Ultrafast synchrotron x-ray radiation from laser systems

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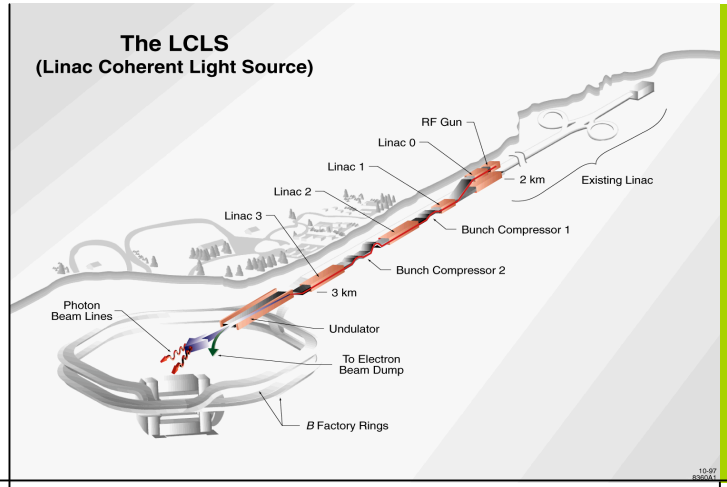
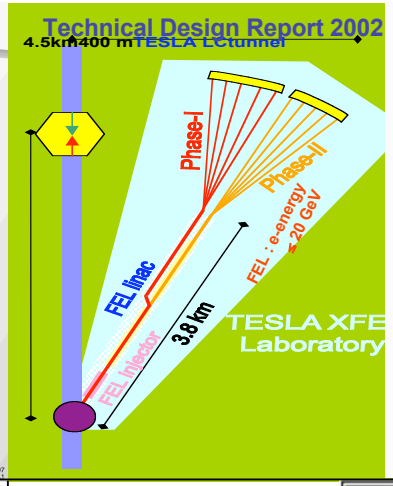
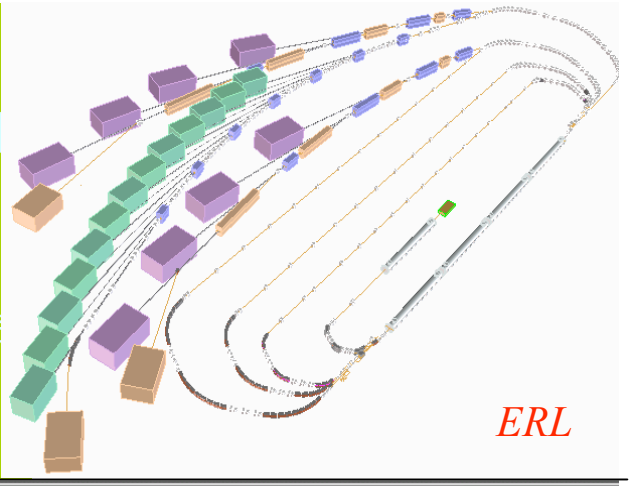
http://loa.ensta.fr/pxf

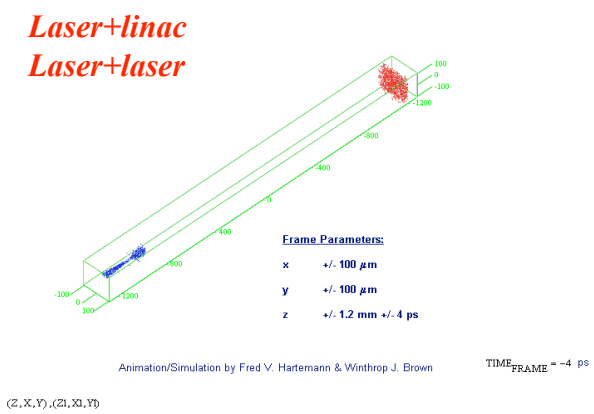
FEL / ERL SPPS



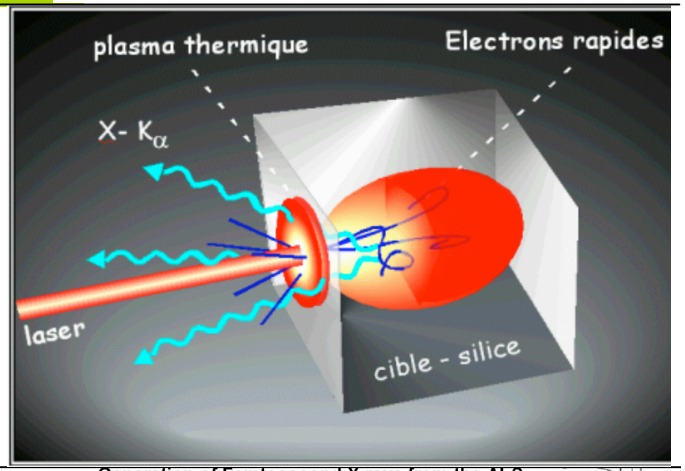




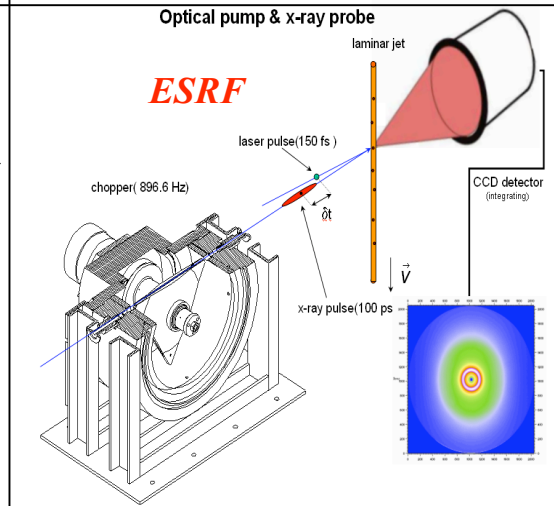
Laser + LINAC

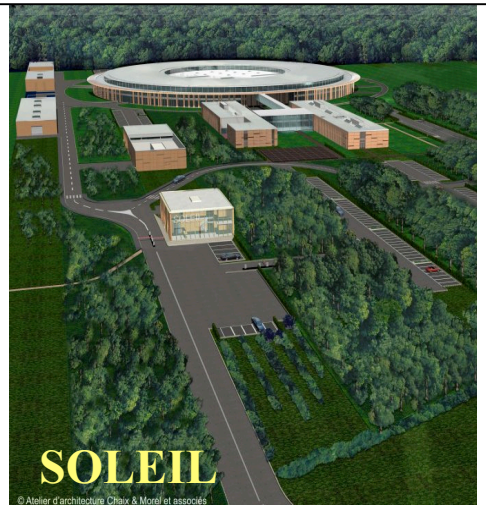


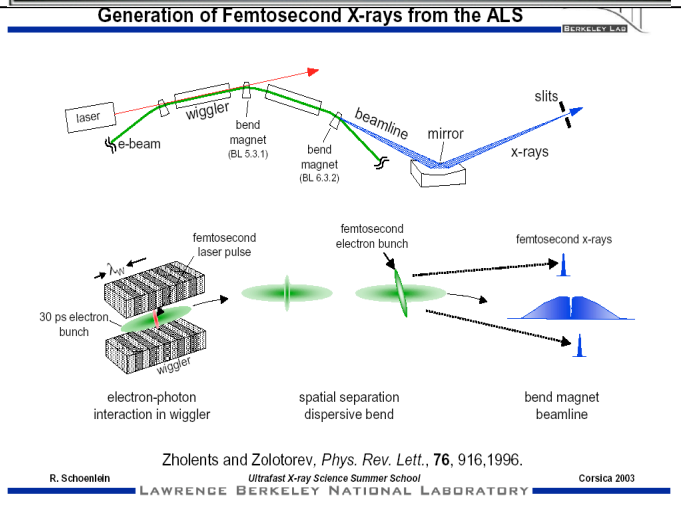
Laser



Synchrotron







What's going on

in the laser-produced plasma field ?

State of the art in the laser field (keV x-rays)

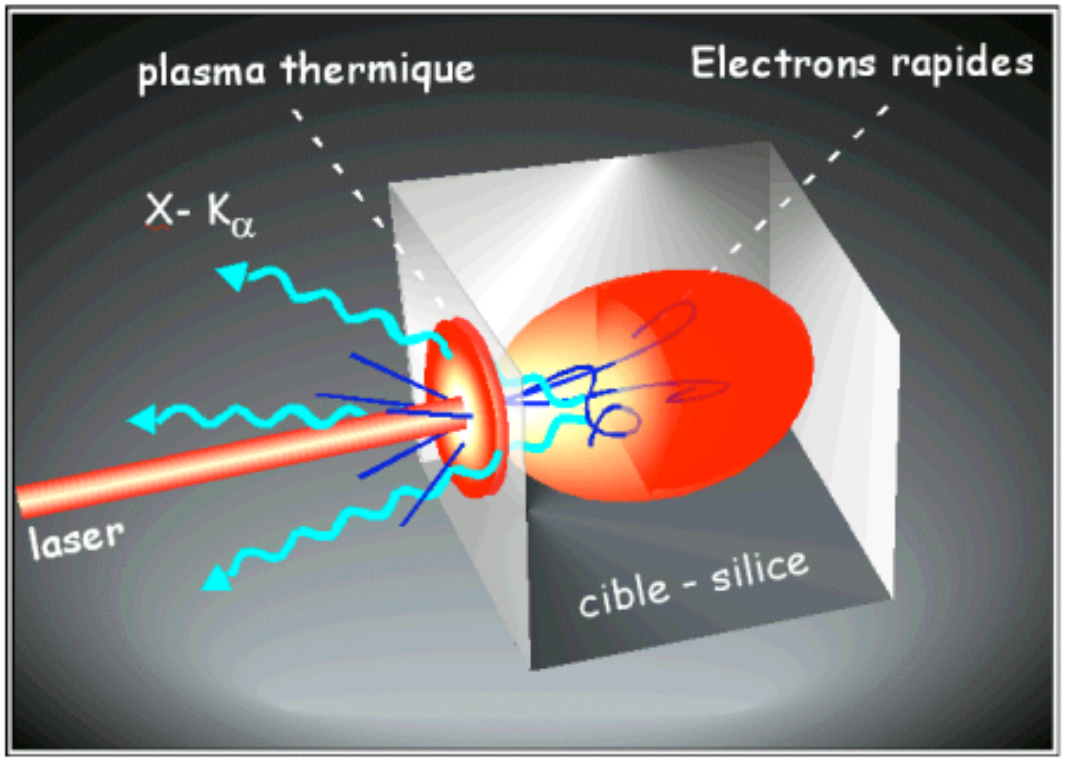
The K_α ultrafast x-ray source

Monochromatic
1 - 8 keV

Fully divergent

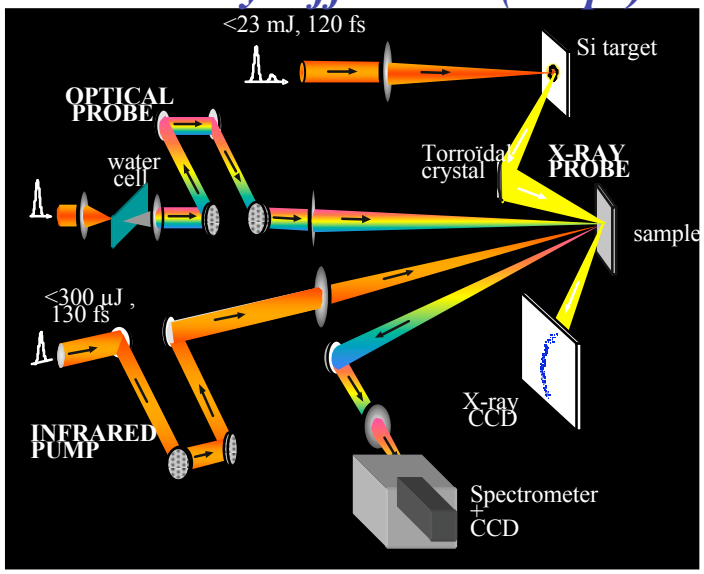
Duration 100 fs

Flux: 10^9 ph/shot/str



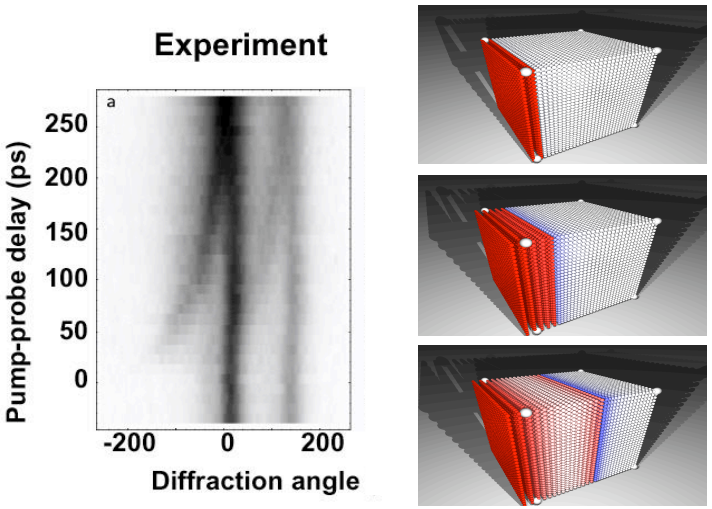
A. Rousse et al, Phys. Rev. E 50 (3) 2200 (1994)
S. Bastiani et al, Phys. Rev. E (1996)

Fs X-ray diffraction (0.1 ps)



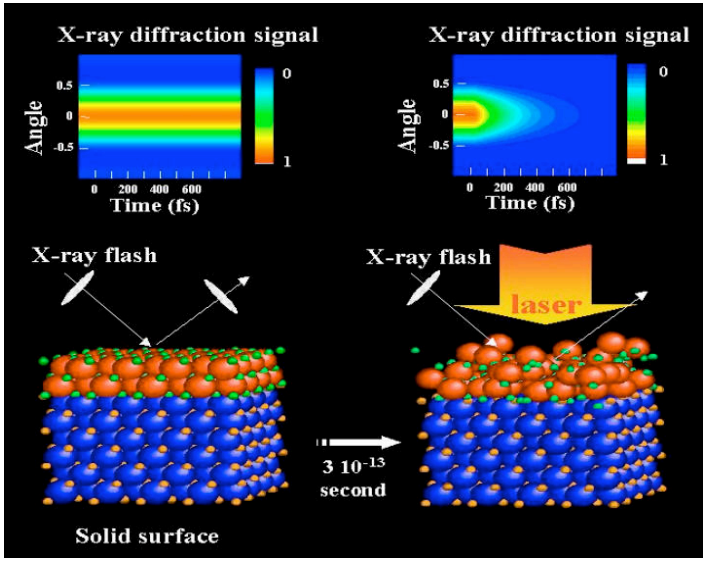
C. Rischel et al, Nature 1997

Strain (10 ps)



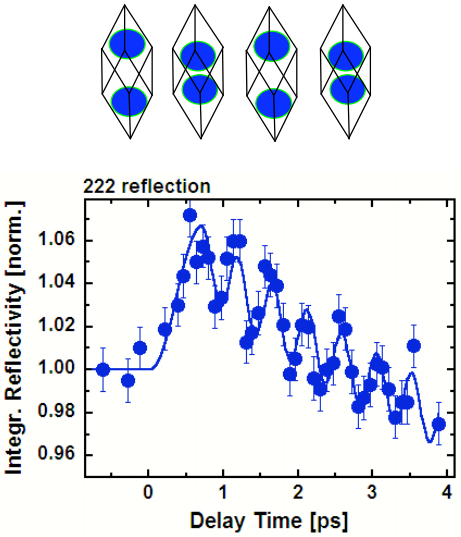
Rose-Petruck et al, Nature'1999

Solid-liquid phase transition (0.1 ps)



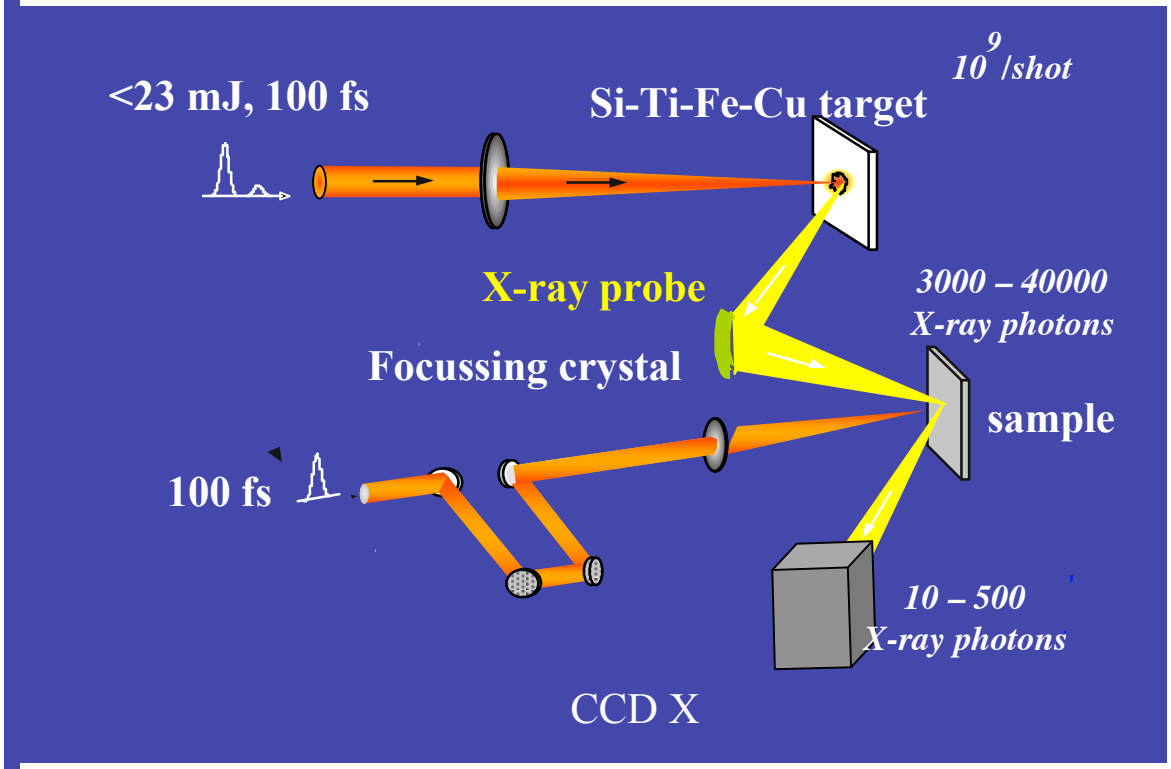
A. Rousse et al, Nature 2001

Optical phonons (0.1 ps)



K. Sokowlovski-Tinten et al, Nature 2003

Main limitations of the K_α x-ray source



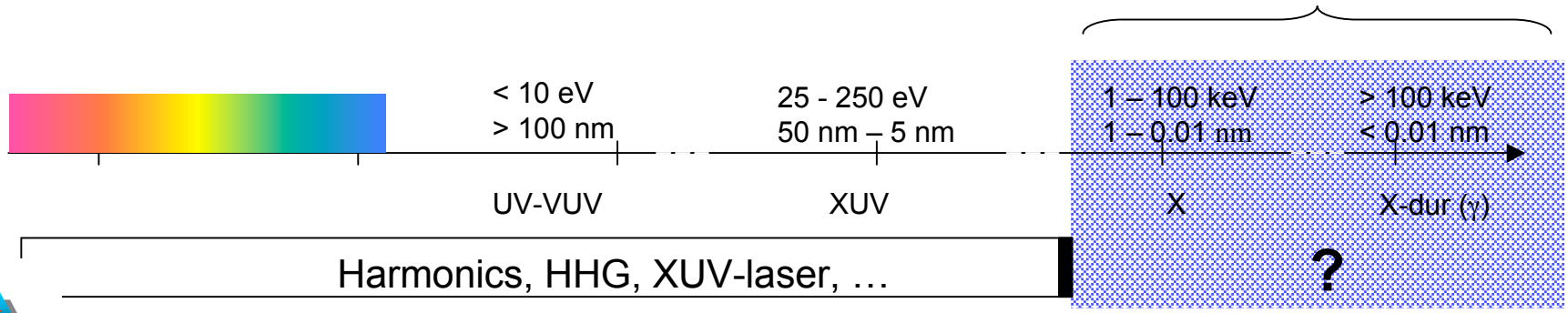
1) tunability

2) polychromaticity

3) Divergence: ☹

A beam of x-rays ?

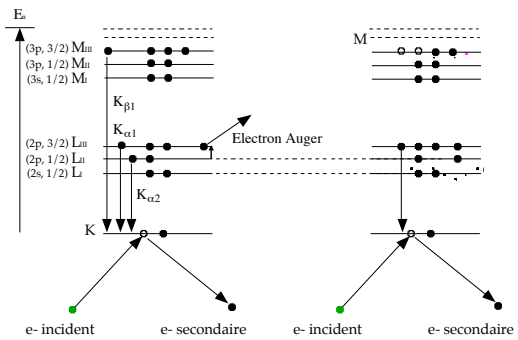
☺



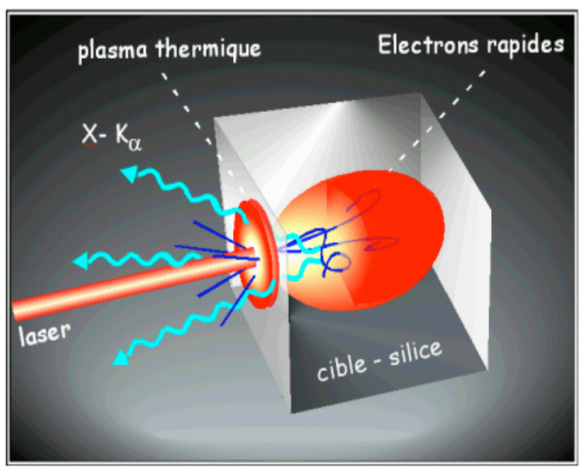
Strategies to generate x-rays

Already used

Atomic transition

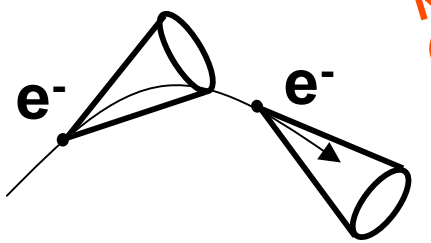


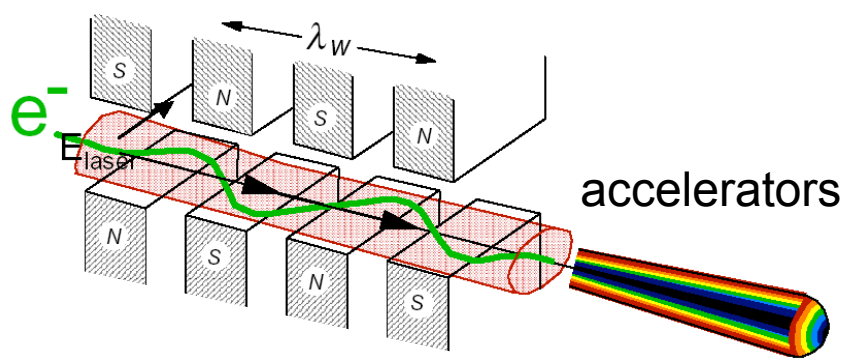
plasma



Charged particule accelerated

Not used until now
(laser-plasma field)





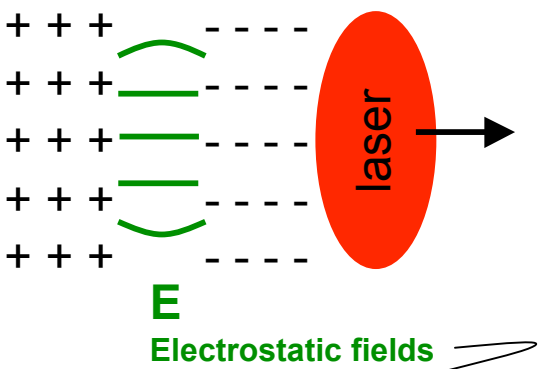
accelerators

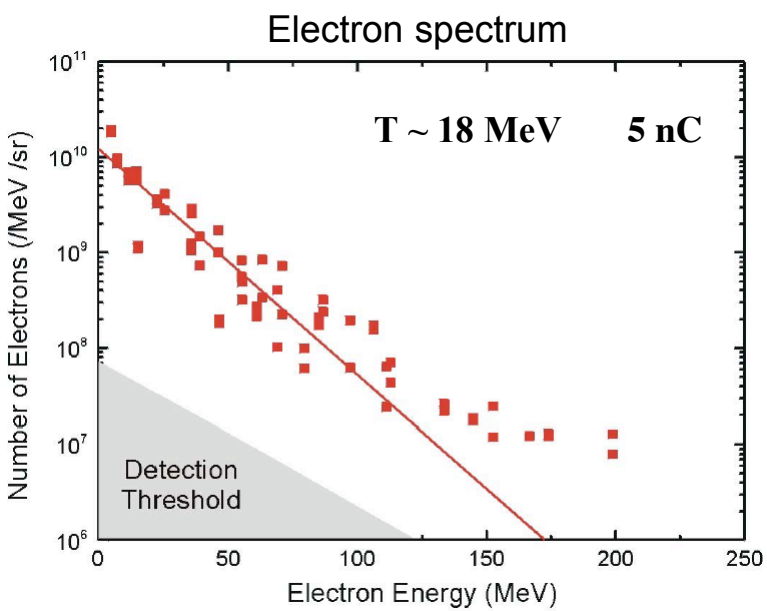
Strategies to generate x-rays

Intense & fs la systems: few joules in 30 fs: I=10^{20} W/cm^2

Relativistic intensities

Energetic particles accelerated





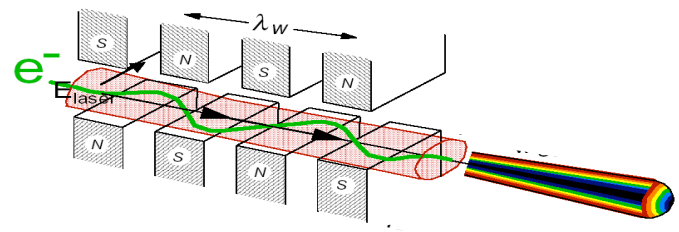
for 1 % Density Perturbation at 10^{17} cm^{-3} : 0.3 GV/m

for 100 % Density Perturbation at 10^{19} cm^{-3} : 300 GV/m

Strategies to generate x-ray beams

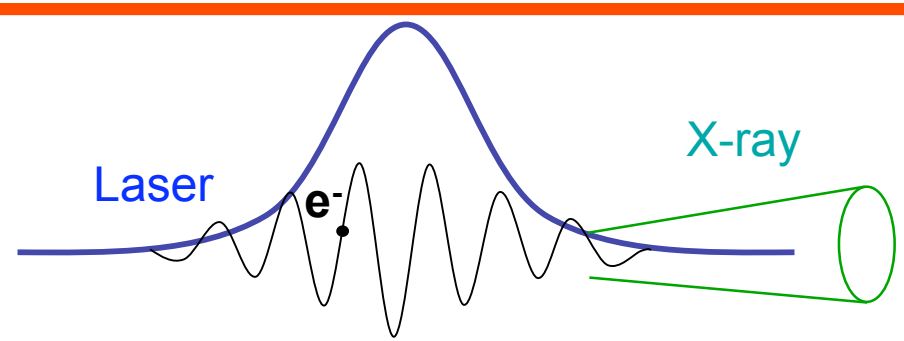
Synchrotron wiggler

X-ray beam : $\lambda_X = \lambda_{und} / 2\gamma^2$



Laser wiggler

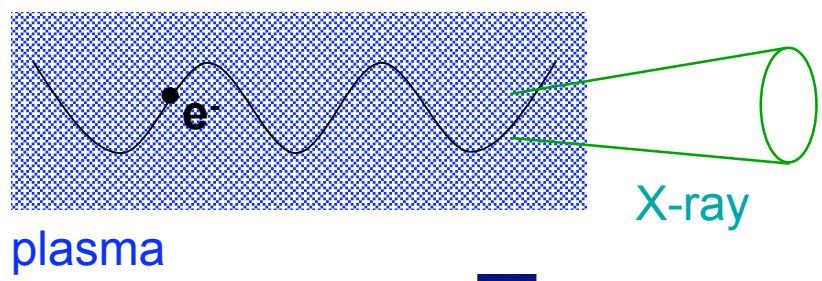
X-ray beam : $\lambda_X = \lambda_{laser} / 2\gamma^2$



γ: jusqu'à 300 MeV
(laser-plasma)

Plasma wiggler

X-ray beam : $\lambda_X = \lambda_{plasma} / 2\gamma^2$

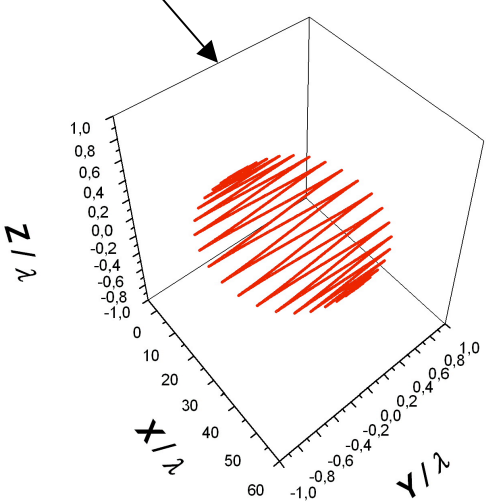


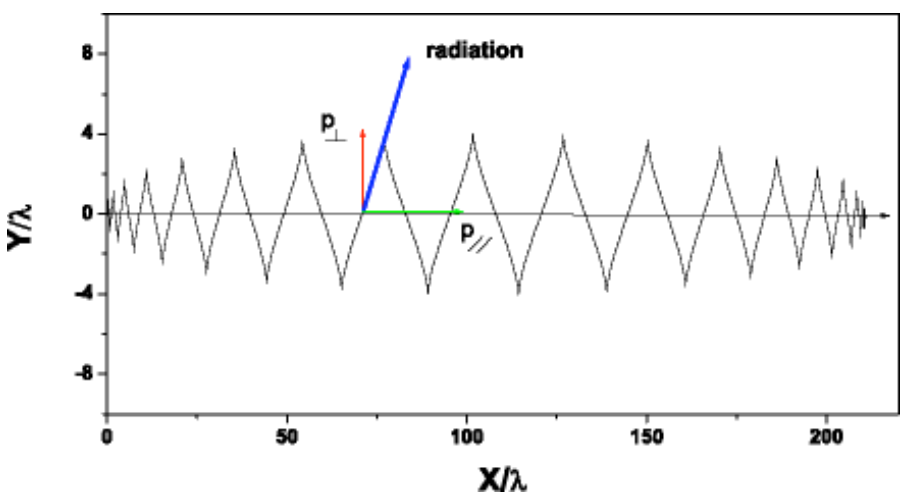
Features of the expected x-ray emission

Trajectories Spatial & spectral distributions

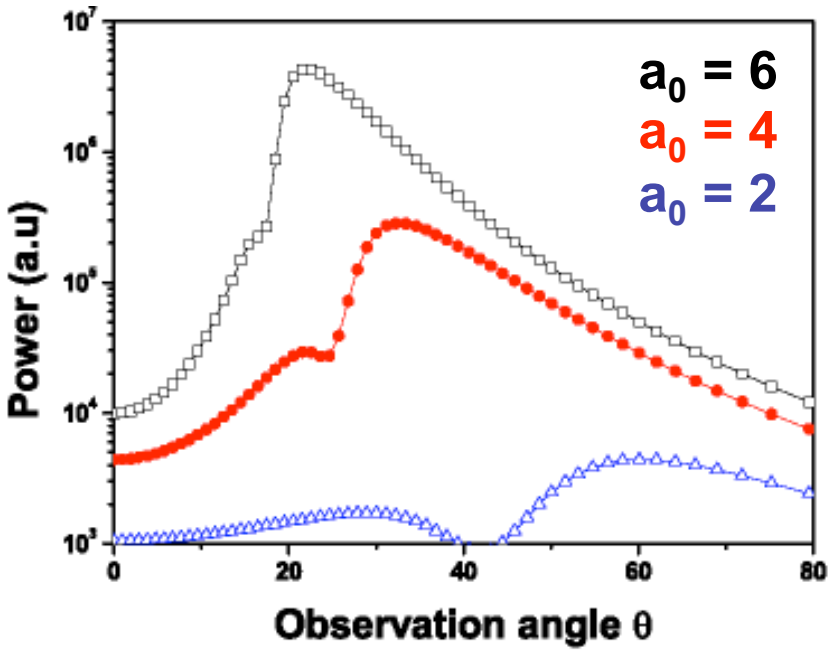
$$\frac{d\vec{p}}{dt} = e\vec{E} + \frac{\vec{v}}{c} \wedge \vec{B}$$

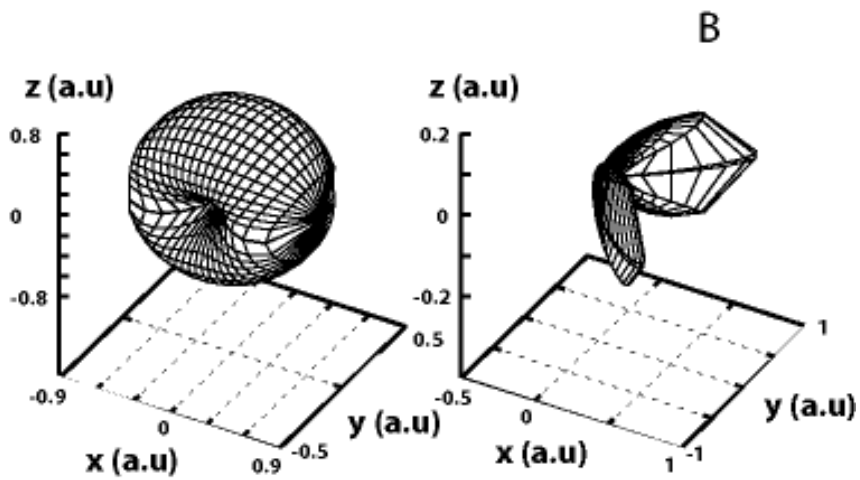
Laser





Spatial distribution





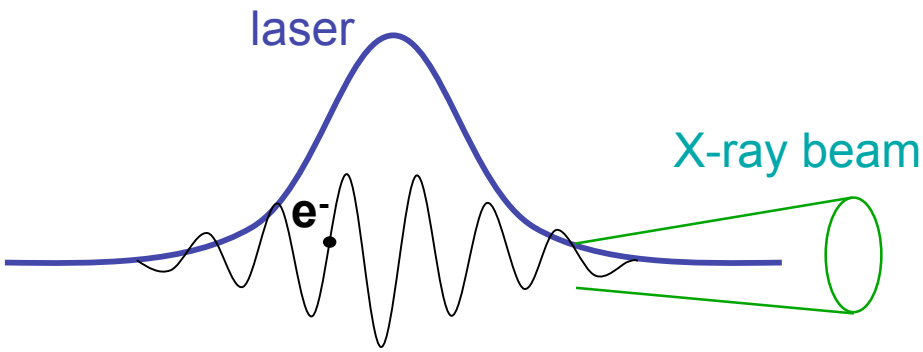
$$a_0 = \frac{eE_0}{m\omega_0 c} = 0.85\left(\frac{I_{W/cm^2}}{10^{18}}\lambda_{\mu m}^2\right)^{\frac{1}{2}}$$

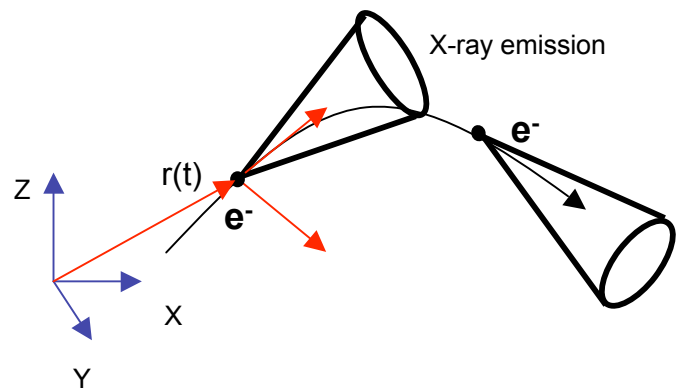
$$\theta \sim 2 / a_0$$

a_o = 5: θ ~ 20 degrees

a_o = 10 : θ ~ 10 degrees

Spectral distribution



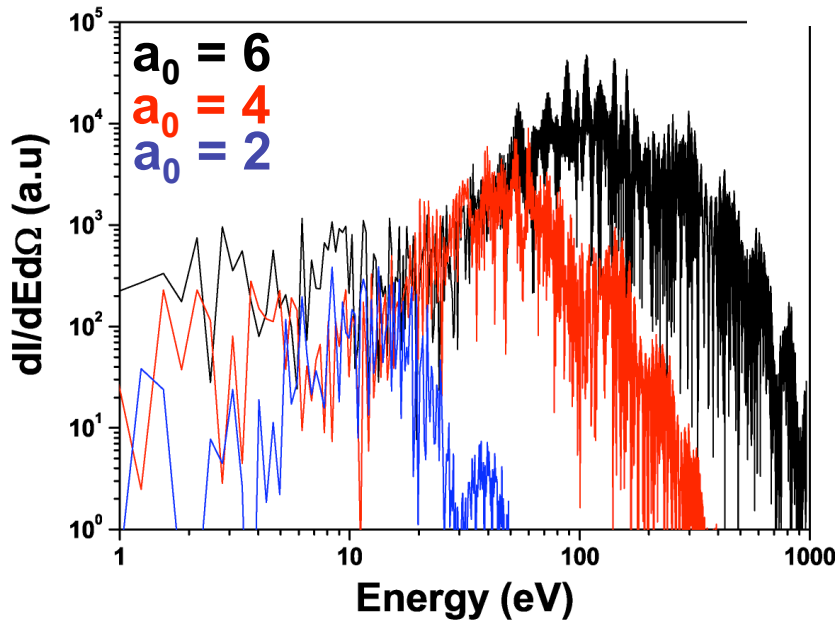


$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{+\infty} e^{i\omega(t-\vec{n}.\vec{r}(t)/c)} \frac{\vec{n}\times\left[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}\right]}{(1-\vec{\beta}.\vec{n})^2} dt\right|^2$$

The produced radiation depends on:

- the electron trajectory (β, $\dot{\beta}$, r)
- the observation angle (n)

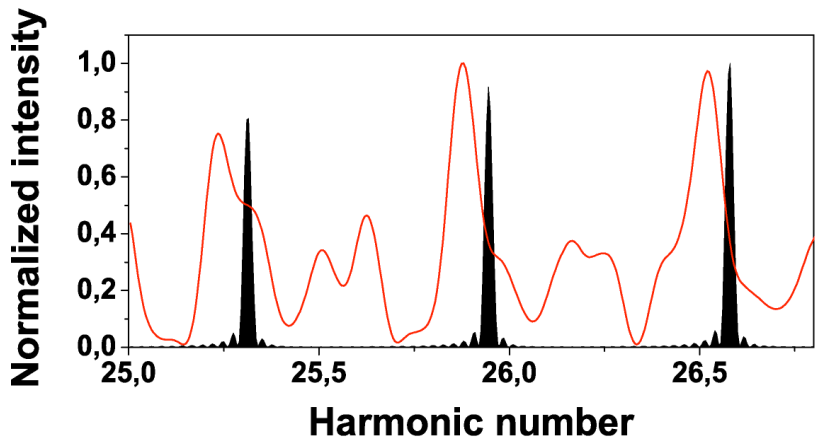
Spectral distribution



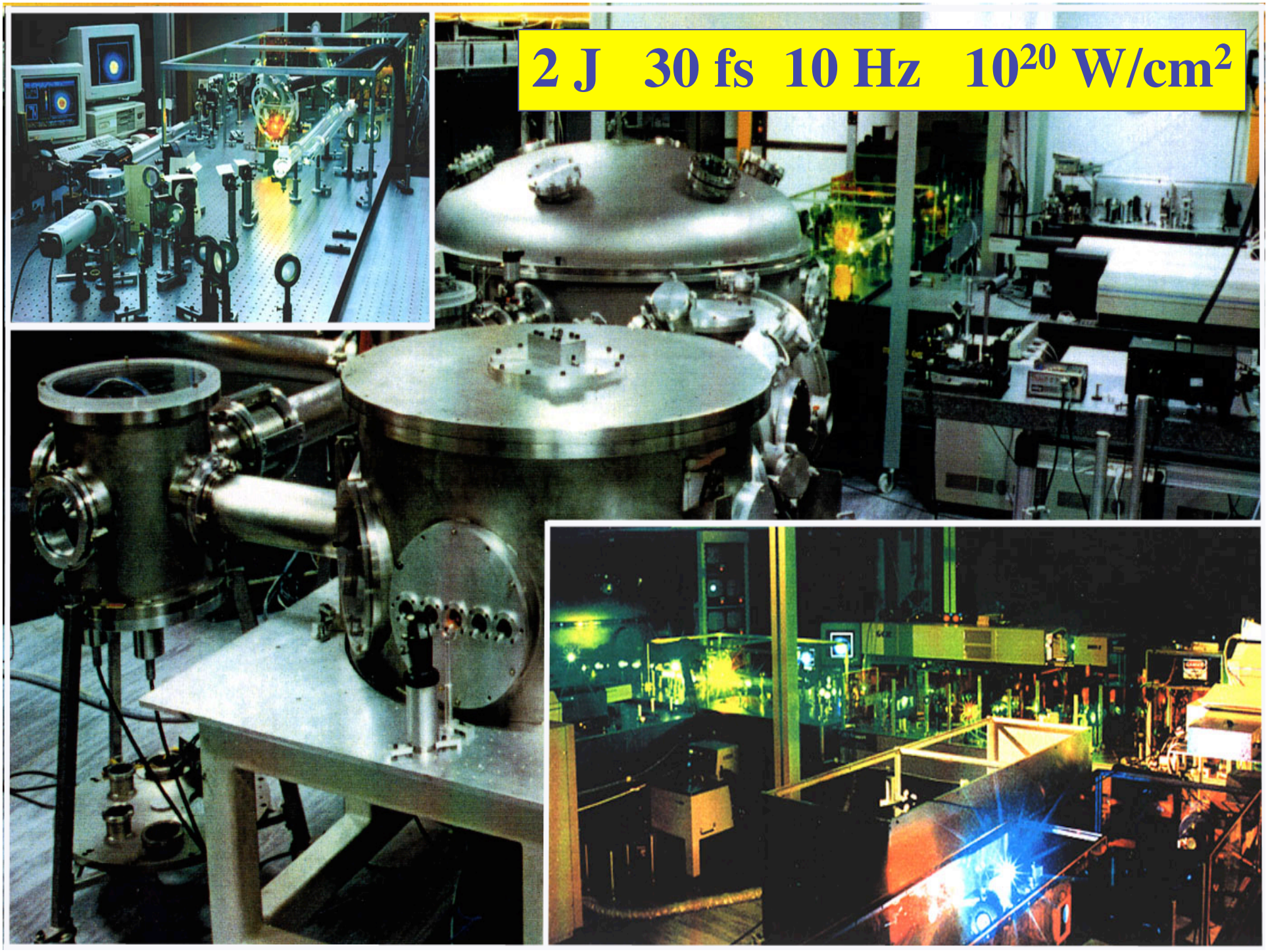
$$E_{X\text{-}ray} \propto a_0^3$$

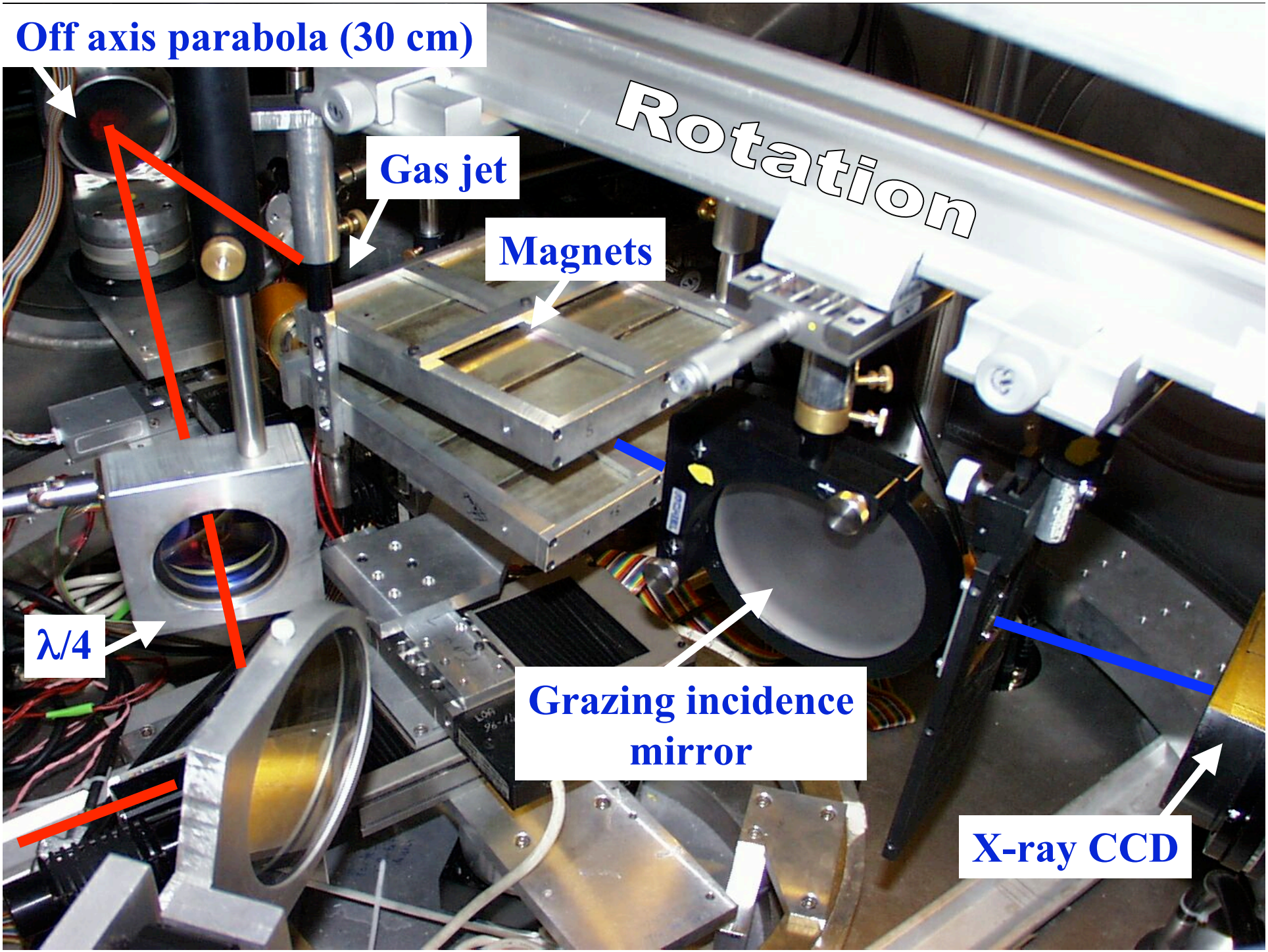
$a_o = 5$: $E \sim 120$ eV

$a_o = 10$: $E \sim 1$ keV

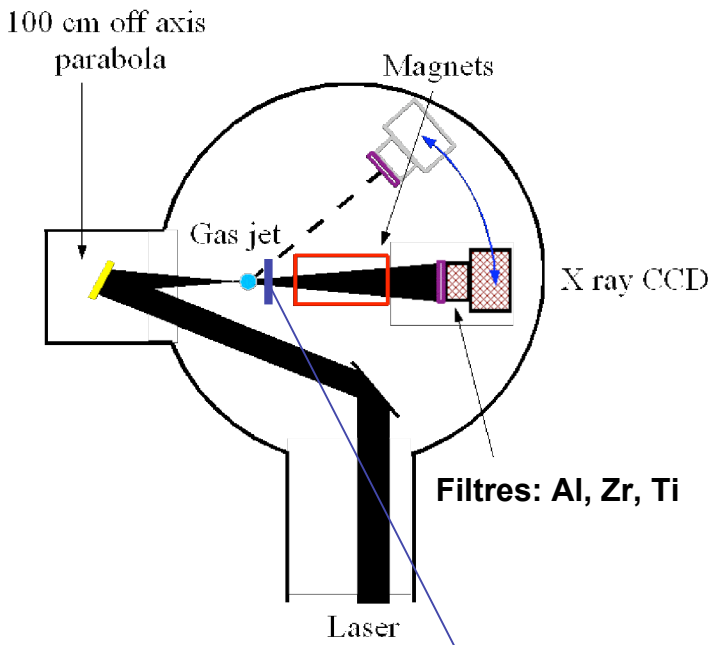


long laser pulse: Harmonics
Short laser pulse: Continuum


2 J 30 fs 10 Hz 10^{20} W/cm^2

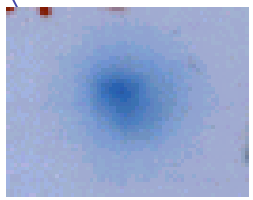

Off axis parabola (30 cm)
Rotation
Gas jet
Magnets
λ/4
Grazing incidence mirror
X-ray CCD

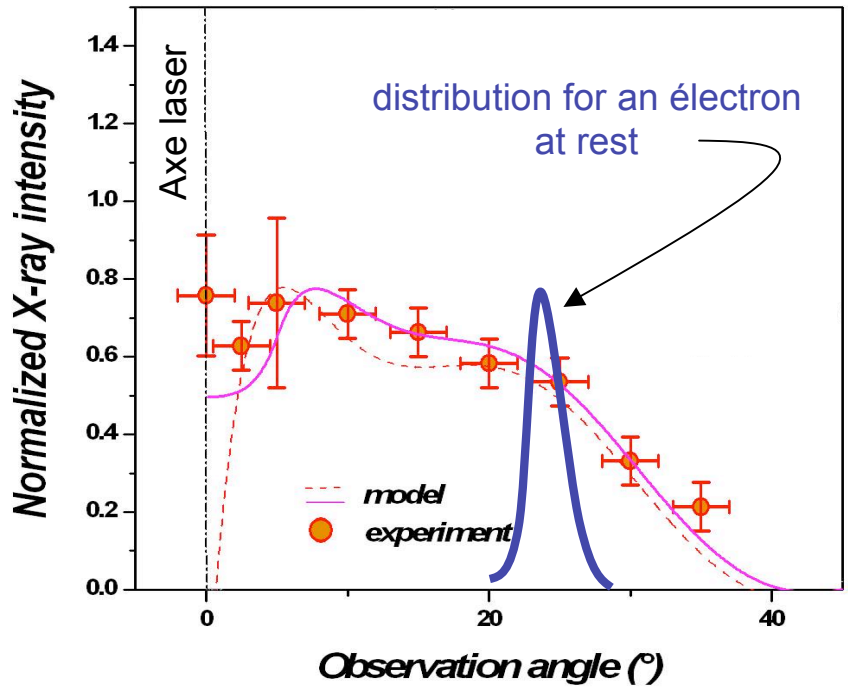
Experimental results: spatial distribution

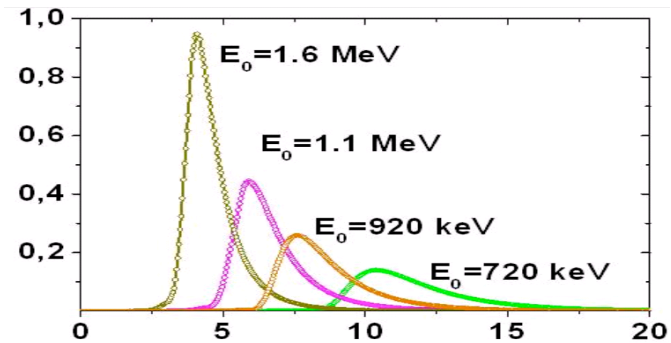


30 TW

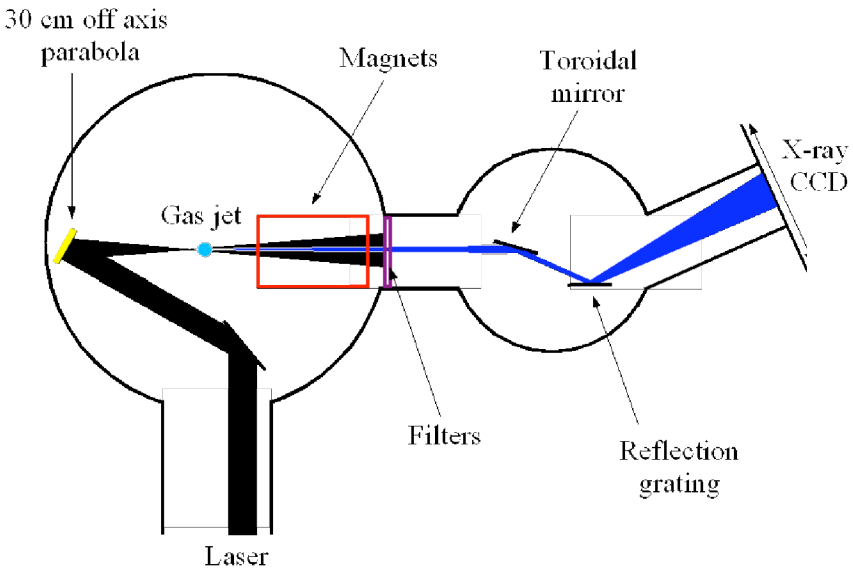
Signature of accelerated electrons



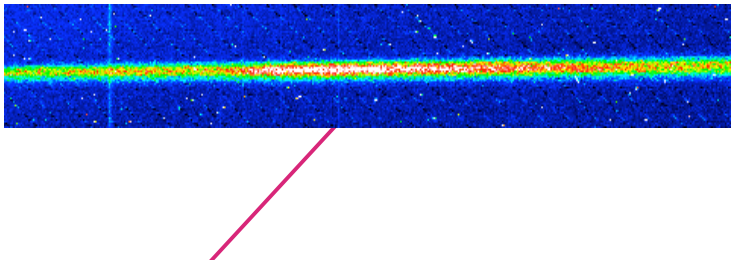


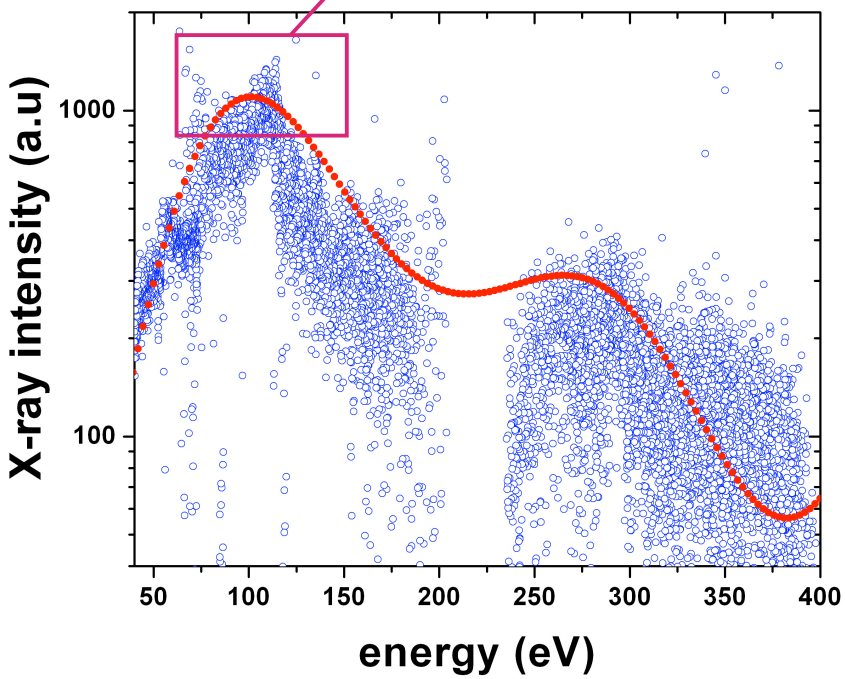


Experimental results: spectrum



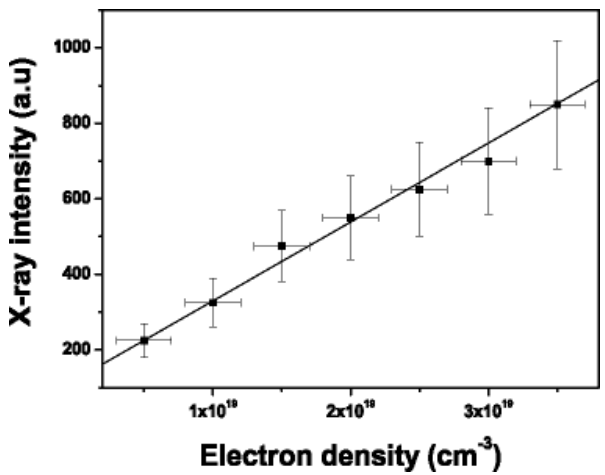
Broad & peaked spectrum

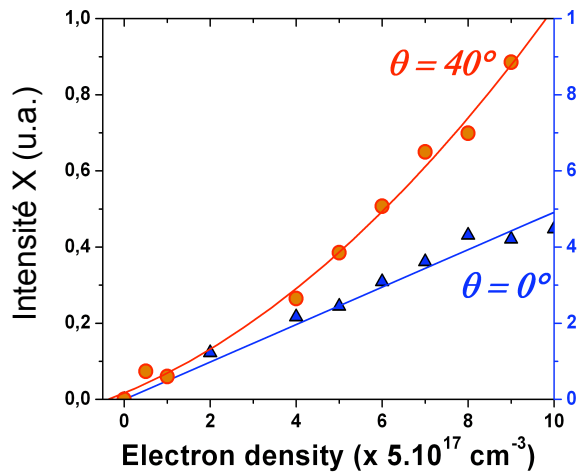


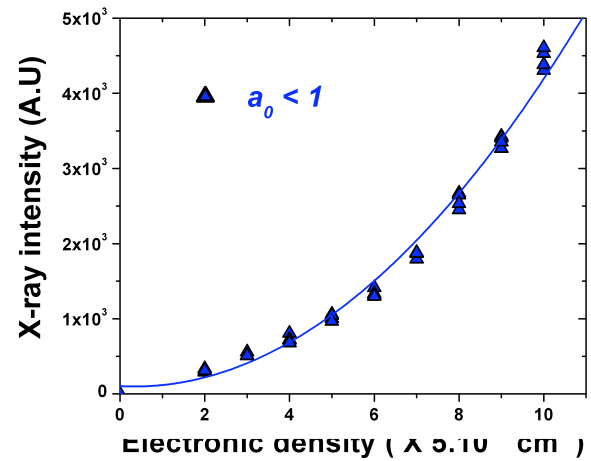


Filters: Al (6000 A)
Zr (4000 A)
Ti (2000 A)

Experimental results







On the laser axis (λ =130 eV)

Off-axis

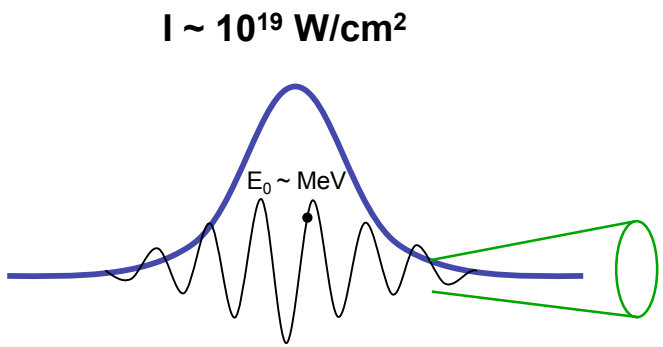
$a_0 < 1$

Laser wiggler
(Diffusion Thomson Non-linéaire)

- Bremsstrahlung
- Radiative recombinaison

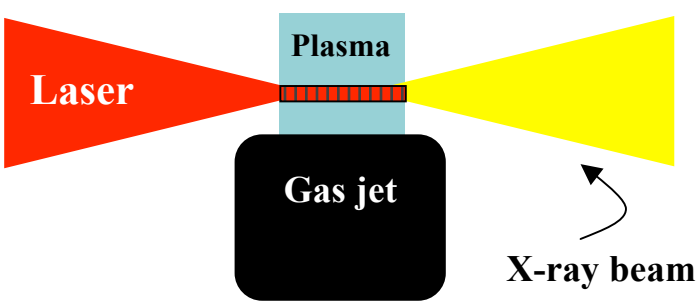
Collisional processes dominant

Conclusion: Laser wiggler



~ 150 eV – broad spectrum
~ 10^{10} photons / shot

~ Divergence: 20°



Next step:

Reach the keV x-ray range

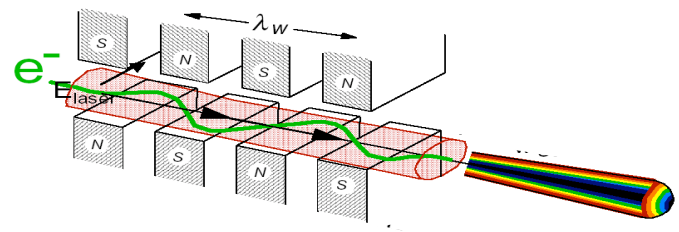
Measurement of the x-ray pulse duration

Phys. Rev. Lett. (2003)

Strategies to generate x-ray beams

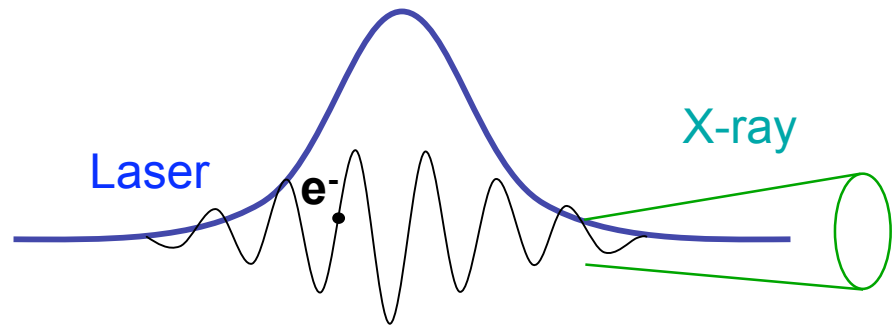
Synchrotron wiggler

X-ray beam : $\lambda_X = \lambda_{und} / 2\gamma^2$



Laser wiggler

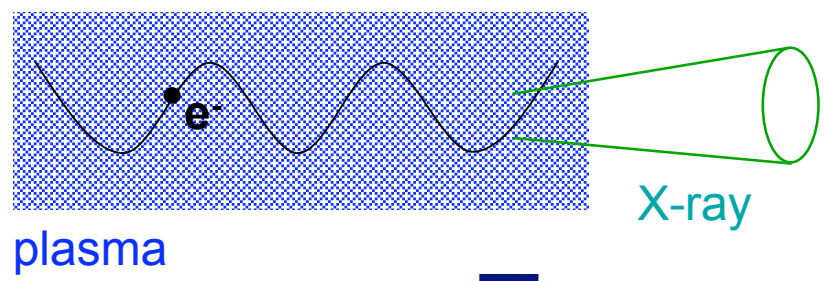
X-ray beam : $\lambda_X = \lambda_{laser} / 2\gamma^2$



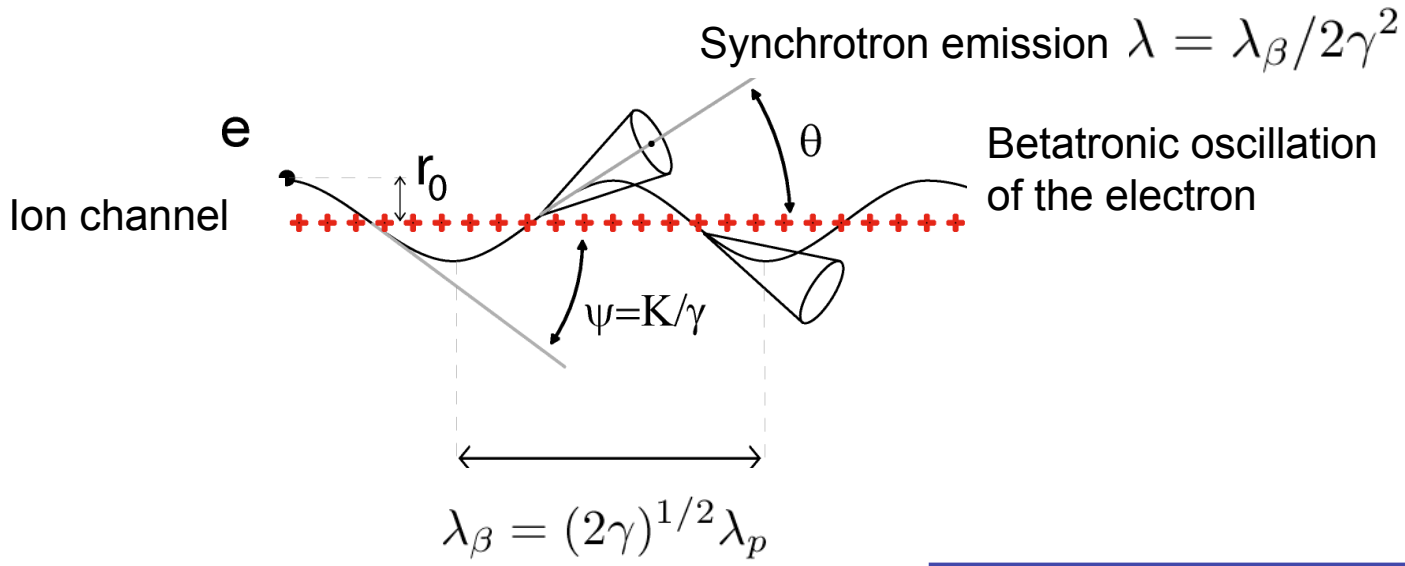
γ: jusqu'à 300 MeV
(laser-plasma)

Plasma wiggler

X-ray beam : $\lambda_X = \lambda_{plasma} / 2\gamma^2$



Betatron oscillations of electrons

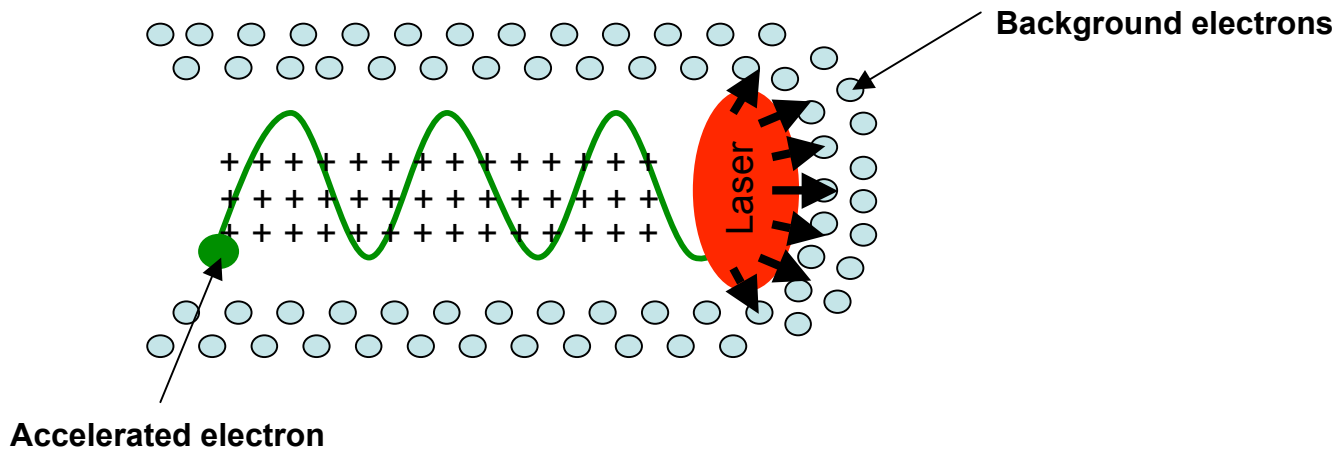


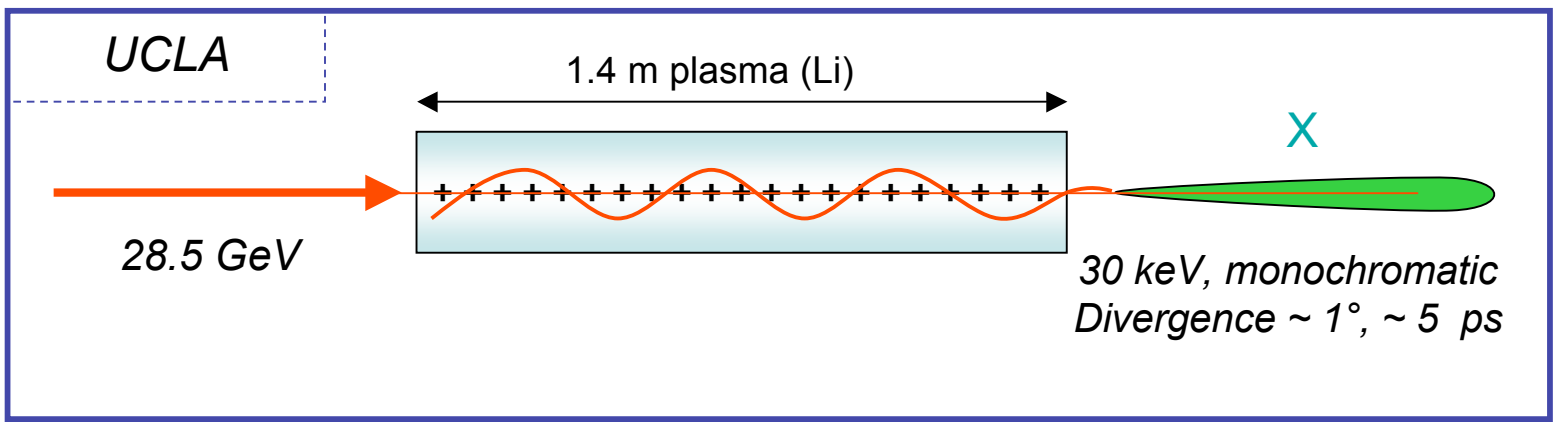
$$\begin{cases} \lambda_\beta = (2\gamma)^{1/2}\lambda_p \\ \lambda = \lambda_\beta/2\gamma^2 \end{cases}$$

$$\boxed{F_{res} = -m\omega_p r_\perp/2}$$

$$\begin{cases} N_\times = 5.6 \times 10^{-3} N_0 K \\ K = 2\pi(\gamma r_0)/\lambda_b = 1.33 \times 10^{-10}\gamma^{0.5} n_e^{0.5}[\mathrm{cm}^{-3}] r_0[\mu\mathrm{m}] \end{cases}$$

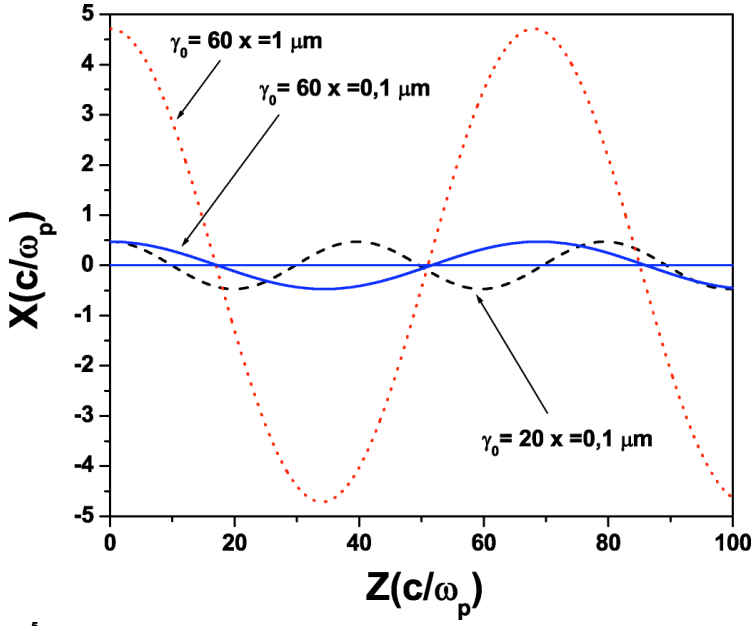
How to make betatron with a laser ?

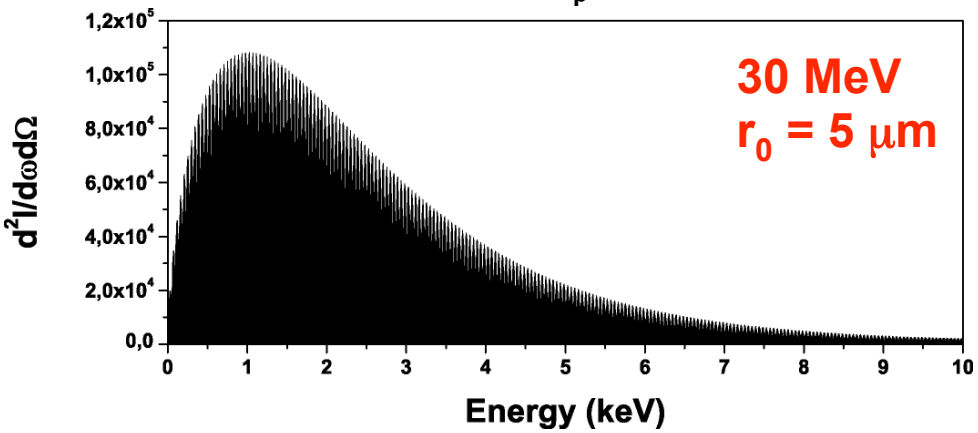




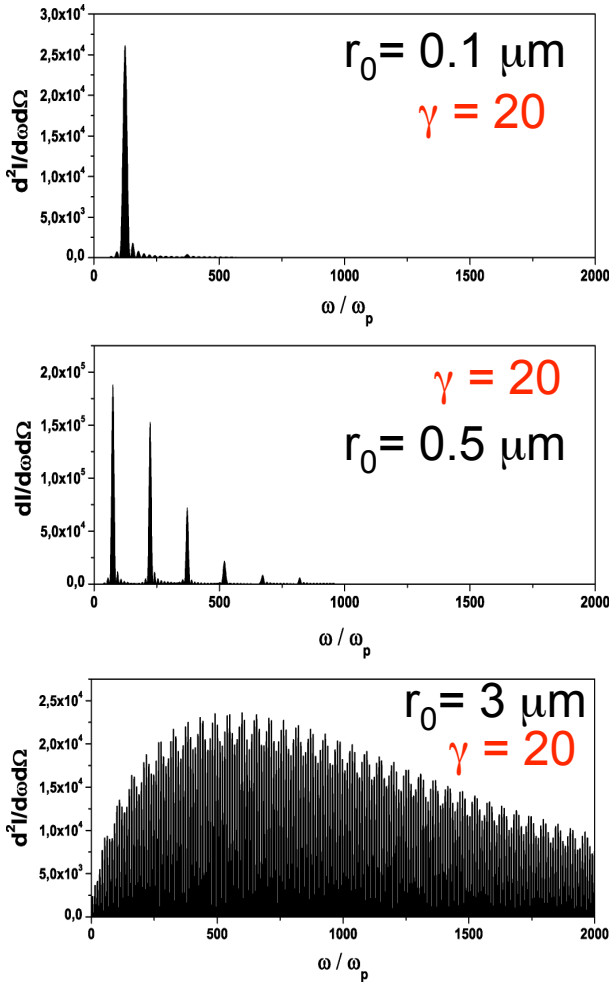
Betatron oscillations of electrons

Betatron oscillation



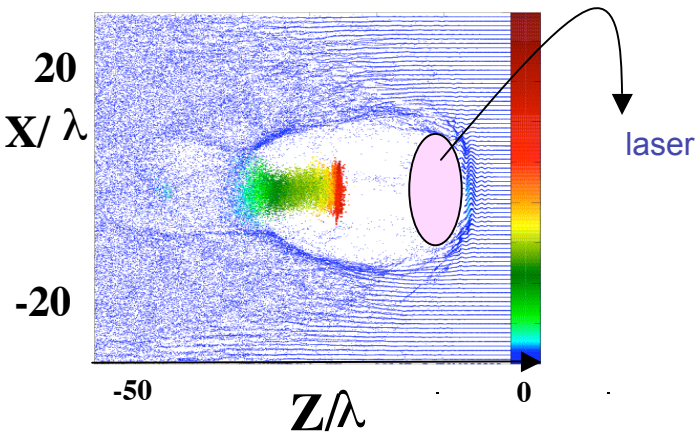


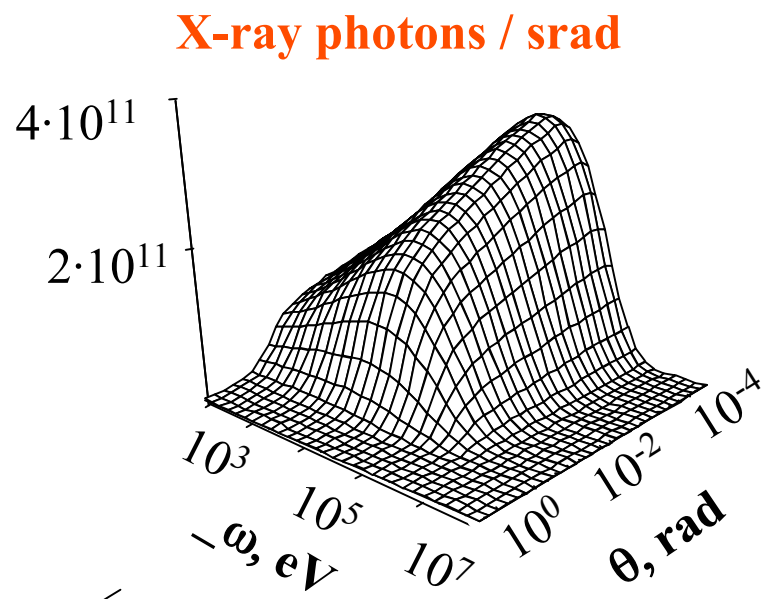
Emission spectrum



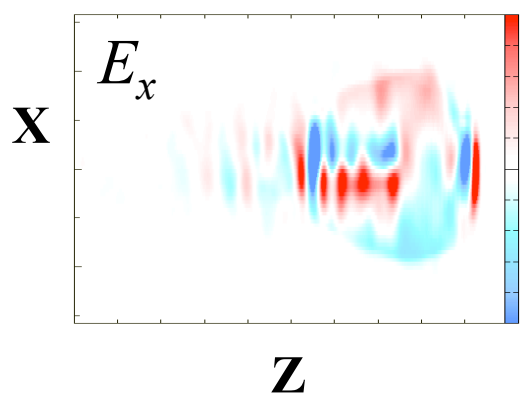
10^8 ph @ 2 keV, divergence: 50 mrad

The betatron x-ray source: how to do this with a laser ?

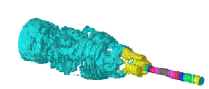




Transverse fields



Few keV
polychromatic
Divergence ~ 40 mrad
Duration~ 50 fs



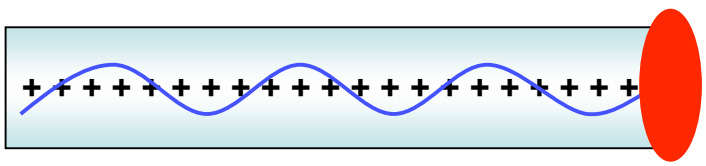
VLPL

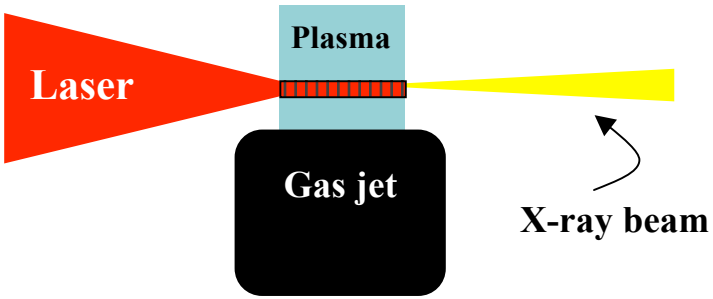
Betatron x-ray source: conclusion

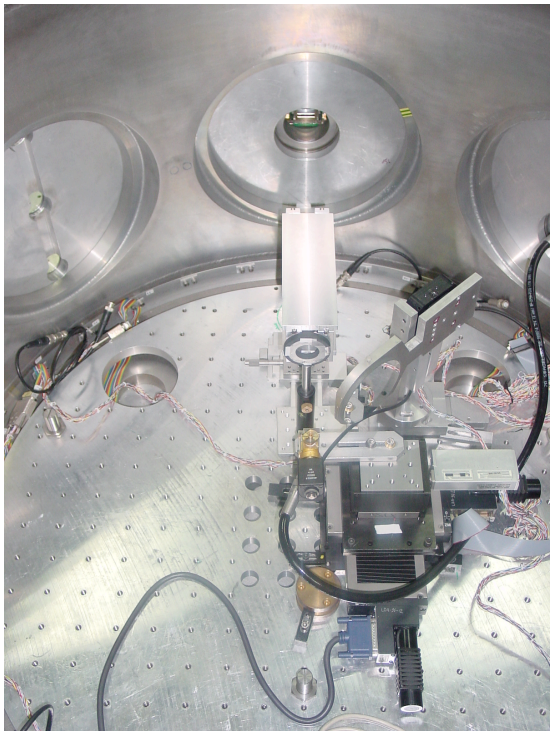
~ few keV - Polychromatic
~ 10^8 photons / shot

~ Divergence: 50 mrad

I ~ 10^{18} W/cm^2



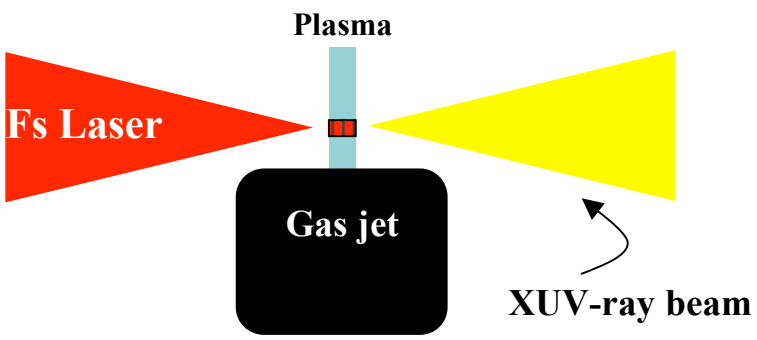




Compact
& « simple »

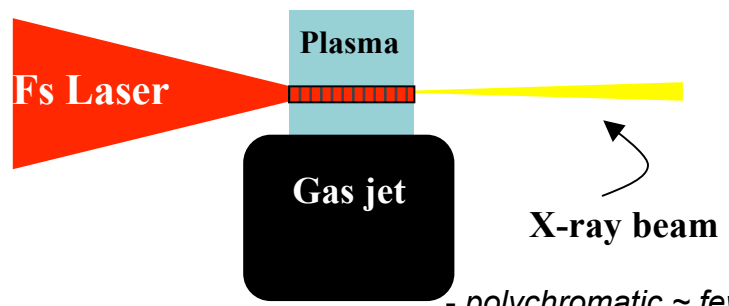
Conclusion: new generation of fs x-ray sources

1) Laser wiggler



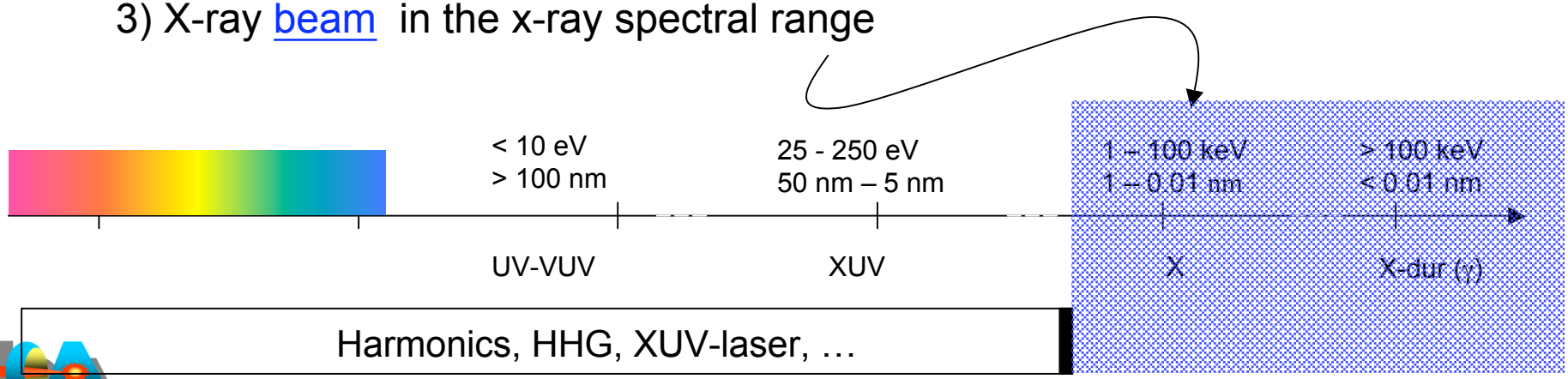
~ 150 eV – broadband
~ 20 degrees divergence
~ 10^{10} photons / shot
Femtosecond
(to be measured)

2) Plasma wiggler



- polychromatic ~ few keV
- collimated ~ 50 mrad
- 10^8 photons / shot
- short duration ~ 30 fs

3) X-ray beam in the x-ray spectral range



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