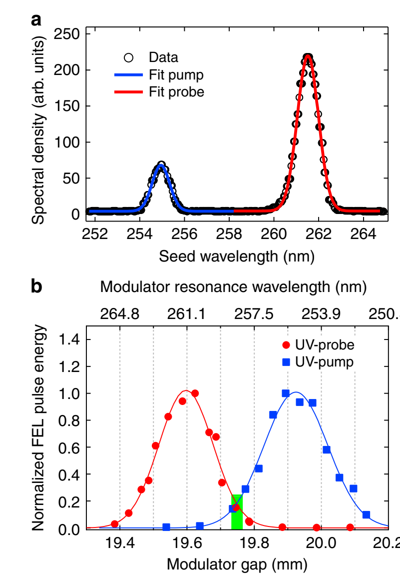
G. De Ninno et al. PRL, 110, 064801 (2013)

M. Labat et al. Phys. Rev. Lett. 103 (2009) 264801

FERMI

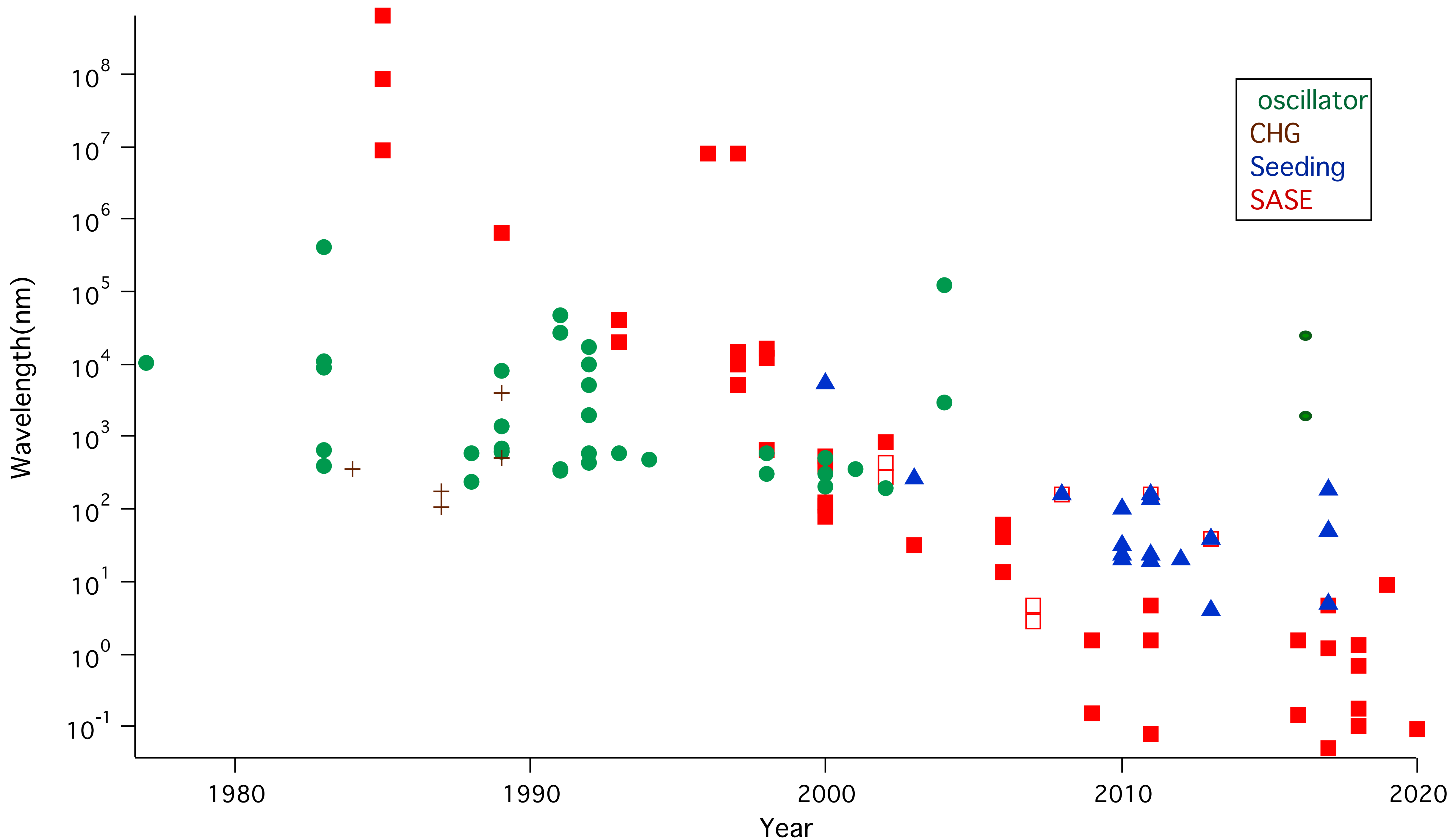


E. Allaria et al., Nature Com. 4, 3476 (2013).
A. Petralia et al., Phys. Rev. Lett. 115, 014801 (2015)



E. Ferrari et al., Nature Photonics 2016

Explosion de X FEL accordables



Panorama des LEL courte longueur d'onde

VUV- soft X ray

hard X ray

Swiss FEL, 5.8 GeV, 0.1-7 nm (now 4.1 nm) 2016-7

Pohang FEL, 3-15 GeV, 0.06-4.5 nm 2016

Dalian FEL, seeded, 0.3 GeV 50-180 nm, 50 Hz, 2017

SACLA, 8 GeV, 0.08 nm SCSS

MaRIE, 20 GeV, 50 keV, 30 fs

LCLS 2009

BNL FEL

LEUTL

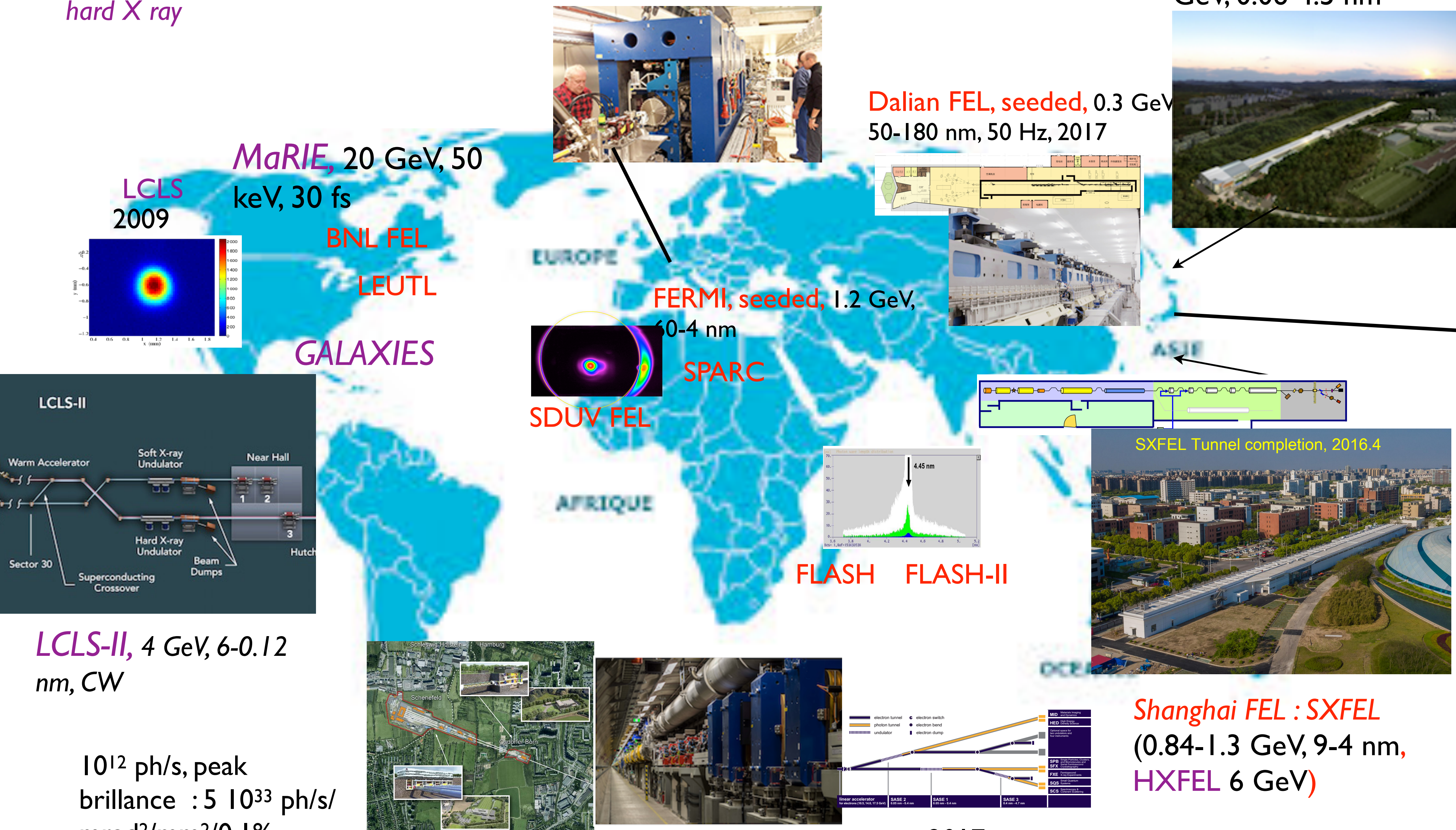
GALAXIES

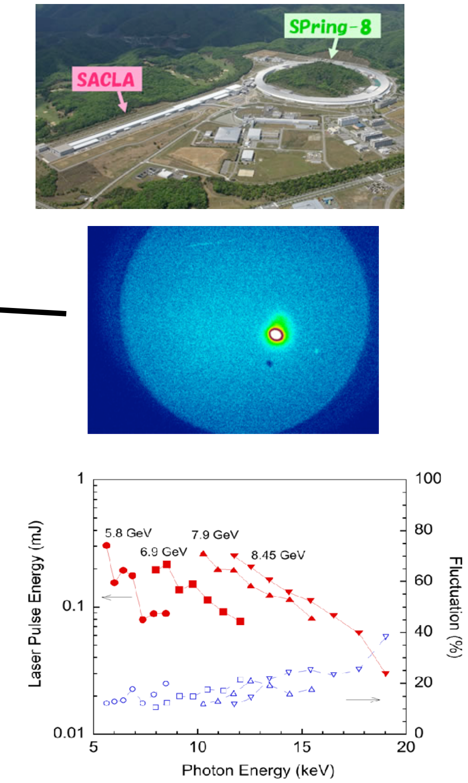
FERMI, seeded, 1.2 GeV, 60-4 nm

SPARC

SDUV FEL

FLASH FLASH-II





LCLS-II, 4 GeV, 6-0.12 nm, CW

10^{12} ph/s, peak brillance : 5 10^{33} ph/s/mrad²/mm²/0.1%

Up to 27 000 pulses/s

Shanghai FEL : SXFEL (0.84-1.3 GeV, 9-4 nm, HXFEL 6 GeV)

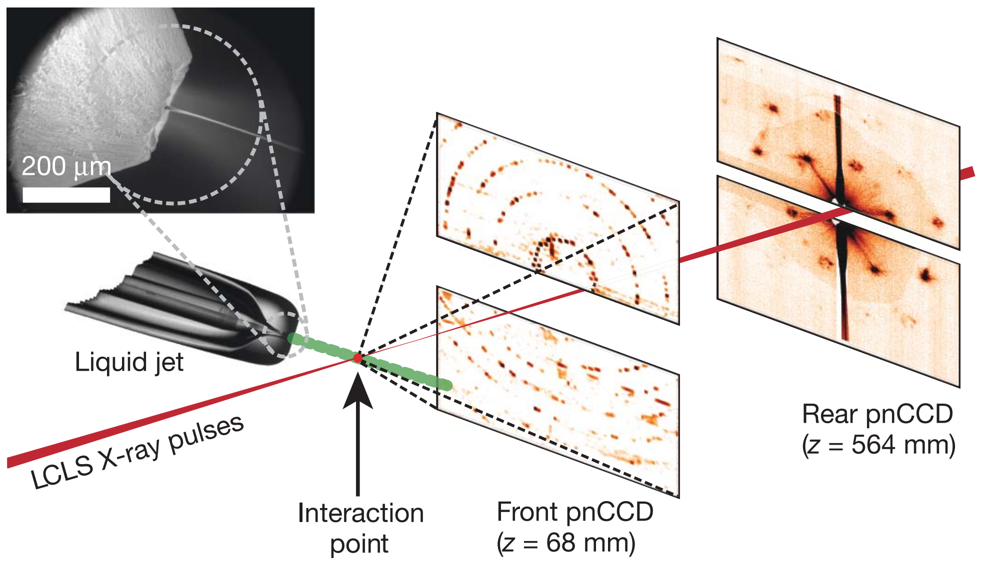
2017

European FEL, 17.5 GeV, 0.05-0.2 nm,

Exemple d'application

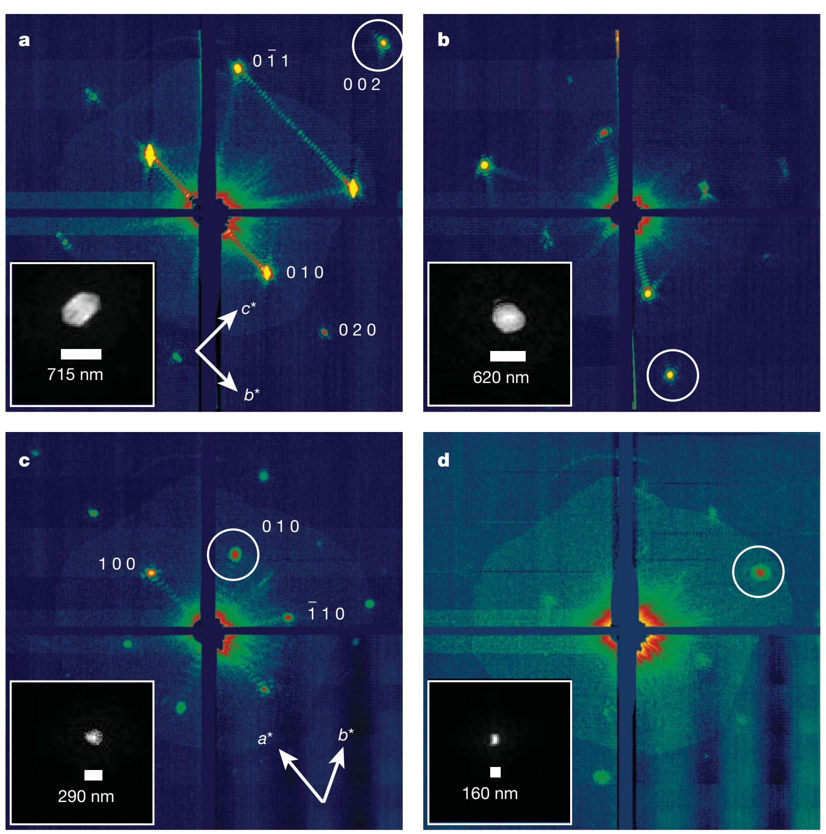
Vers l'imagerie des cellules vivantes

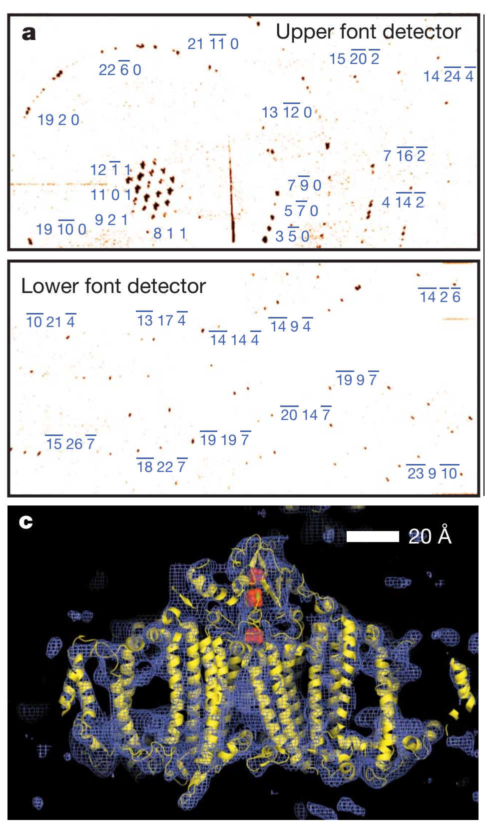
Jet (10 m/s)



Membran protein photosystem I

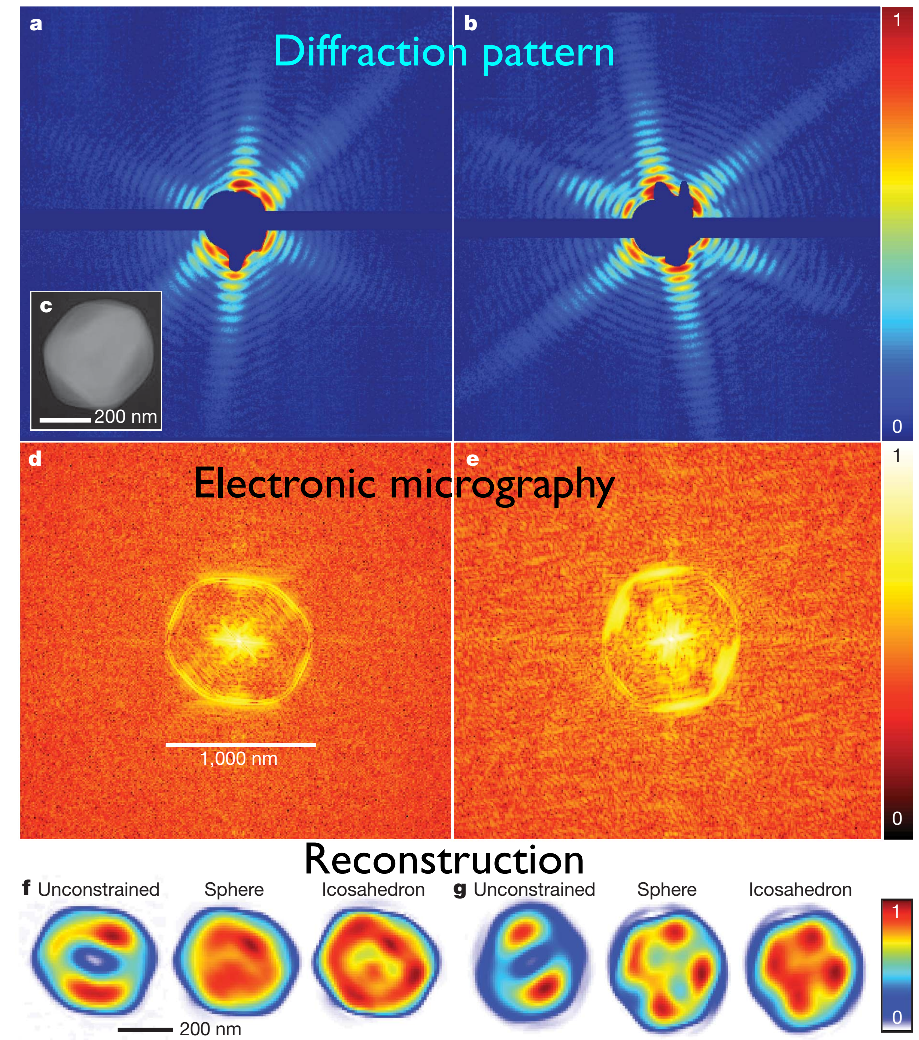
Diffraction pattern





H. Chapman et al., Femtosecond X-ray protein nanocrystallography, Nature, 470, 2011, 73

Mimivirus (Acanthamoeba polyphaga) : (diameter of 0.75 µm)

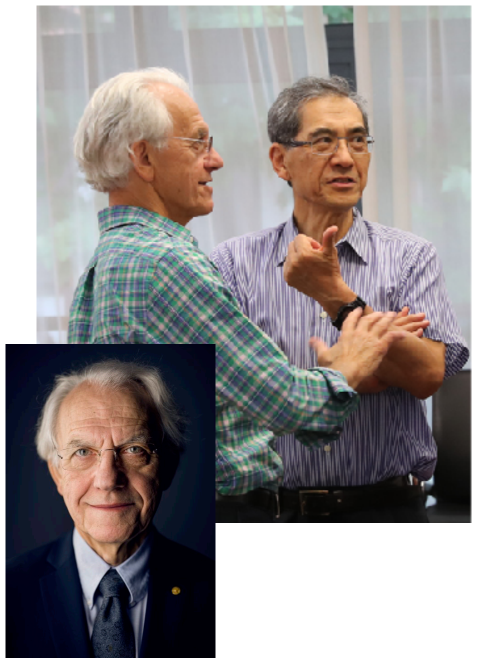


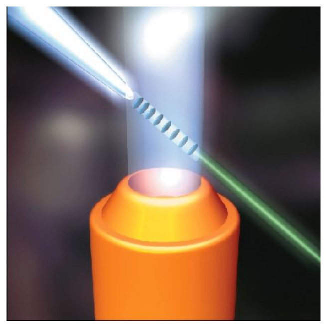
M. M. Seibert et al., Single mimivirus particles intercepted and imaged with an X-ray laser, Nature, 470, 2011, 78

Concepts alternatifs d'accélération

Acceleration Laser Plasma

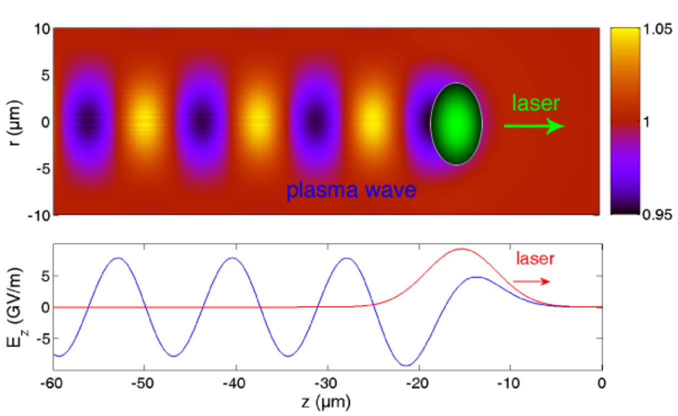
G. Mourou T.Tajima





Laser wakefield in resonance with the plasma : $\tau_{laser} \sim T_p/2$
=> perturbation of the electronic density
longitudinal accelerator field

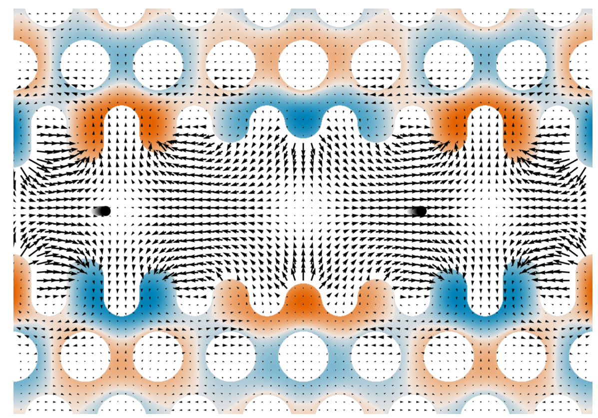
T.Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979) 267

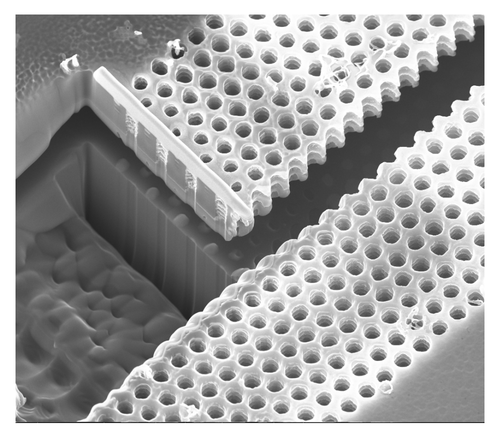


- few pC
- Strongly diverging (1 mrad)
- small size
- larger energy spread (1 %)
- low repetition rate

Acceleration diélectrique

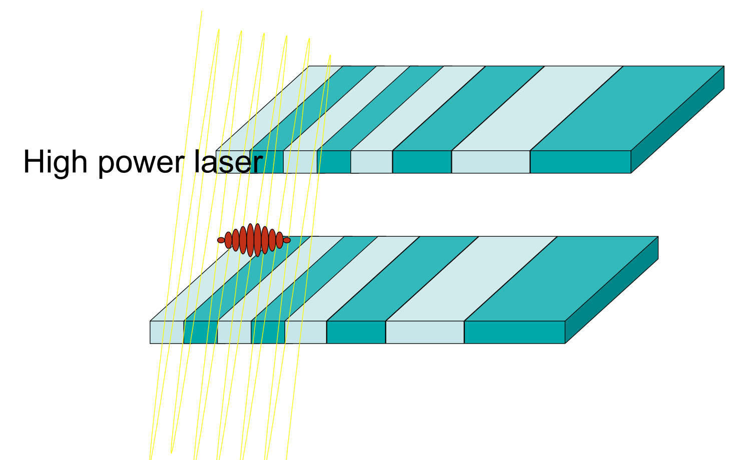
B. Naranjo et al. Phys. Rev. Lett. 109, 176803 (2012)
J. Breuer, et al. Phys. Rev. Lett. 111, 134803 (2013)
E.A. Peralta et al., Nature Lett. 503, 2013





Inverse Free Electron Laser

W. Kimura et al. PRL92, 154801 (2004)
P. Musumeci et al. PRL94, 154801 (2005)
P. Musumeci EAAC , Elba, May 2013

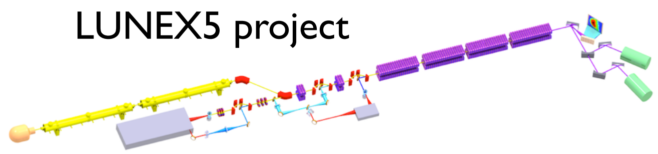


$$\gamma_r^2 \cong \frac{\lambda_w}{2\times\lambda}\cdot\left(1+\frac{K^2}{2}\right)$$

Expérience test COXINEL

Collaboration SOLEIL / LOA/ PhLAM

LUNEX5 project

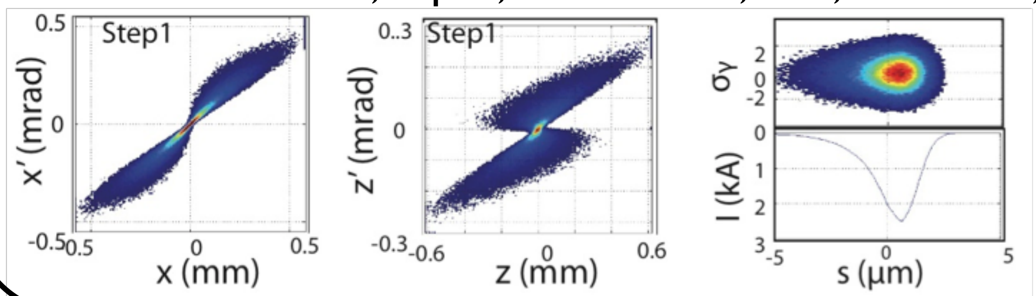


free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation

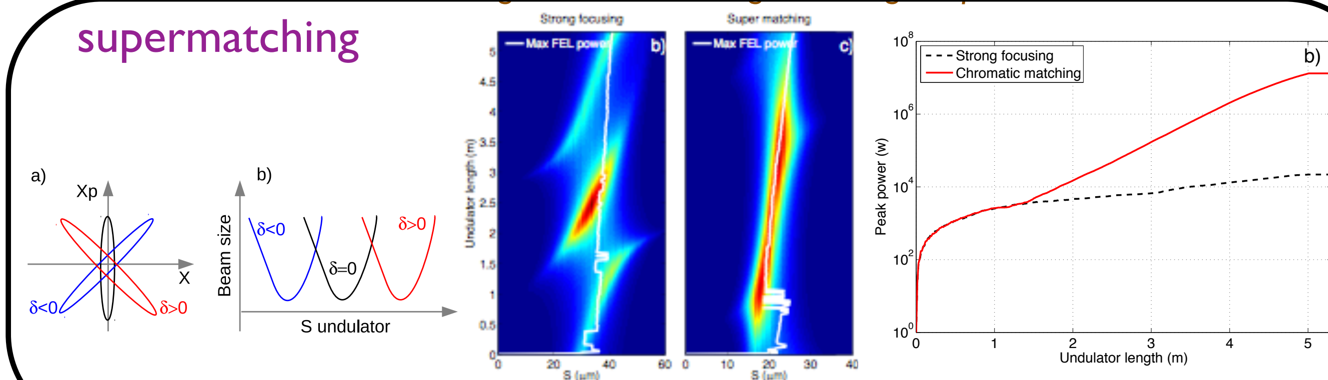
M. E. Couprie et al., Proceedings FEL'14, Basel, Switzerland 574-579 (2014)
M. E. Couprie et al., Proceedings FEL'14, Basel, Switzerland 569-573 (2014)
A. Loulergue et al. Proceeding SPIE, Prague, April 2015

strong focusing

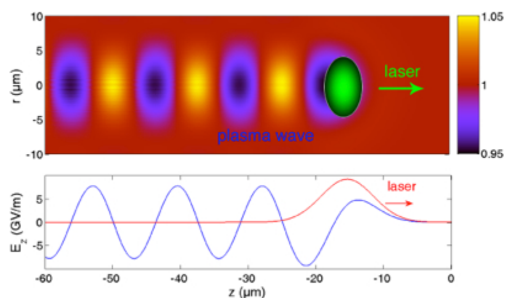
start : 400 MeV, 1 µm, 1.25 mrad, 1 %, 2 fs RMS, 20 pC



supermatching

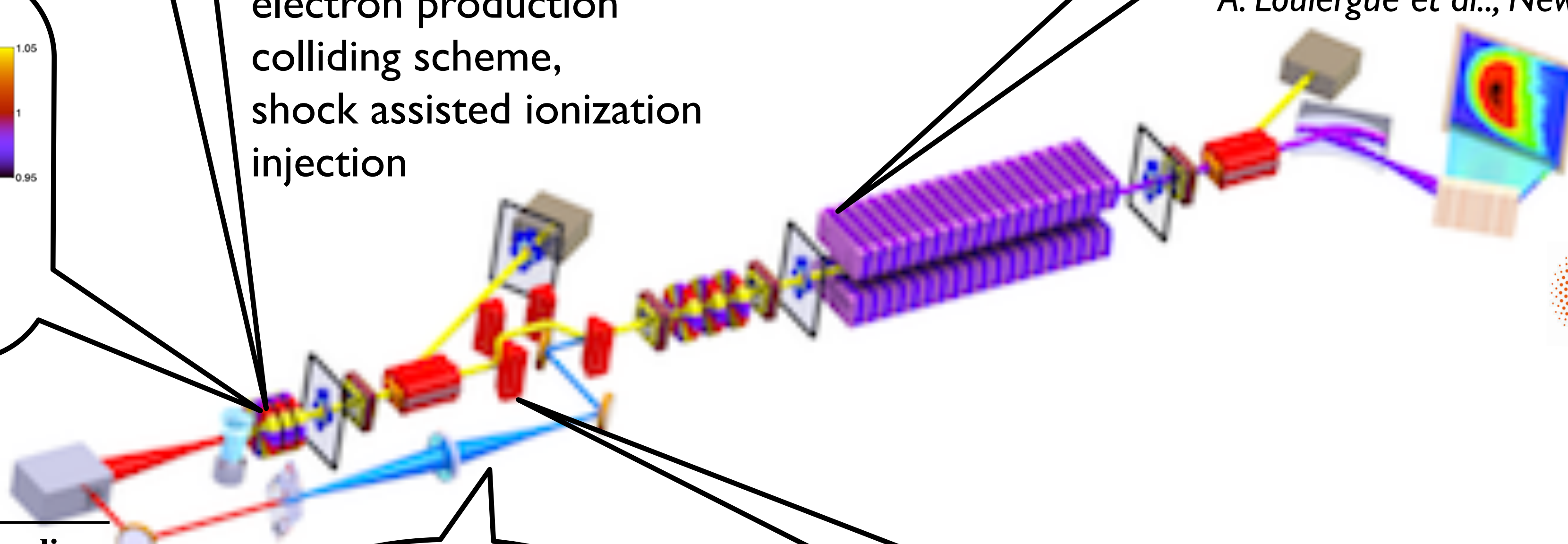


LWFA



electron production
colliding scheme,
shock assisted ionization
injection

A. Loulergue et al.., New J. Phys. 17 (2015) 023028 (2015)



COXINEL
(M. E. Couprie,
SOLEIL)

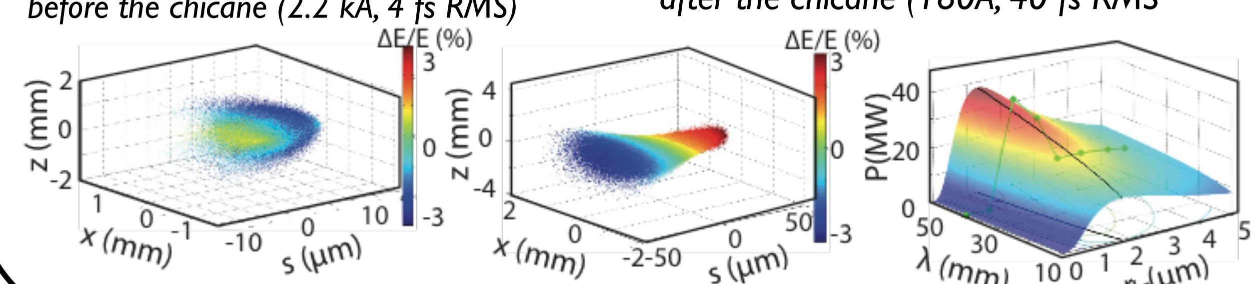
X-Five
(V. Malka, LOA)

seeding

Parameter (unit)	Baseline Source
Vert. divergence (mrad)	1
Hor. divergence (mrad)	1
Beam size (µm)	1
Bunch length (fs RMS)	3.3
Charge (pC)	34
Charge density (pC/MeV)	5
Peak Current (kA)	4.4
Energy spread RMS %	1
Norm. emittance ϵ_N (mm.mrad)	1

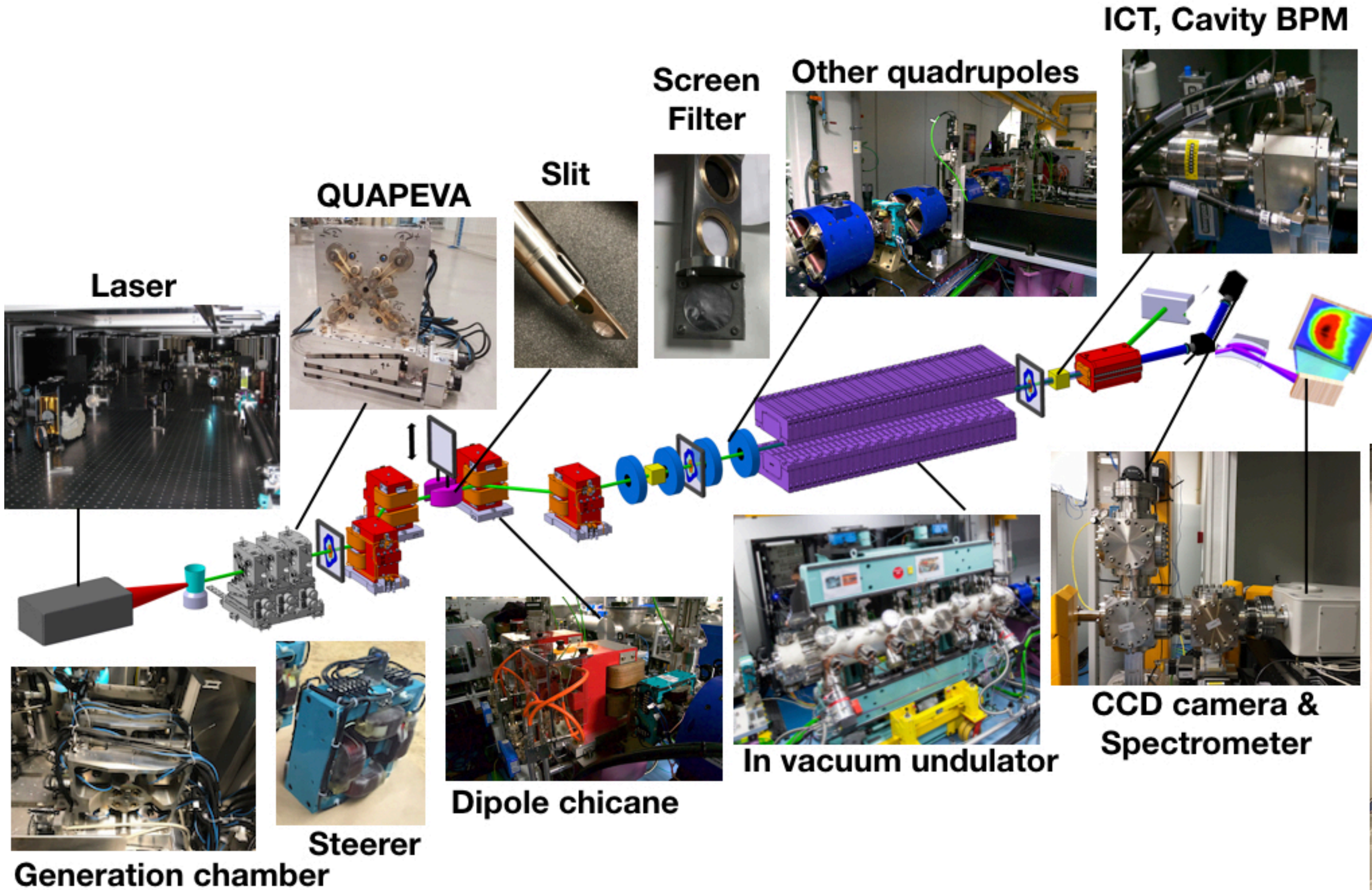
decompression (1 % -> 0.1 %, 2 fs -> 20 fs)

before the chicane (2.2 kA, 4 fs RMS) *after the chicane (180A, 40 fs RMS*



start : 400 MeV, 1 µm, 1.25 mrad, 1 %, 2 fs RMS, 20 pC

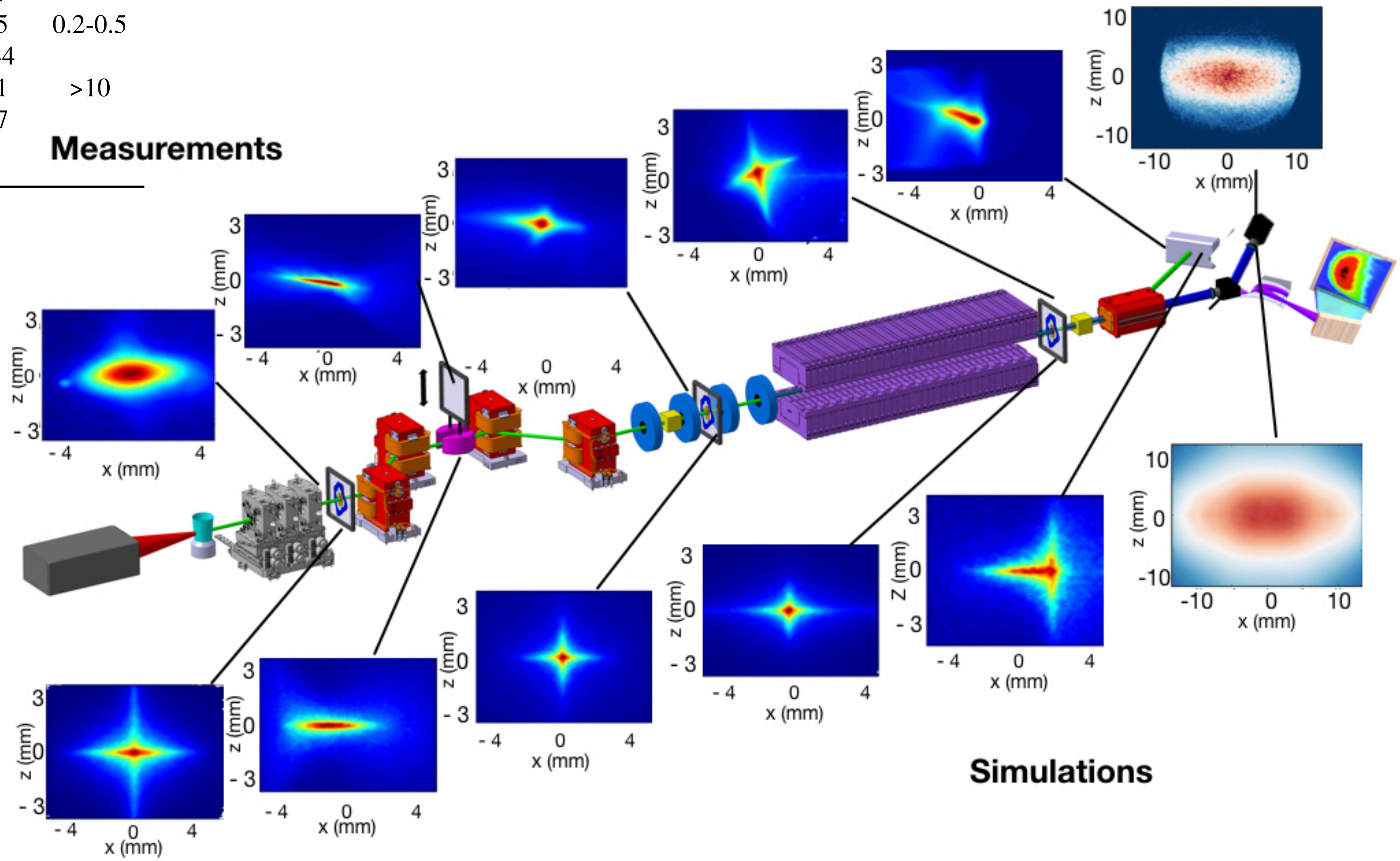
Expérience test COXINEL



COXINEL : transport d'électrons maîtrisé

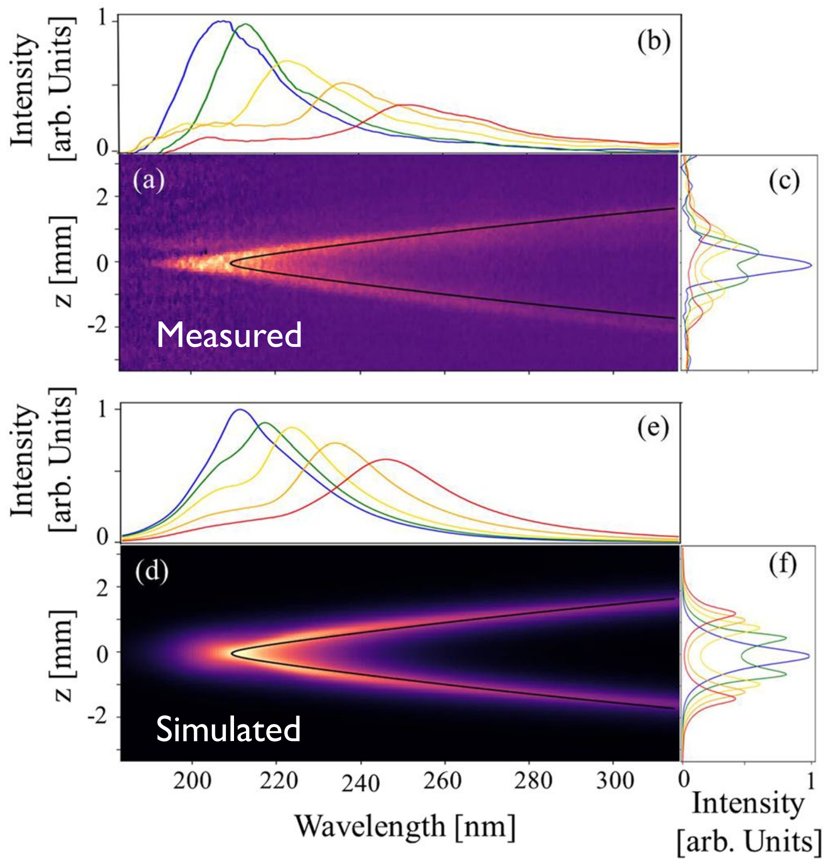
Table 1: COXINEL baseline reference case at the source and undulator (Und.), measured (Meas.) beam at the source.

Parameter (unit)	Baseline Source	Und.	Meas. Source
Vert. divergence (mrad)	1	0.1	1.2-5
Hor. divergence (mrad)	1	0.1	1.8-7.5
Beam size (µm)	1	50	
Bunch length (fs RMS)	3.3	33	
Charge (pC)	34	34	
Charge density (pC/MeV)	5	0.5	0.2-0.5
Peak Current (kA)	4.4	0.44	
Energy spread RMS %	1	0.1	>10
Norm. emittance ϵ_N (mm.mrad)	1	1.7	

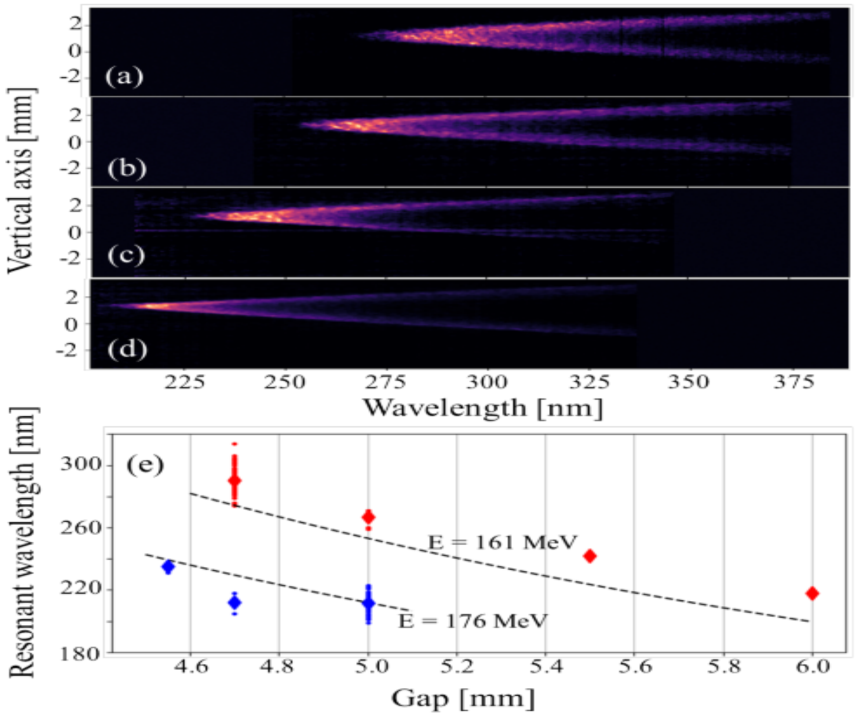


T. André et al., Control of laser plasma accelerated electrons for light sources, Nature Communications (2018) 9:1334

COXINEL : rayonnement spontané de l'onduleur

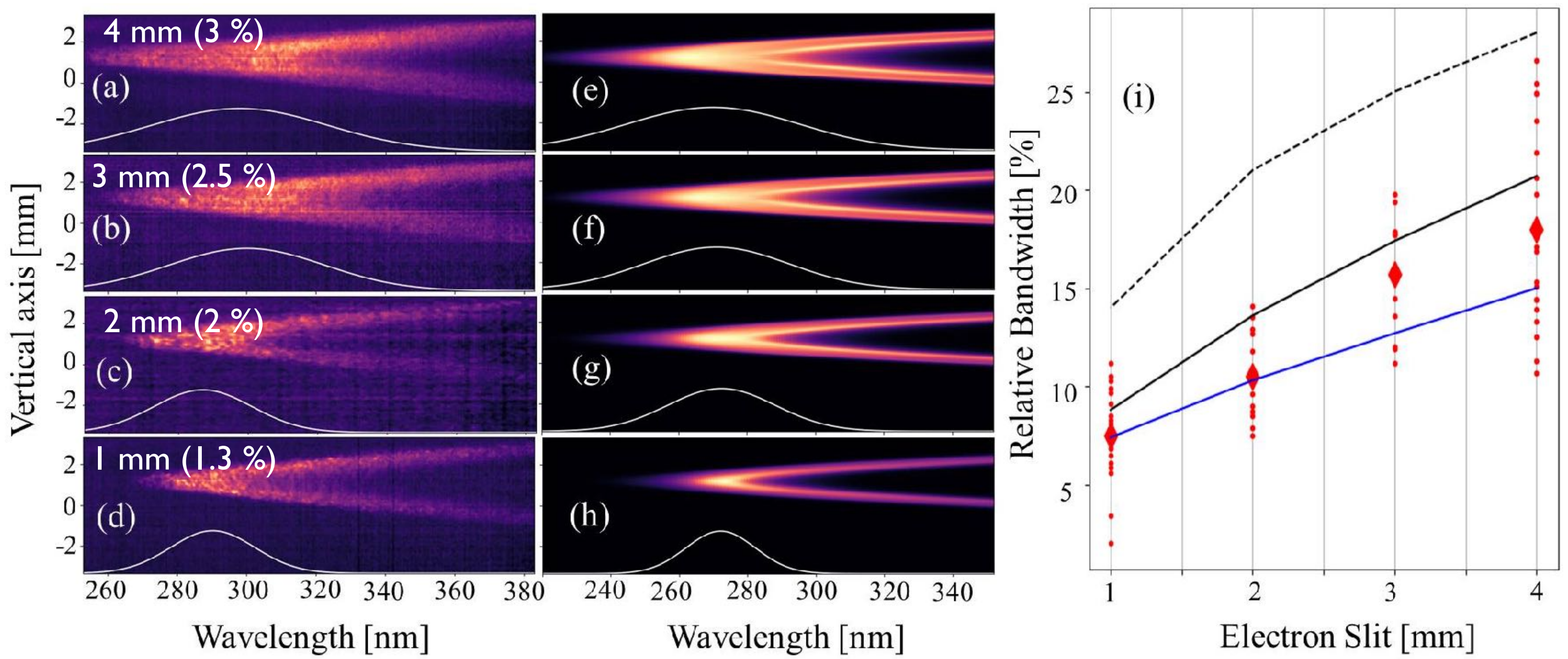


Accordabilité en longueur d'onde par le champ de l'onduleur

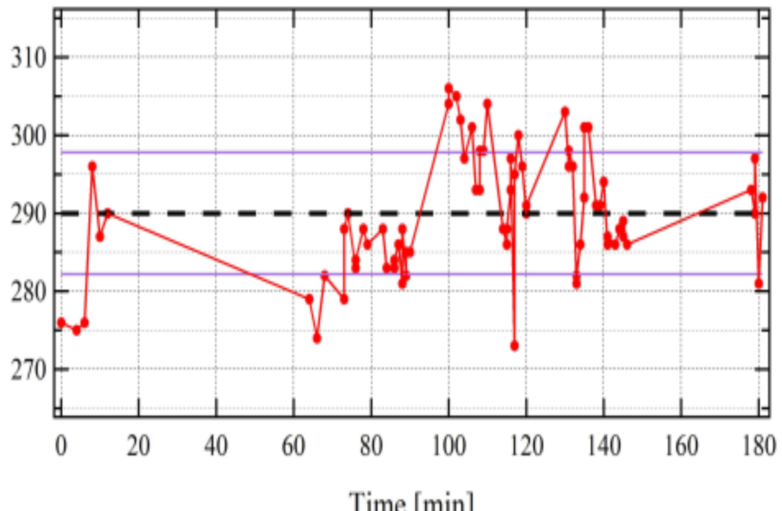


Contrôle de la largeur de raie

Mesures Simulations

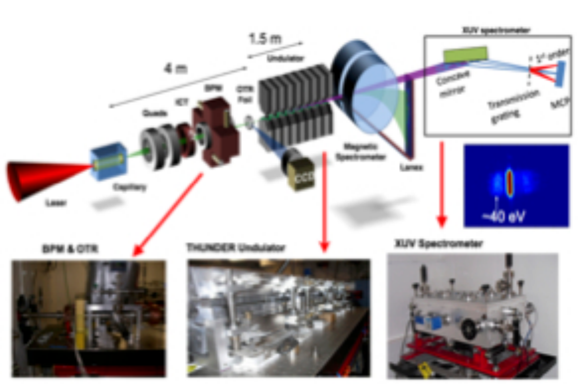


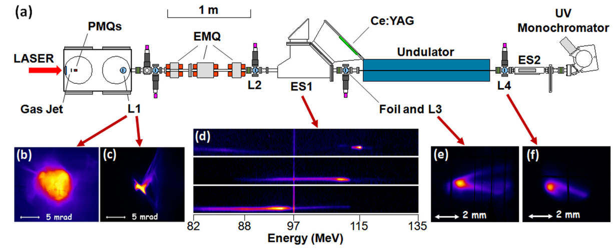
Stabilité en longueur d'onde

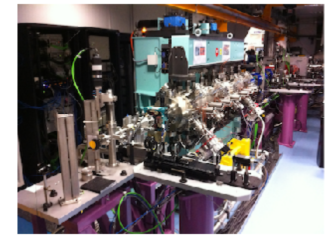


A. Ghaith et al., Scientific Reports 9: 19020 (2019)

Panorama d'expériences LEL test sur accélération laser plasma







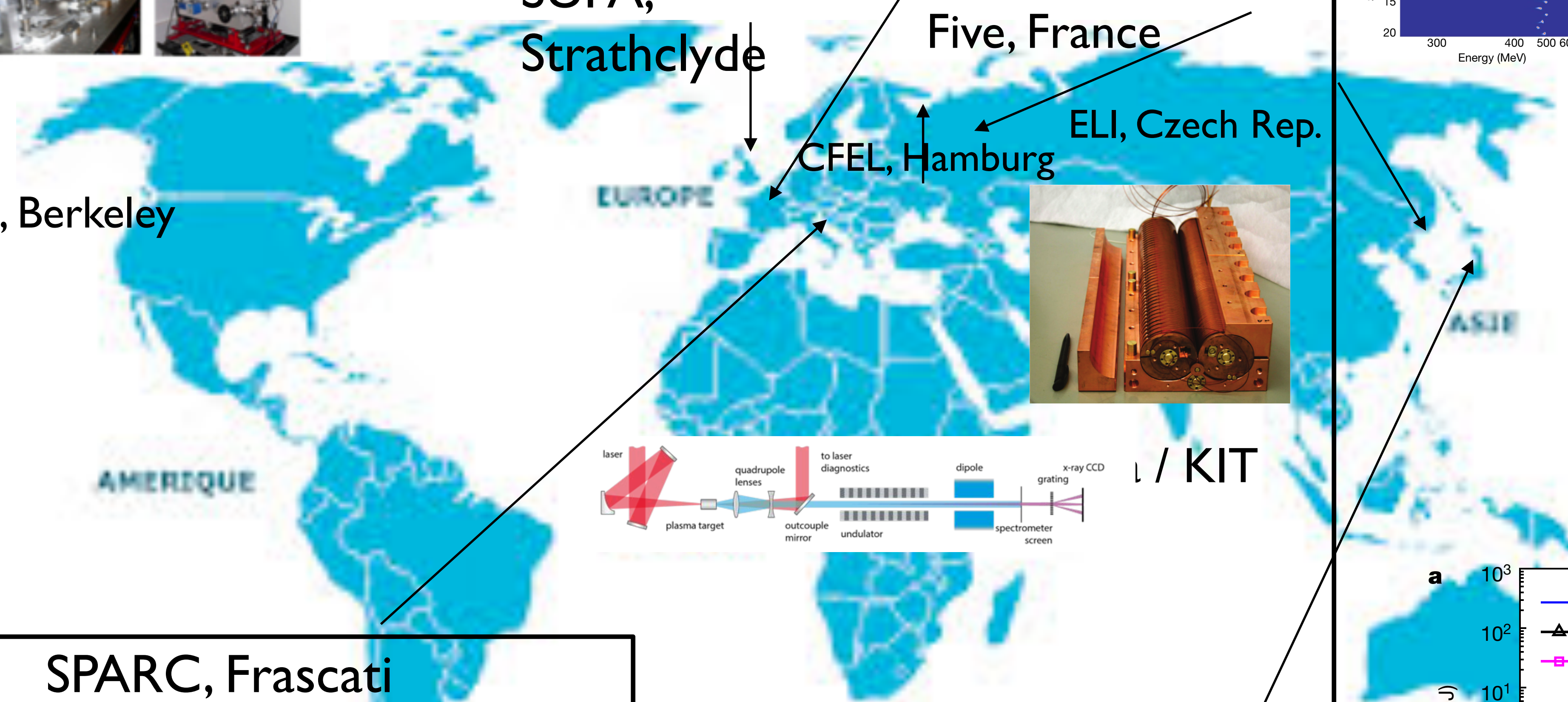
SUPA, Strathclyde

COXINEL / X-Five, France

CFEL, Hamburg

ELI, Czech Rep.

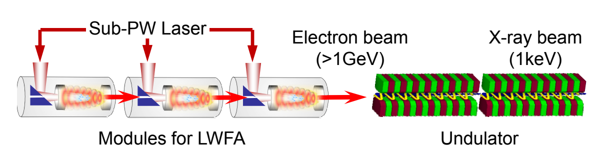
LOASIS, Berkeley



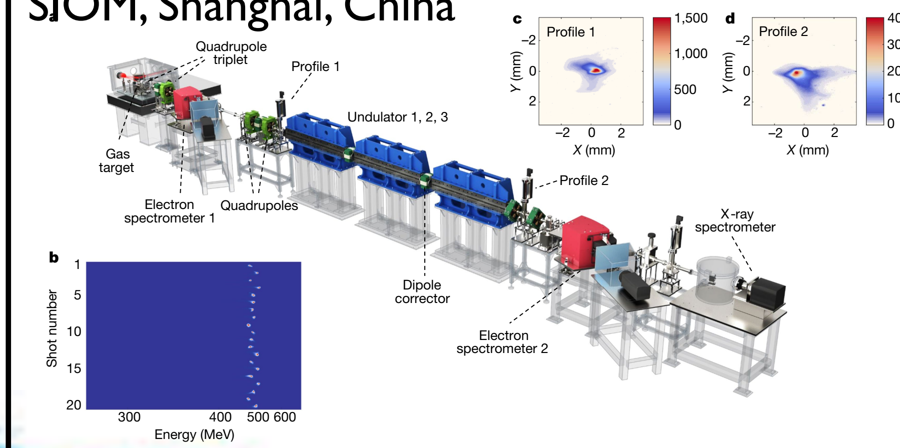
/ KIT

SPARC, Frascati
Acc. RF+ Acc. Plasma
Demo SASE et seeding dans le visible

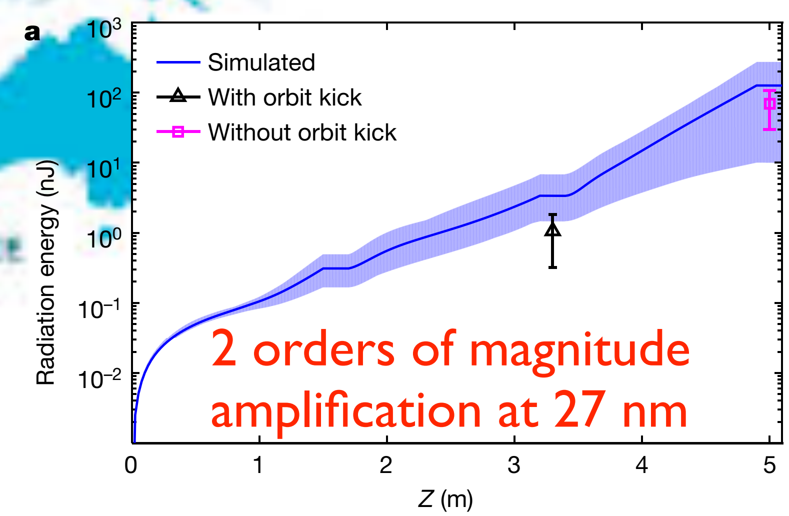
ImPACT, MIRAI
Osaka Univ / Riken Harima



SIOM, Shanghai, China



200 TW laser, 1-5 Hz, 3.8 10^{18}W/cm^{2}, a_0 = 1.3
pure helium supersonic nozzle
Chock front
high-quality electron beams :
a ~ 490 MeV peak energy,
~ 0.5% energy spread,
~ 30 pC average integrated charge
~r.m.s. 0.2 mrad divergence

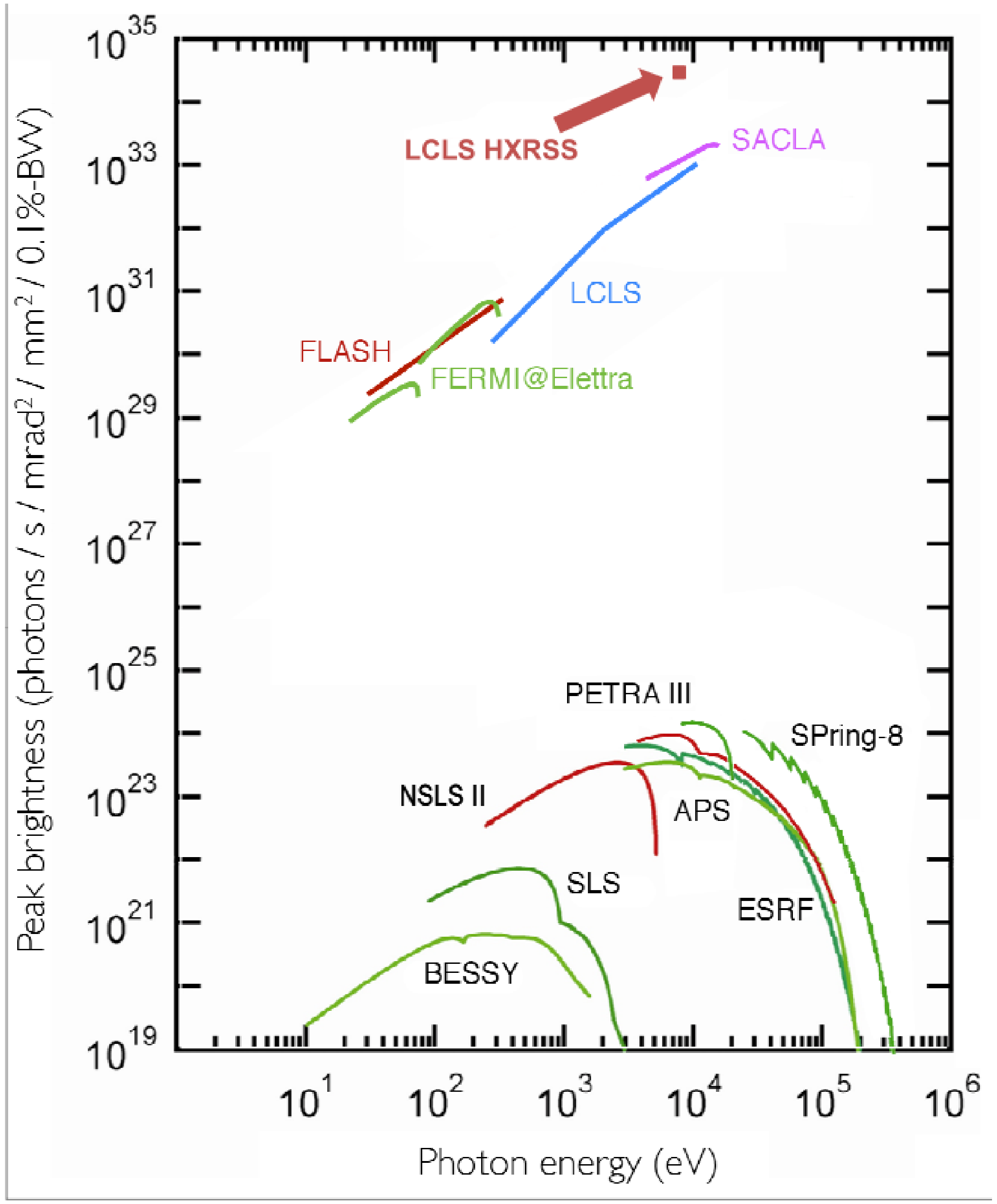


Nouveaux concepts d'accélération appliqués au LEL: encore dans l' « enfance »

Révolution des XFEL agiles et de haute brillance

De la recherche de l'effet LEL des débuts à l'avènement des XFEL : lasers les plus intenses dans le domaine X

Milieu de gain agile permettant manipulation et contrôle du processus => propriétés avancées pour satisfaire les demandes utilisateur (attoseconde..)



Applications

Femtosecond pulses : snapshots d'objets « figés » avant destruction (diffract before destruction) appliqués aux cristaux petits, fragiles et aux particules isolées avec une très haute résolution spatiale

XFEL femtosecond + optical laser optique (pompe pour manipuler la structure/sonde) : « molecular movies » (tracking de la structure et des niveaux électroniques)

Laser X ultra-intense X ray beams : Optique non linéaire dans le domaine X sous conditions

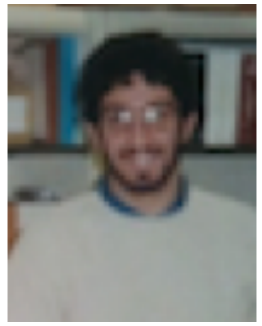
Imagerie cohérente,

Nanoresolution

Etudiants de thèse et post-docs

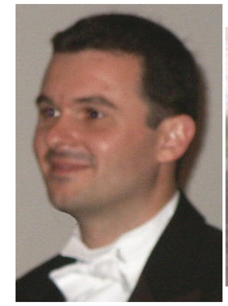
PhD Students

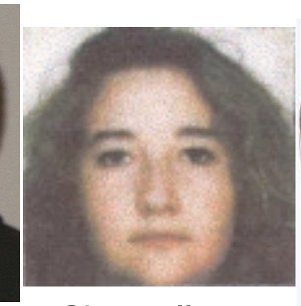

Toru Hara 1992-1995, Paris XI

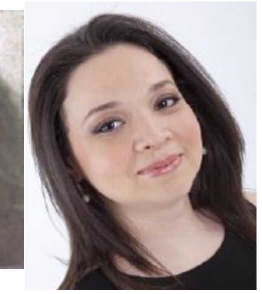

David Garzella 1993-1996, Paris-XI

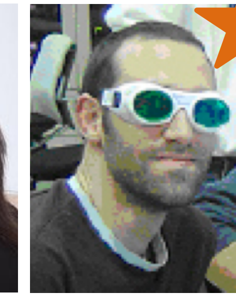

Raphaël Roux 1995-1999, Paris-VI


Daniele Nutarelli 1996-2000, Paris-XI


Cyrille Thomas 1999-2003, Paris-XI/ Eindhoven

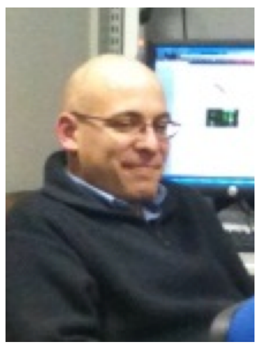

Christelle Bruni 2001-2004, Paris-XI


Mahdia Belgroune 2003-4, Paris-XI


Guillaume Lambert 2004-2008, Paris-XI

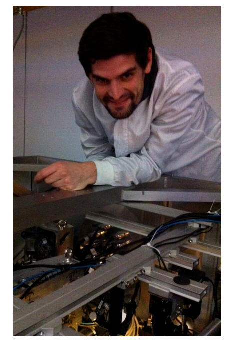

Marie Labat 2005- 2008, Paris-XI


Chamseddine Benabderrahmane 2006-2012, Paris-XI

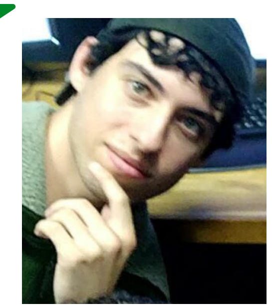

Fabien Briquez 2009-2014, Paris XI


Hadil Abualrob 2011-2015 Paris XI


Xavier Nuel Gavalda 2012-2016 Paris-Saclay


Thomas André 2015-2018 Paris-Saclay


Amin Ghaith 2016-2019 Paris-Saclay


Driss Oumbarek-Espinos 2018-2021 Paris-Saclay/Osaka

FEL Young Scientist Award

SFP Prize

Post-docs Students

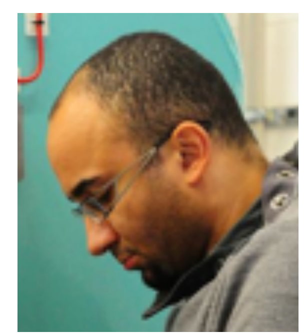

R.Bakker 1994-1996

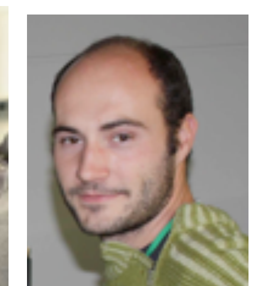

E. Renault 1998-2000


G. de Ninno 1999-2001


G. L. Orlandi 2002-2004


O.Tcherbakoff 2006-2007


C. Kitégi 2008-2009


R. Bachelard 2008-2009


C. Evain 2009-2011

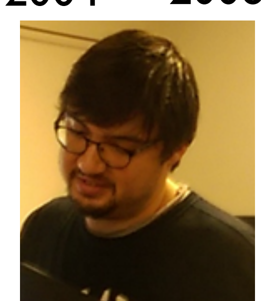

T. Tanikawa 2012-2013


C. Bourassin-Bouchet 2013-2015

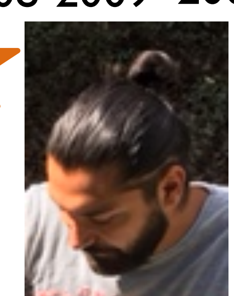

S. Tripathi 2014-2016


G. Sharma 2015-2016


M. Khojoyan 2015-2017


Andriyash 2015-2017


E. Roussel 2017


A. Ghaith 2019-2021

Collaborateurs

Michel Billardon, Jean-Michel Ortéga,
Michel Velghe, Rui Prazeres

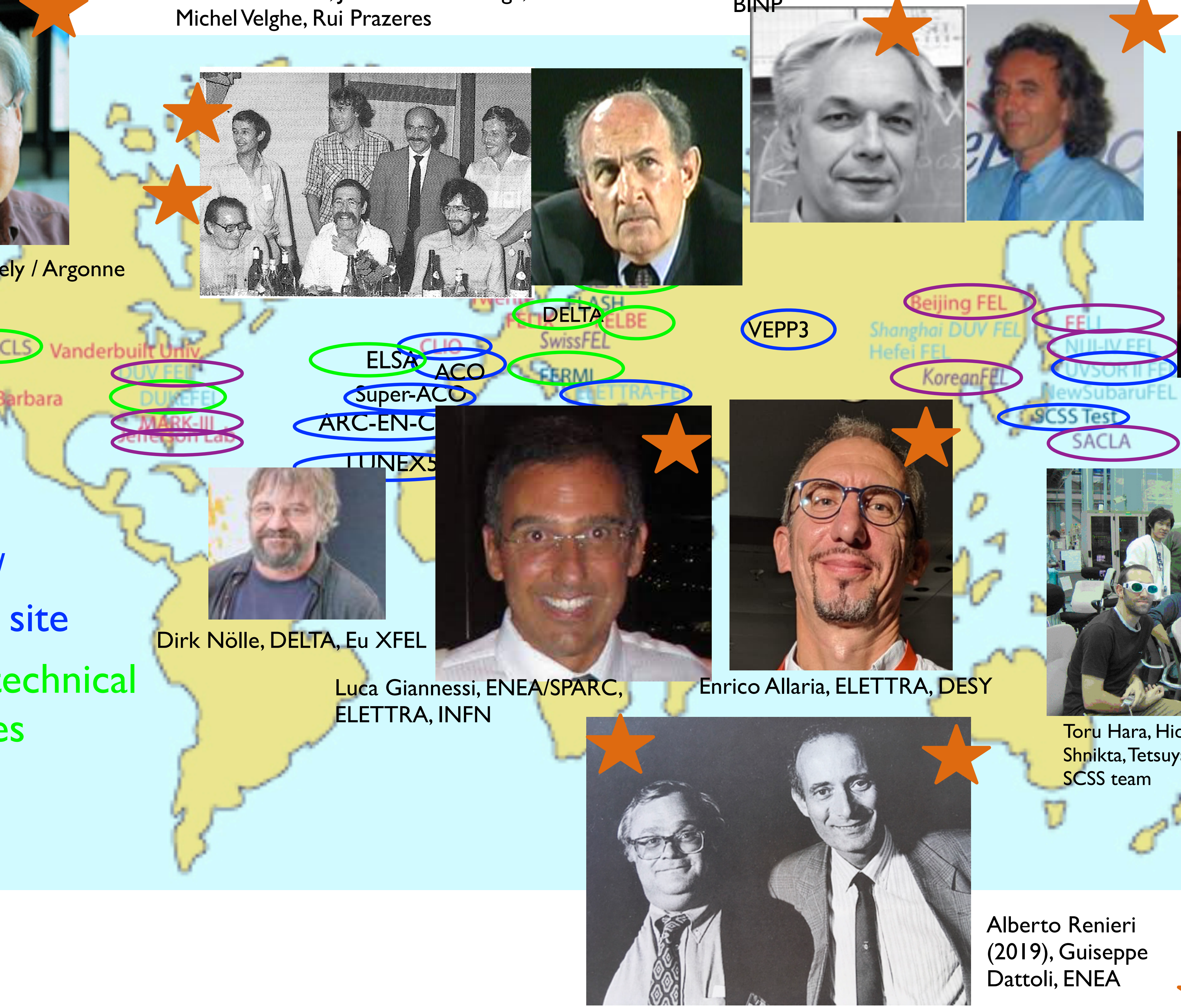
Vladimir Litvinenko,
BINP:/DUKE / BNL

Nikolai Vinokurovn
BINP

Kwang Je Kim Berkely / Argonne

Hiroyuki Hama,
UVSOR, Sendai Univ.

Masahito Hosaka
UVSOR, Nagoya Univ.



Dirk Nölle, DELTA, Eu XFEL

Luca Giannessi, ENEA/SPARC,
ELETTRA, INFN

Enrico Allaria, ELETTRA, DESY

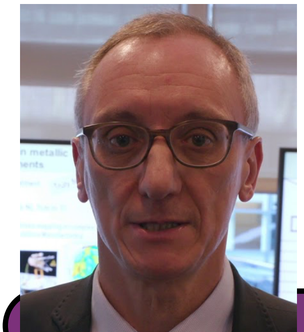
Toru Hara, Hideo Kitamura, Tsumoru Shnikta, Tetsuya Ishikawa, Makina Yabashi
SCSS team

joint work /
experiments on site

collaboration/ technical
exchanges

visits

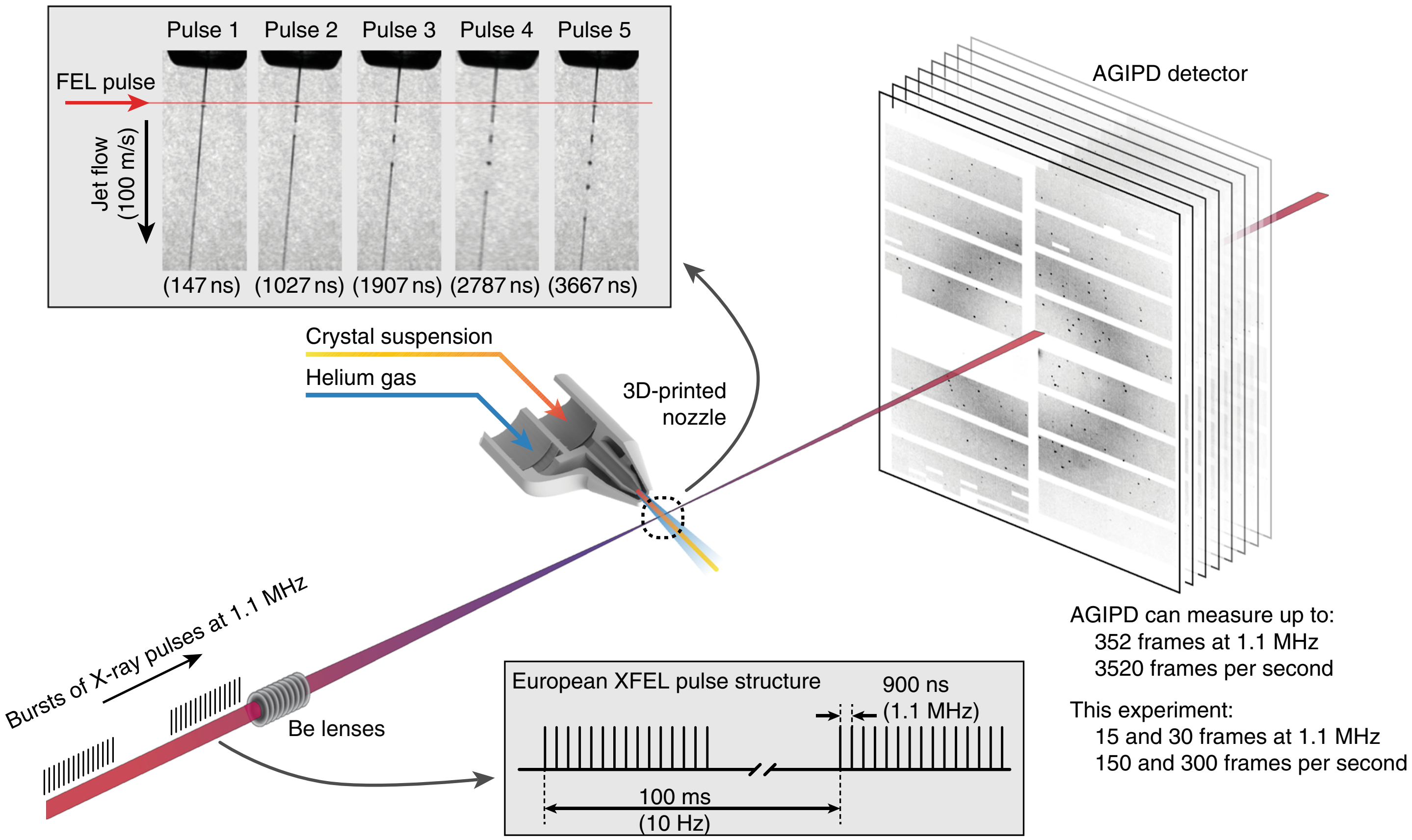
Jean Daillant, SOLEIL



Alberto Renieri
(2019), Guiseppe
Dattoli, ENEA

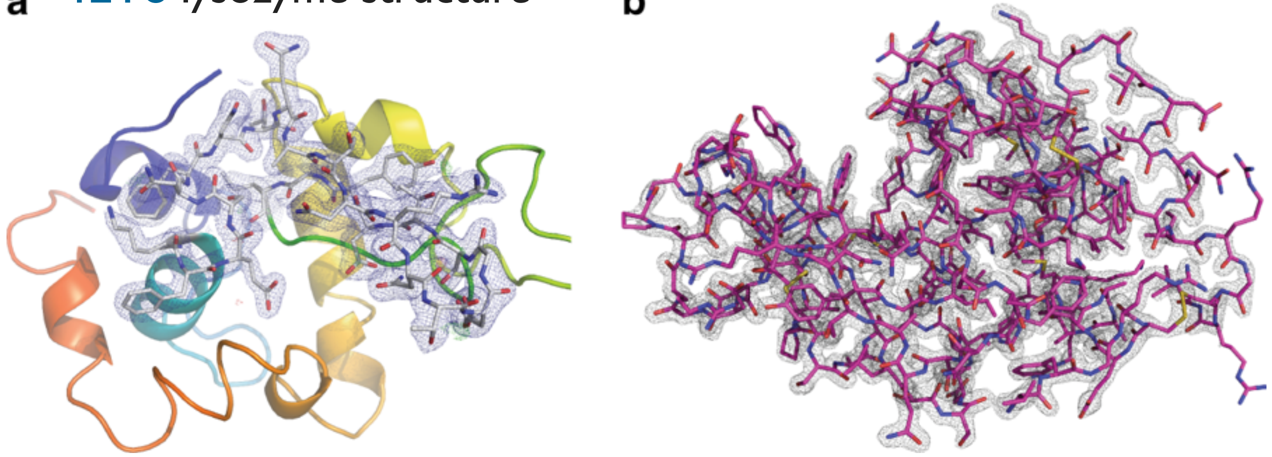
FEL prize

Applications of XFELs

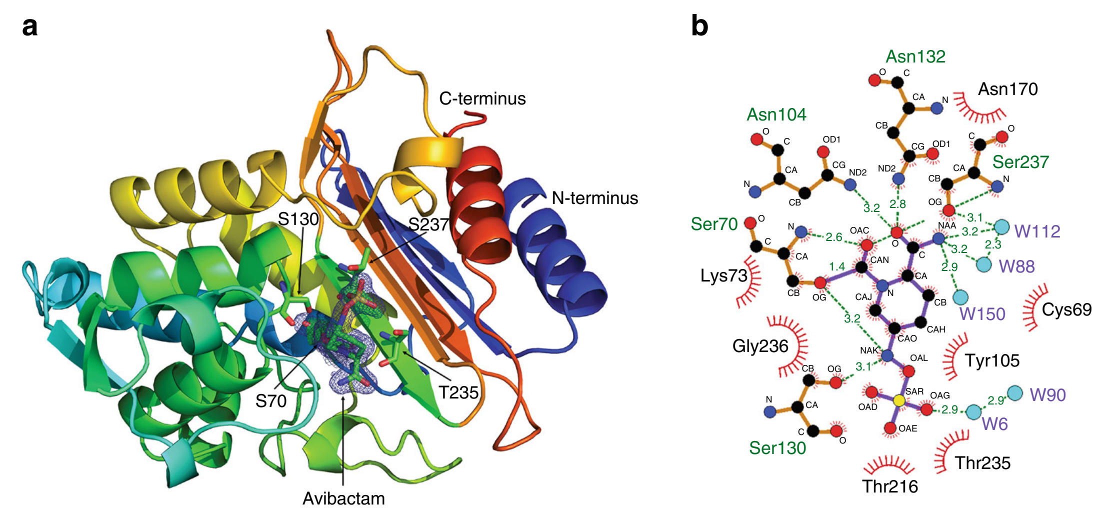


XFEL pulses focused on the interaction region using a set of Beryllium lenses.
Protein crystals in crystallization solution introduced into the focused XFEL beam using a liquid jet of 1.8 µm diameter moving at speeds between 50 m/s and 100 m/s.
Diffraction from the sample measured using an AGIPD, capable of measuring up to 3520 pulses per second at megahertz frame rates.
In-situ jet imaging (inset) : the liquid column does explode under the X-ray illumination conditions of this experiment using a jet with a speed of 100 m/s, but that the liquid jet recovered in less than 1 µs to deliver fresh sample in time for arrival of the next X-ray pulse.

a 4ET8 lysozyme structure



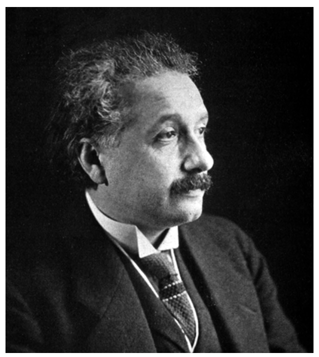
CTX-M-14 β-lactamas



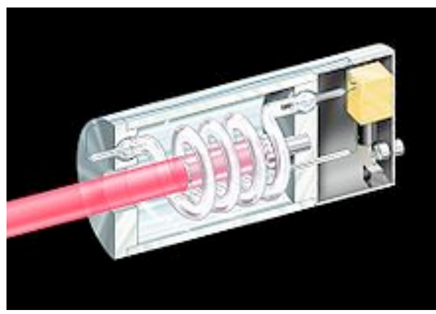
M. O. Weidorn et al., Megahertz serial crystallography, Nat. Comm. (2018) 9: 4025

Accelerator light source : from the past to the future

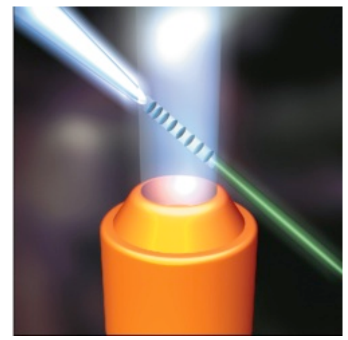
Stimulated emission



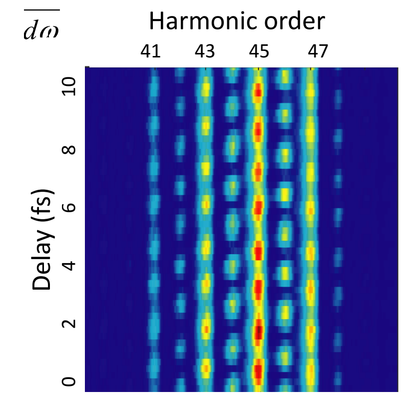
Ruby laser



LPA concept

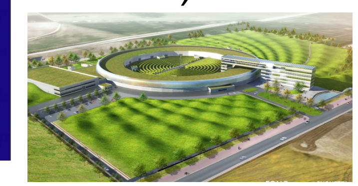


HHG, atto second



Paul, Science 2001

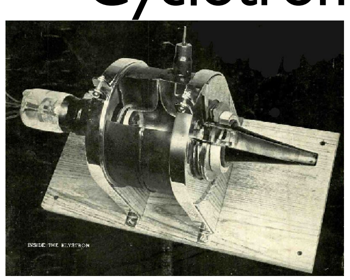
MAX IV (3 GeV, 330 pm, 7BA, 528 m)



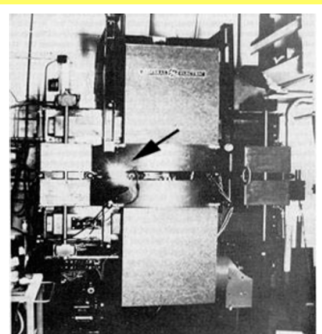
10 pm ring ?

1900 1920 1940 1960 1980 2000 2020 2040

Cyclotron

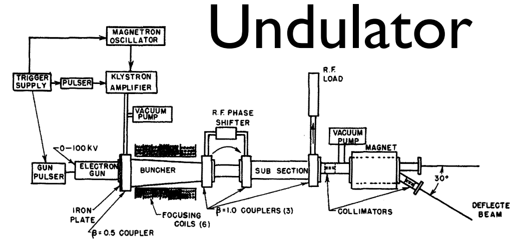


Klystron

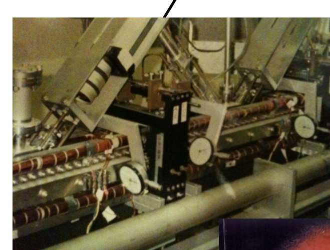


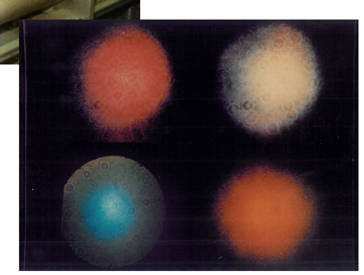
Synchrotron radiation

Undulator



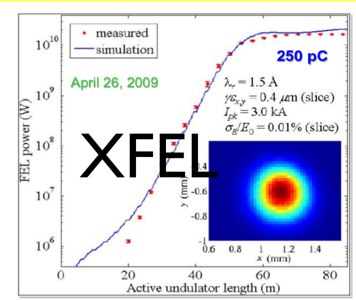
First FEL (IR)

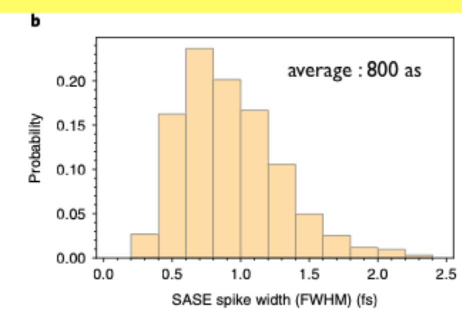




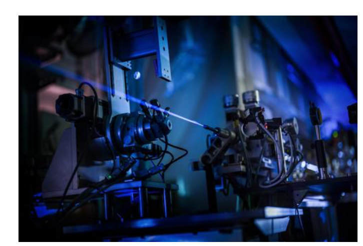
2nd FEL (vis.)

XFEL





as XFEL



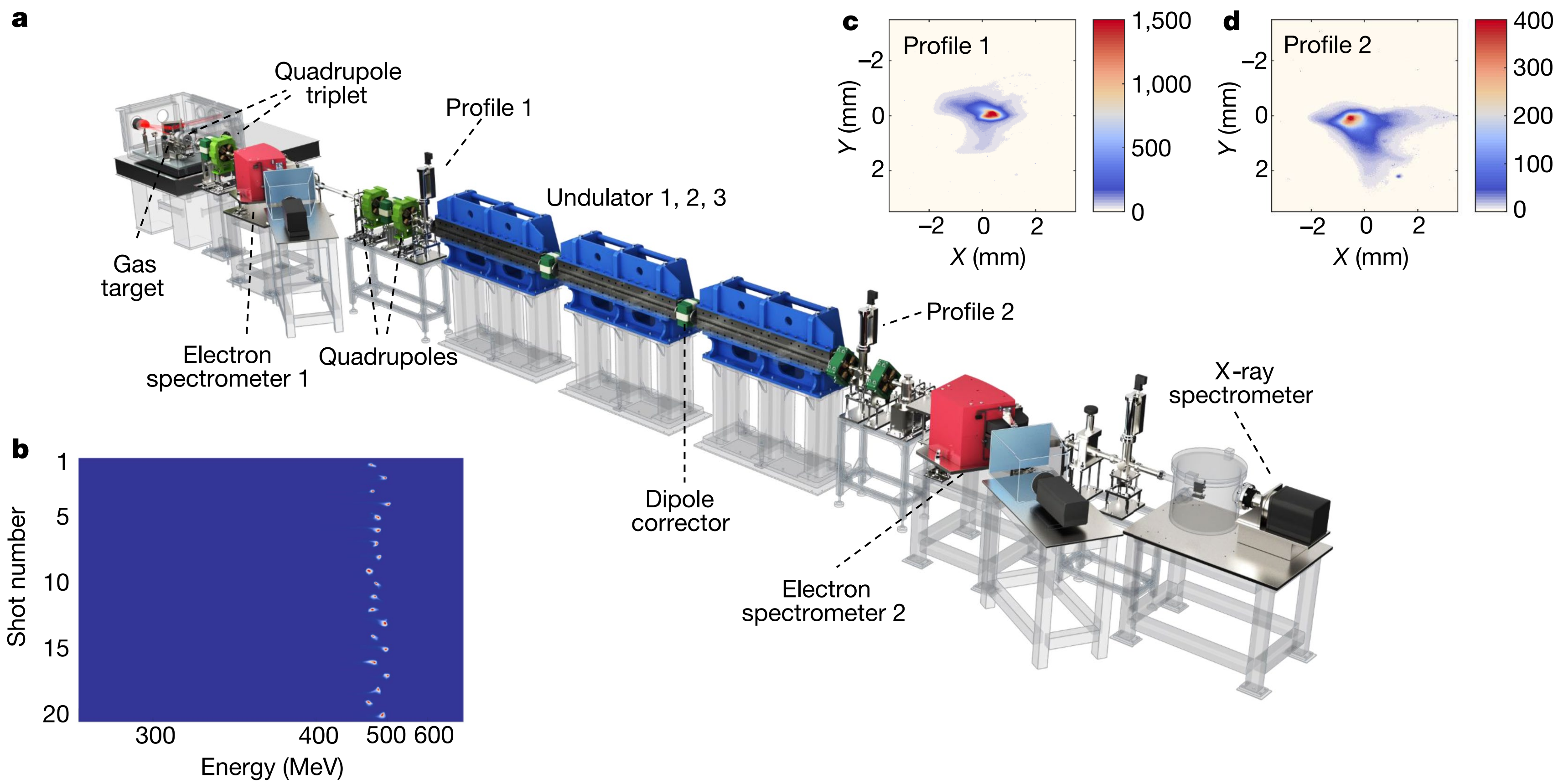
MHz XFEL

Plasma based FEL

XFELO

FEL based EUV lithography?

A first promising result at SIOM



200 TW laser, 1-5 Hz, 3.8 10^{18}W/ cm^2, a_0 = 1.3

pure helium supersonic nozzle

Chock front

high-quality electron beams :

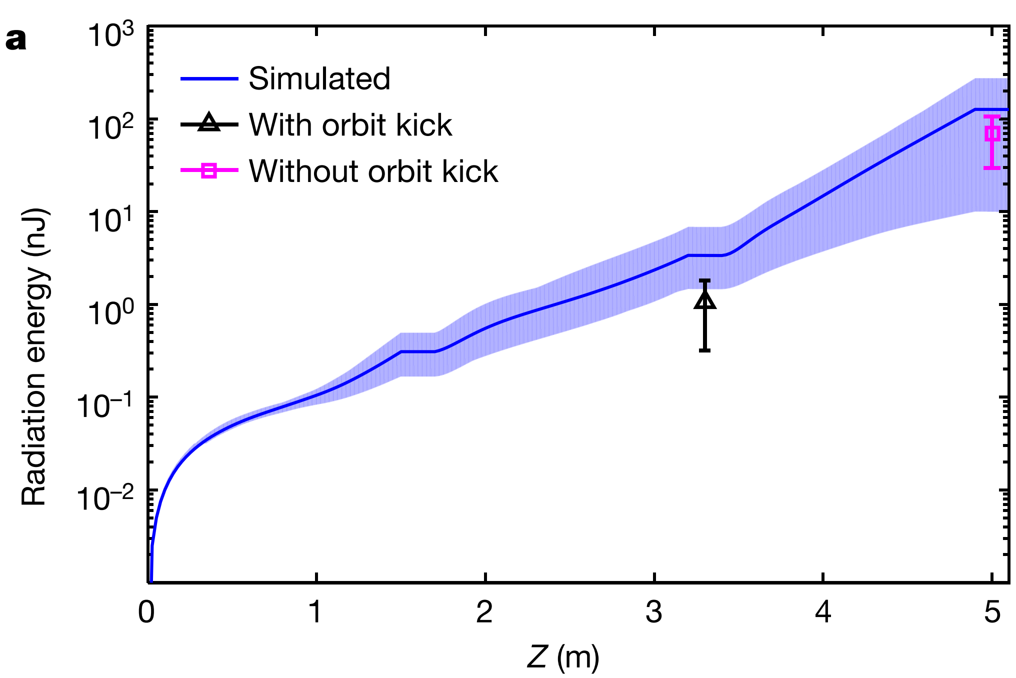
a ~ 490 MeV peak energy,

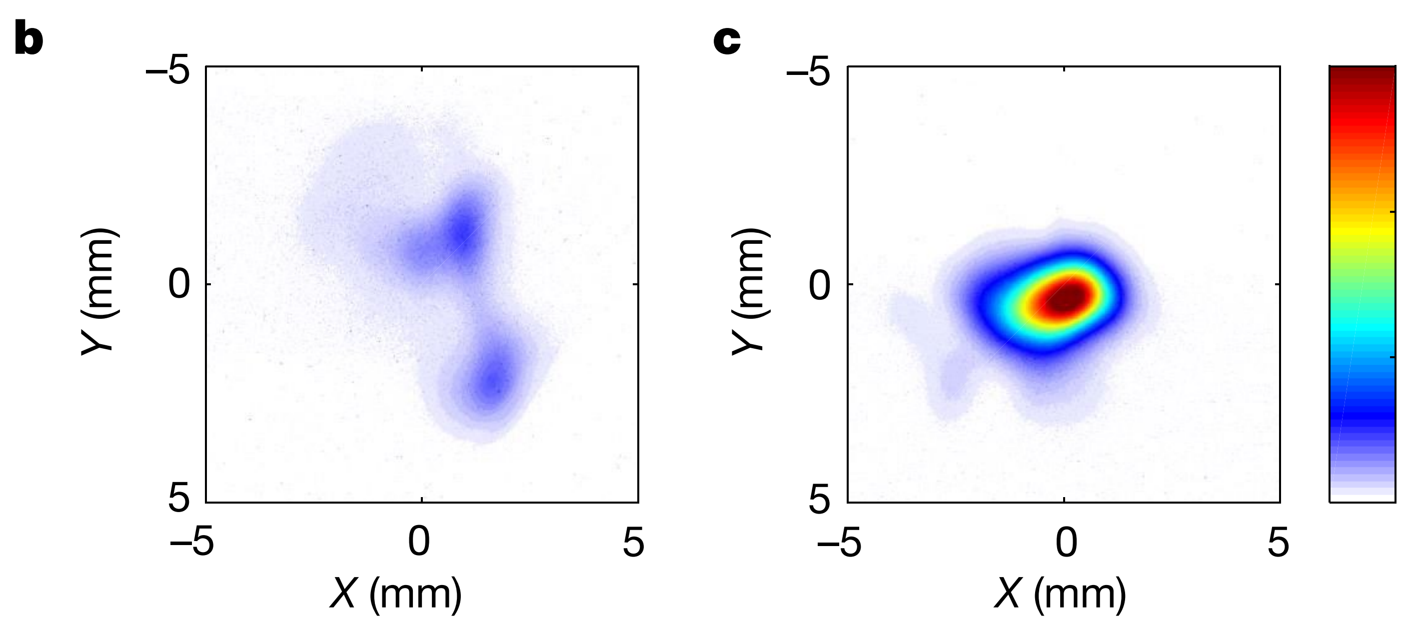
~ 0.5% energy spread,

~ 30 pC average integrated charge

~r.m.s. 0.2 mrad divergence

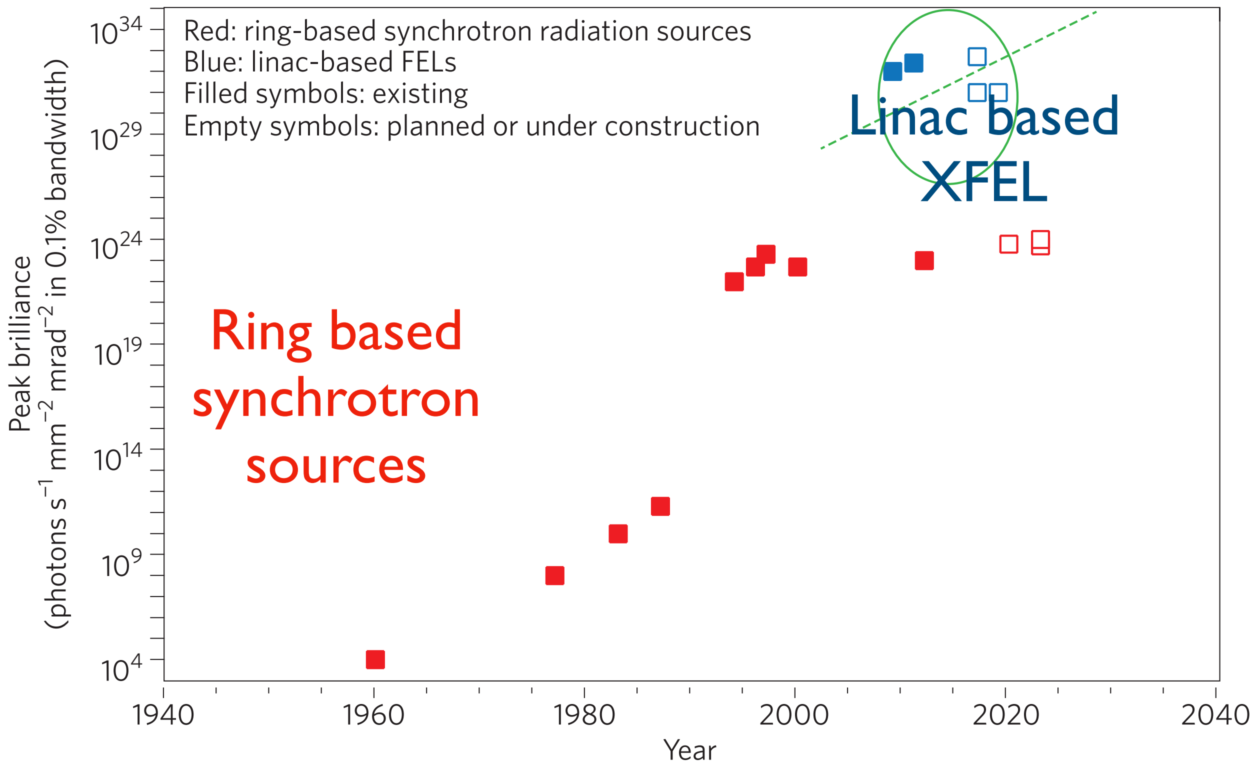
2 orders of magnitude amplification at 27 nm

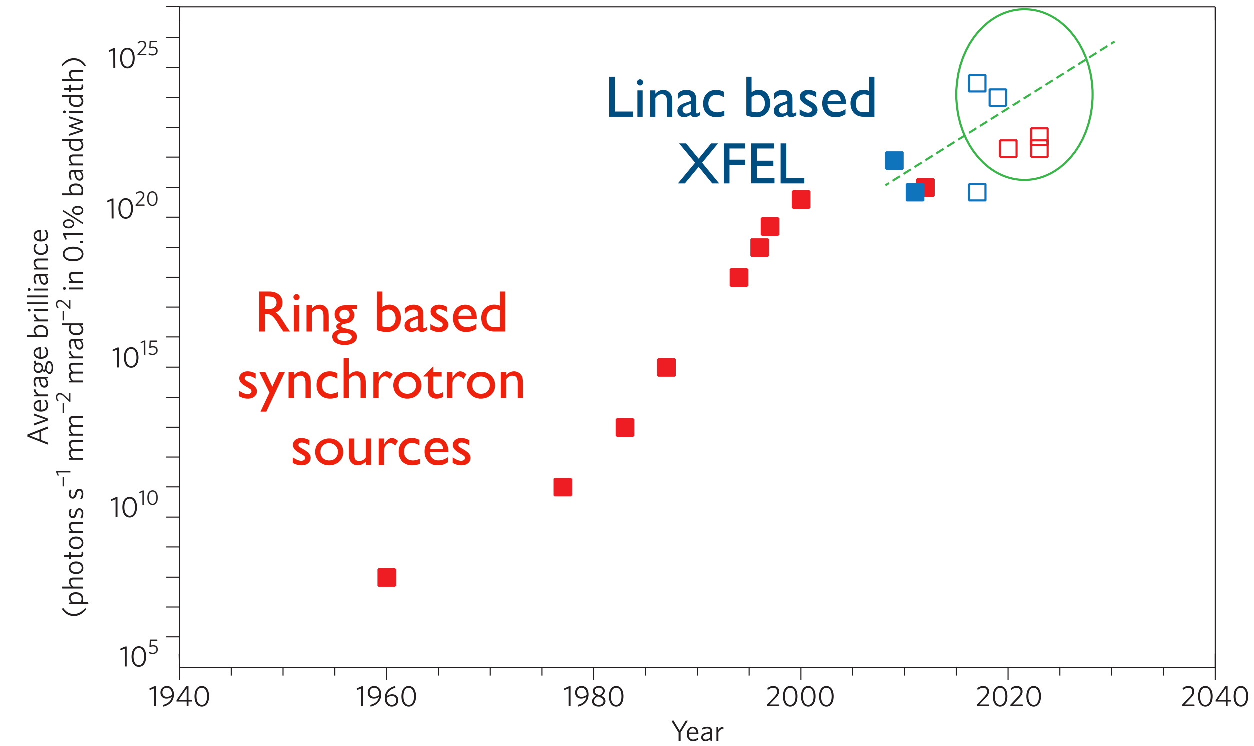




W. Wang et al., 516 | Nature |595, 517 (2021)

Brightness on X FEL and DSLR





Coherence related imaging (Coherent X-ray diffraction imaging, ptychography…)

Nearly circular beam-shape => nano beam flux gain

Nanoresolution combined with chemical, physical, electronic and magnetic properties of complex objects (non destructive)

M. Yabashi, H. Tanaka, .The next ten years of X-ray science, Nature Photonics 11, 12-14 (2017)

Femtosecond XFEL : snapshots of « frozen » objects before destruction (diffract before destruction) applied to tiny, fragile crystals and single particules with very good spatial resolution

Femtosecond XFEL + optical laser (pump for manipulating the internal electronic state/probe) : « molecular movies » (tracking of structure and electronic states)

Ultra-intense X ray beams : X-ray non linear optics under extreme conditions