



FemtoPhysique

Emmanuel ROSENCHER PHY 569 C

A: Impulsions ultra-courtes

A travers les ans
Bloquage de modes

B: Blocage actif

Équation des modes couplés
Impulsions gaussiennes

C: Blocage passif

Absorbants saturables
Equations de Siegmann-Hauss
Impulsions sécantes
Solitons

D: Caractérisation des impulsions

Autocorrélation
FROG

E: Physique avec des impulsions ultra-courtes

Contrôle cohérent
Génération d'harmoniques
élevées (UV, X)
Lidar TeraWatt
Impulsions relativistes
Accélération de particules

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Université Bordeaux I, FRANCE

CEA-DAM/LMJ

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Krausz¹**

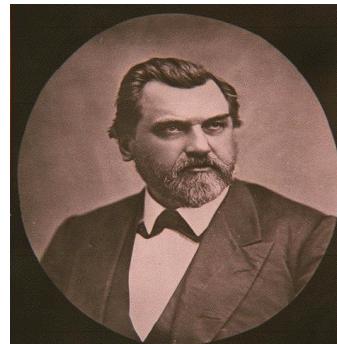
¹Institut für Photonik, Technische Universität Wien, AUSTRIA

**²Fakultät für Physik, Universität Bielefeld,
GERMANY**

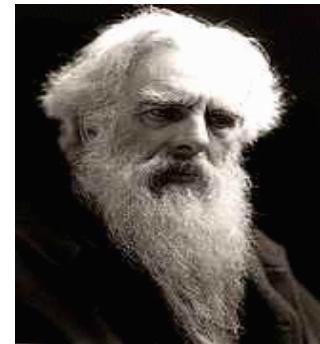


Naissance des technologies ultra-rapides

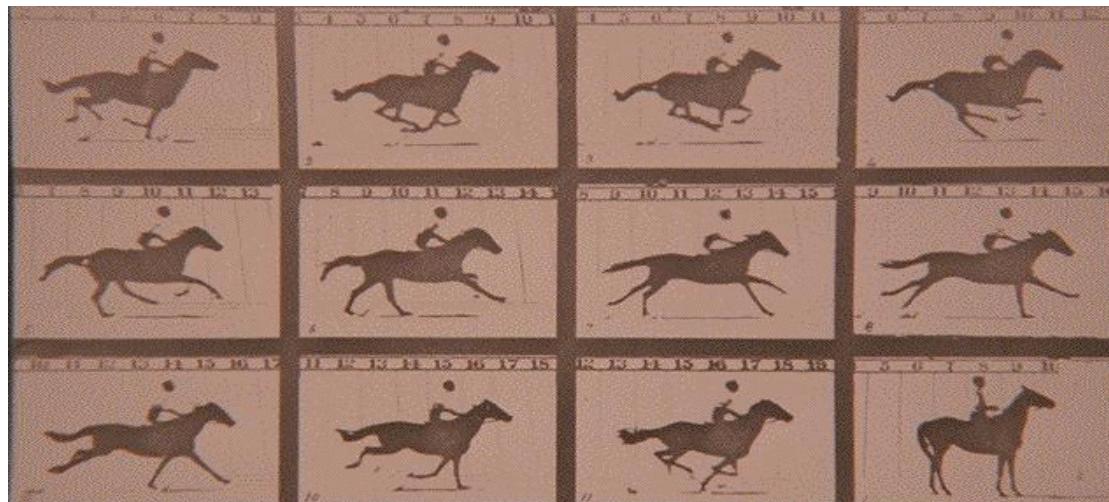
Pari: Les 4 sabots d'un cheval peuvent-ils quitter le sol simultanément ?



Leland Stanford



Eadweard Muybridge



The "Trotting Horse"
Controversy
Palo Alto, CA 1872

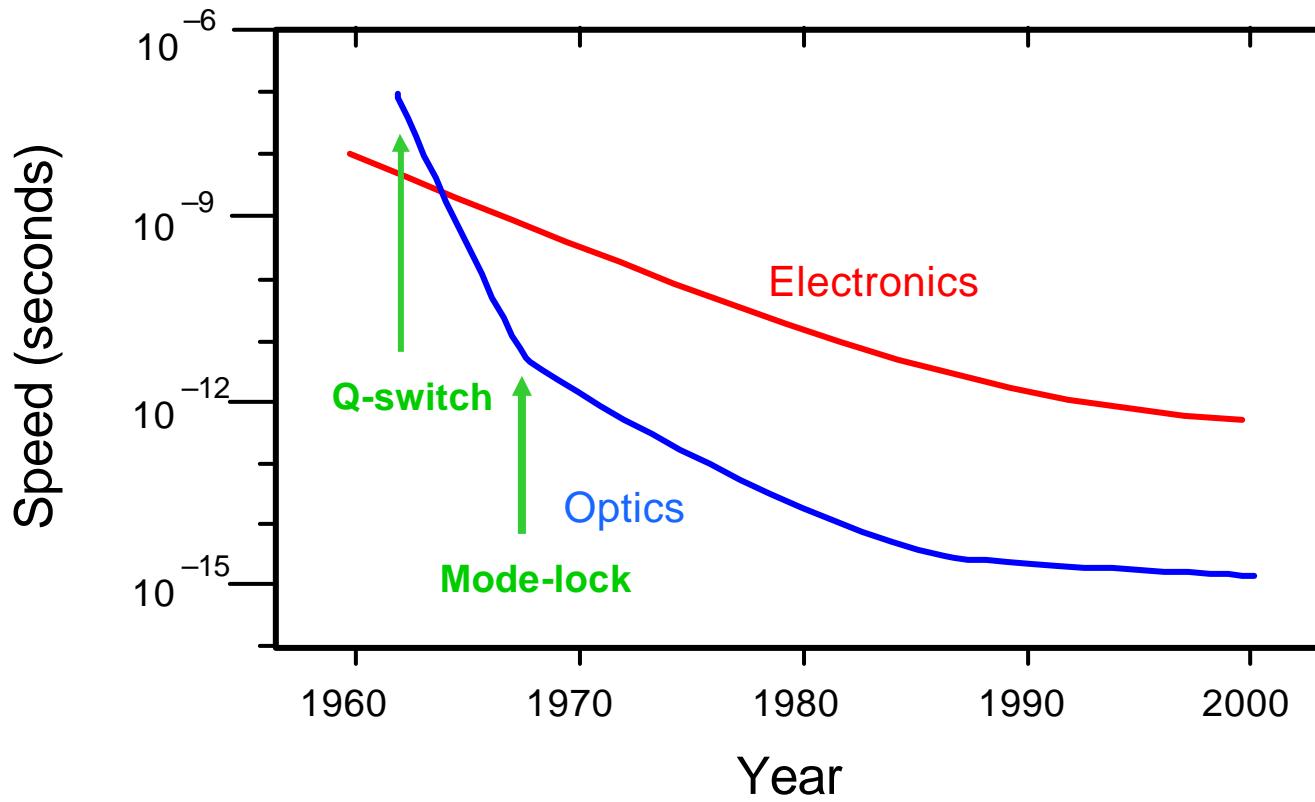
Résolution temporelle:
1/60eme de seconde

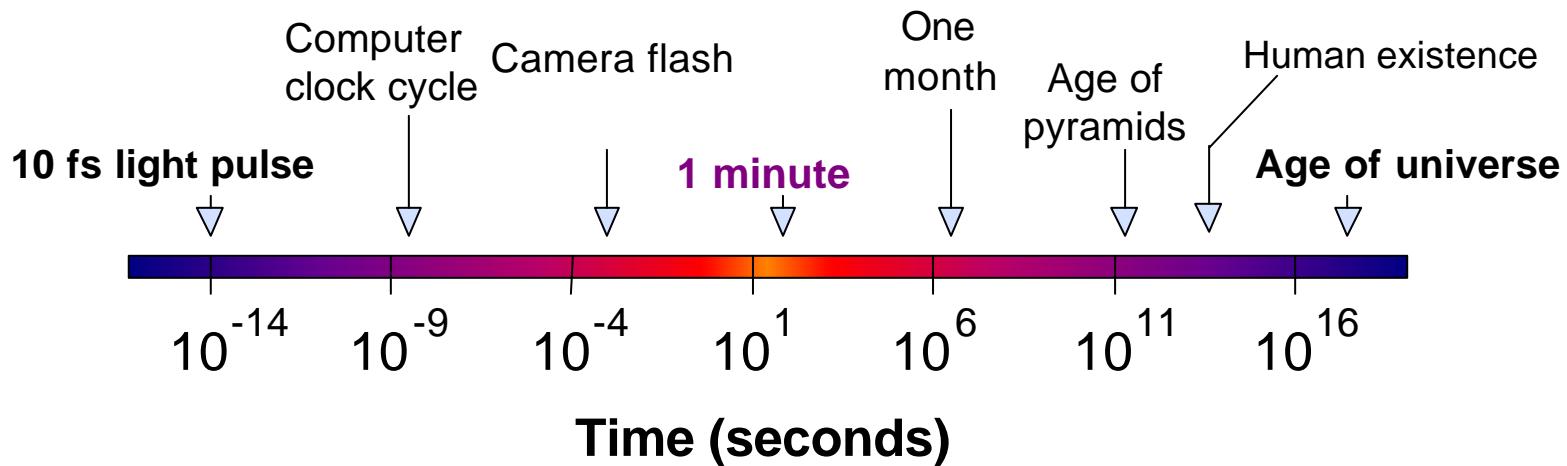
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378 Thanks Trebino



Ultra-rapide: Optique vs. Electronique





FEW APHORISMS...

10 fs is to 1 minute as 1 minute is to the age of the universe.

Alternatively, 10 fs is to 1 sec as 5 cents is to the US national debt.

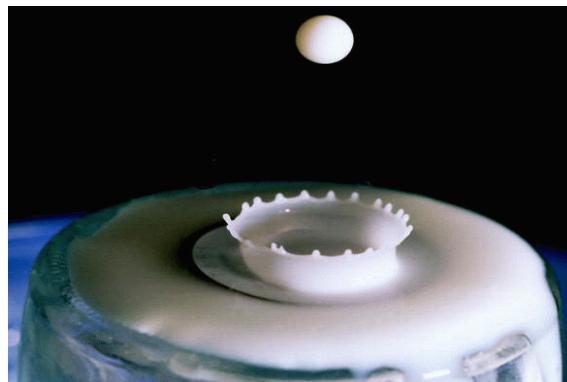
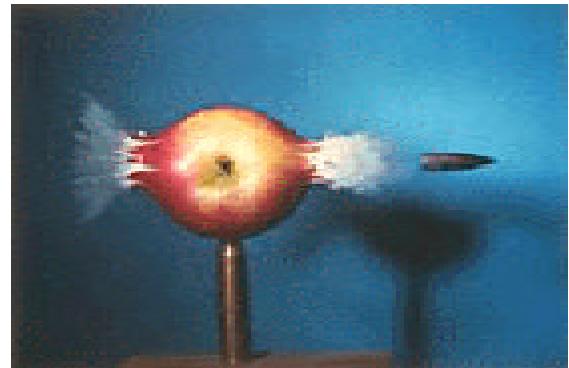


'Doc' Edgerton - Strobe Photography



Harold
Edgerton
MIT, 1942

"How to Make
Apple sauce
at MIT"
1964

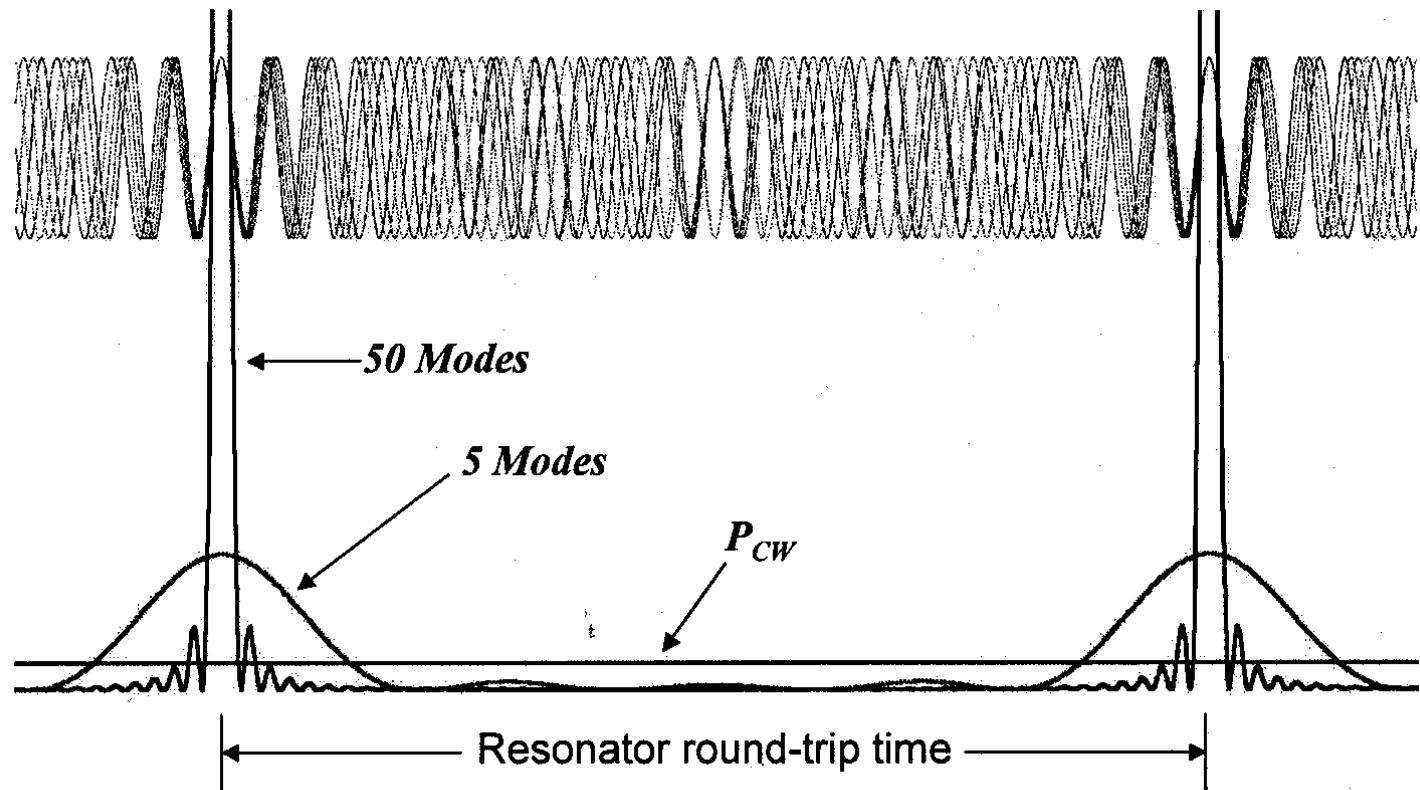


"Splash on a
Glass"
Curtis Hurley
Junior High
School student
1996

Time Resolution: a few microseconds



Blocage de modes: principe du verrouillage de phase

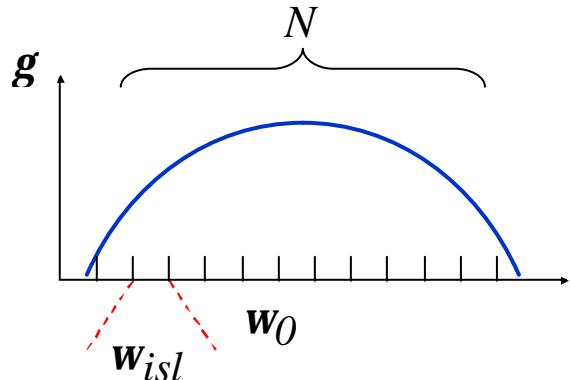


M. Didomenico, J. Appl. Phys. Lett. 35, 2870 (1964); L. Hargrove *et al.*, Appl. Phys. Lett 5, 4 (1964)

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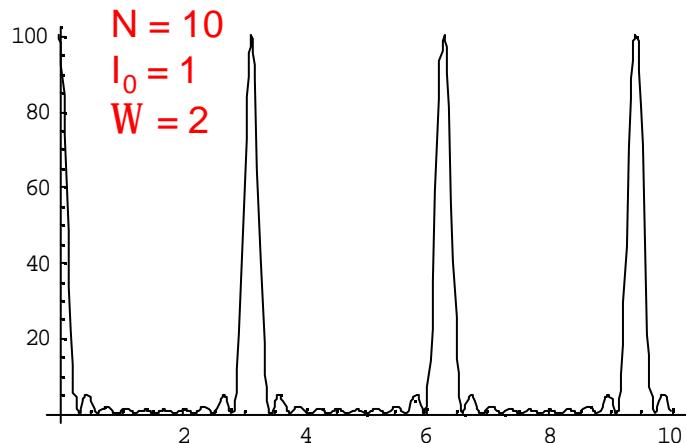
Blocage de modes: principe du verrouillage de phase



$$E(t) = E_0 \frac{e^{i w_{isl} N t} - 1}{e^{i w_{isl} t} - 1} e^{i w_0 t} \quad \rightarrow$$

$$E(t) = \sum_{n=0}^{N-1} E_0 e^{i(w_0 + n w_{isl})t}$$

$$I(t) = I_0 \frac{\sin^2(N w_{isl} t / 2)}{\sin^2(w_{isl} t / 2)}$$



Maximum: $I_{\max} = N^2 I_0$

Période: $T = \frac{2\pi}{w_{isl}} = \frac{2L}{c}$

Durée: $\Delta T = T / N$

Intensité moyenne: $I_{\max} \frac{\Delta T}{T} = NI_0$



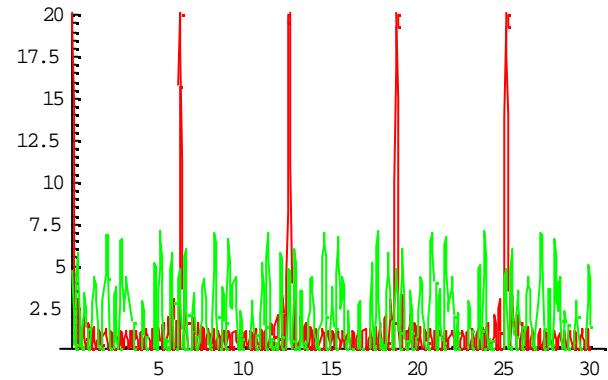
Blocage de mode: principe du verrouillage de phase

$$\sum_n E e^{in\mathbf{w}t + \mathbf{j}_n} \xrightarrow{n \rightarrow \infty} \text{bruit blanc}$$

Si \mathbf{j}_n variables aléatoires indépendantes

$$\sum_n E e^{in\mathbf{w}t} \xrightarrow{n \rightarrow \infty} \text{peigne de Dirac}$$

Si mise en phase des modes



```
In[26]:= nmax = 20
```

$$\mathbf{F} = \sum_{n=0}^{n_{\max}} \mathbf{E}^n \mathbf{e}^{int}$$

```
In[35]:= Plot1 = Plot[Re[F], {t, 0, 30}, PlotRange -> {0, nmax}, PlotStyle -> {RGBColor[1, 0, 0]}]
```

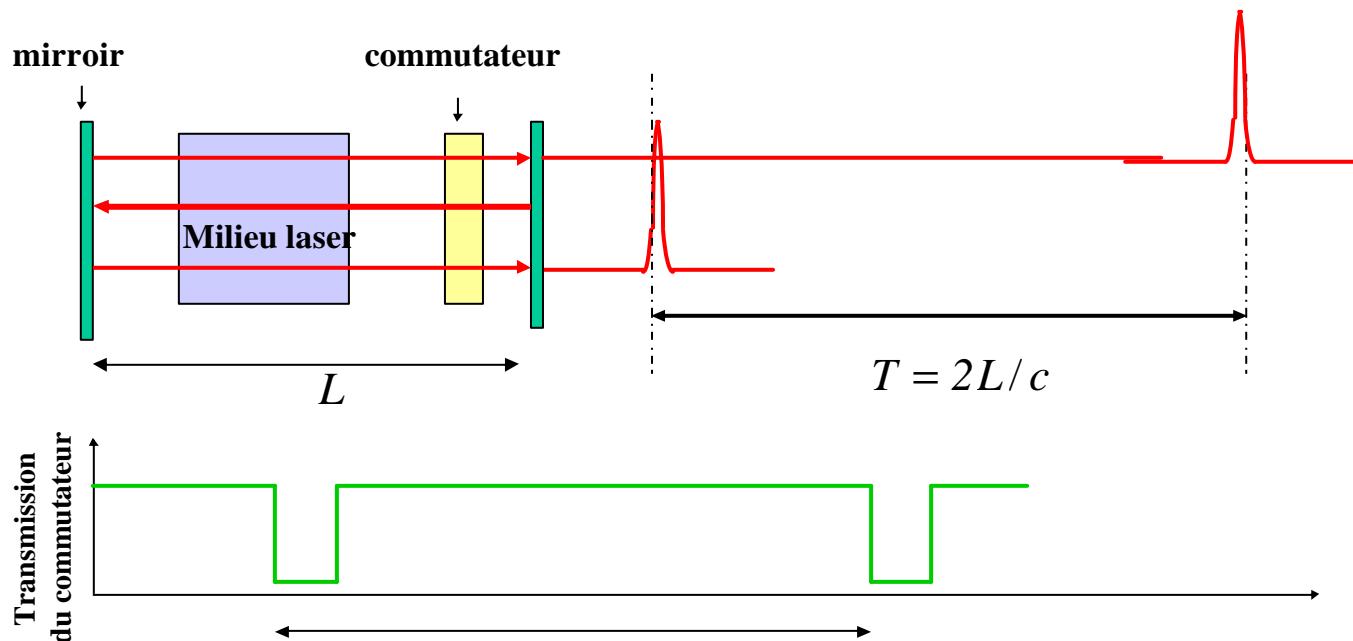
$$\mathbf{In[30]:= G} = \sum_{n=0}^{n_{\max}} \mathbf{E}^n (n t + 2 \text{Random}[] \pi)$$

```
In[36]:= Plot2 = Plot[Re[G], {t, 0, 30}, PlotRange -> {0, nmax}, PlotStyle -> {RGBColor[0, 1, 0]}]
```

```
In[38]:= Show[Plot1, Plot2]
```



Principe du blocage de mode: vision temporelle



Maximum:

$$I_{\max} = N^2 I_0 \quad T = 2L/c$$

Période:

$$T = \frac{2p}{w_{isl}} = \frac{2L}{c}$$

$$\begin{aligned} L &= 1.5m & n_{isl} &= 100 \text{ MHz} \\ N &= 10^6 & T_{pulse} &= 10^{-14} \text{ s} \end{aligned}$$

Durée:

$$\Delta T = T/N$$

Intensité
moyenne:

$$I_{\max} \frac{\Delta T}{T} = NI_0$$



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Génération d'harmoniques
élevées (UV, X)

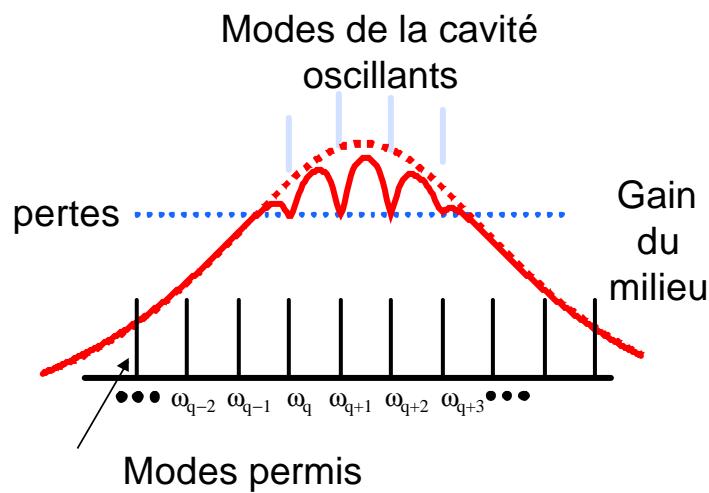
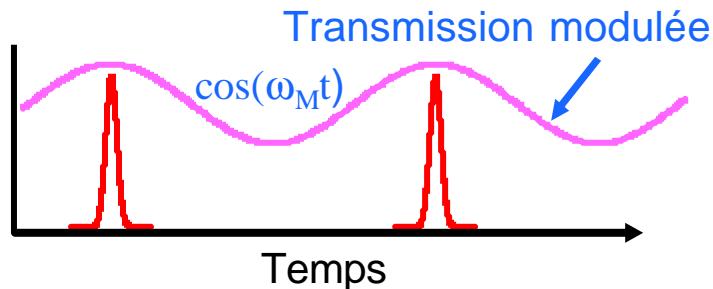
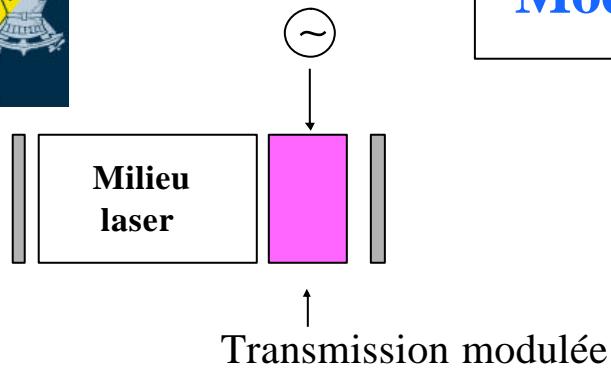
Lidar TeraWatt

Impulsions relativistes

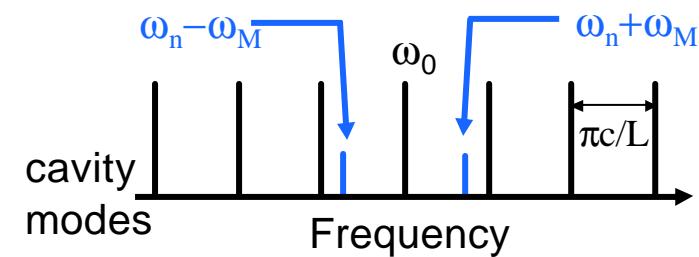
Accélération de particules



Mode lock actif: principe



Recette:
La modulation couple les modes
par effet de bandes latérales



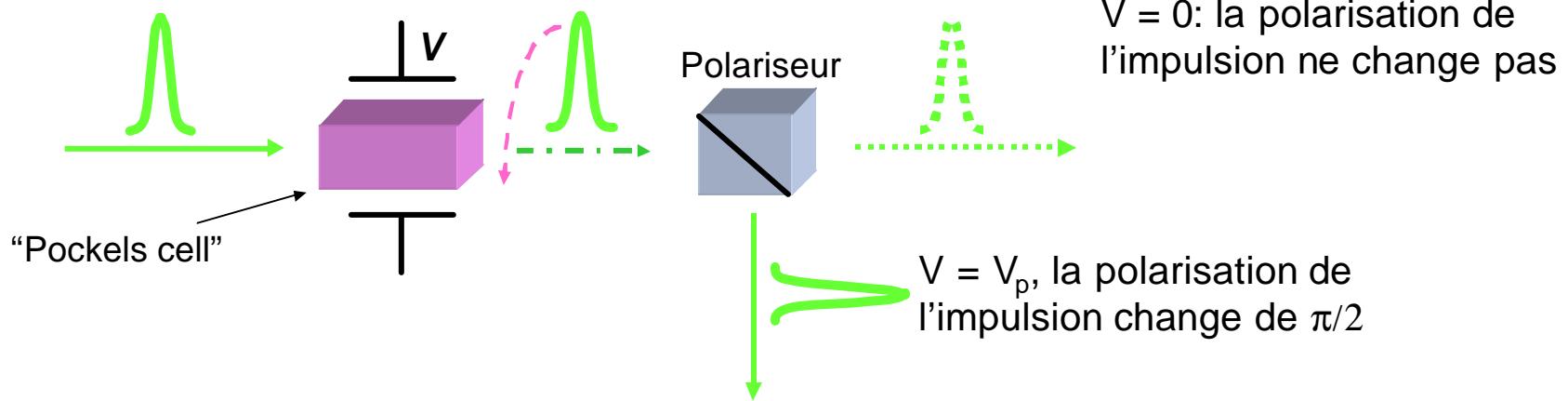


MODULATEUR ELECTRO-OPTIQUE

Cristaux électro-optiques: matériaux dont l'indice optique dépend du champ électrique appliqué

Effet d'optique non linéaire: $w+0 \rightarrow w$

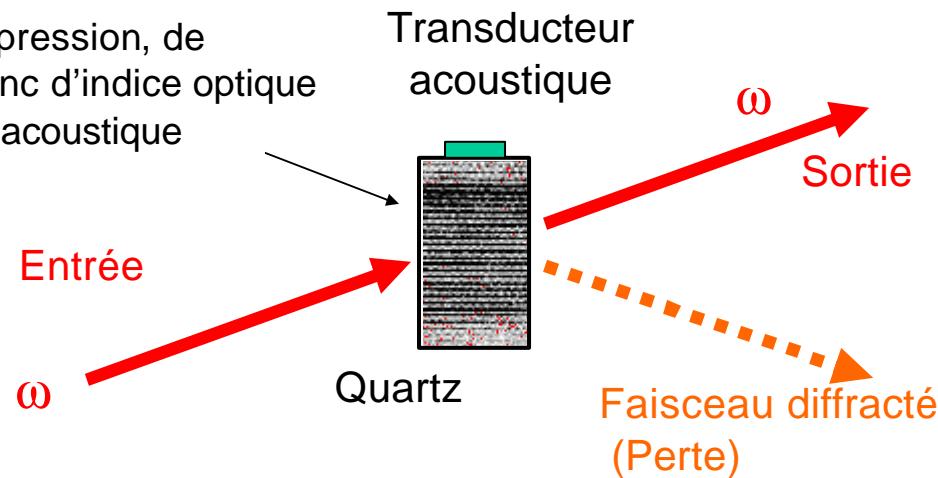
Effet Pockels: $n_k = \sum d_{ijk} E_{ij}$





MODULATEUR ACOUSTO-OPTIQUE

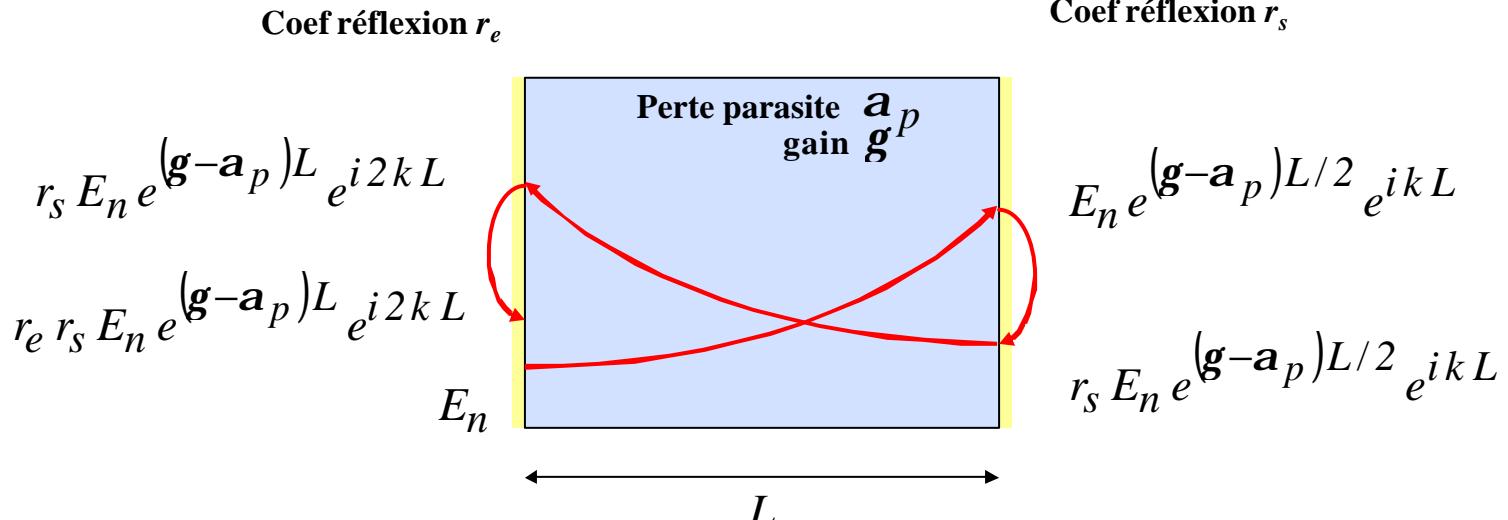
Variation de pression, de densité et donc d'indice optique due à l'onde acoustique



Efficacité: ~70%



EVOLUTION DES PHOTONS DANS LA CAVITE



L'équation d'évolution du champ électrique: $E_{n+1} = E_n r_e r_s e^{(\mathbf{g}-\mathbf{a}_p)L} e^{2ikL}$

$$E_{n+1} - E_n = E_n \left(e^{(\mathbf{g}-\mathbf{a})L} r_e r_s - 1 \right) = E_n \left(e^{(\mathbf{g}-\mathbf{g}_s)L} - 1 \right) \approx G E_n - l E_n$$

$G = \text{gain}$ $l = \text{loss}$

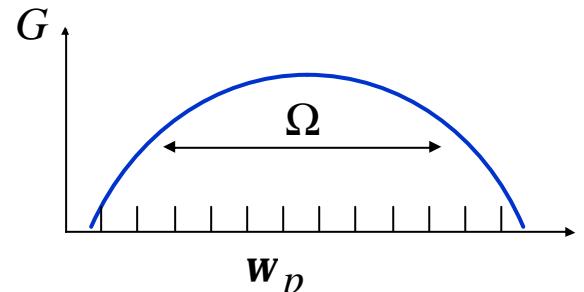


Mode lock actif: théorie

$E_n^{(m)}$ Champ du mode m après n aller-retour

Gain du milieu:

$$G(w) = \frac{G_p}{1 + \left(\frac{w - w_p}{\Omega}\right)^2}$$



Pulsation du mode m

$$w_m = w_p + m w_{isl}$$

Gain du mode m

$$G_m = \frac{G_p}{1 + \left(\frac{m w_{isl}}{\Omega}\right)^2} \approx G_p \left(1 - \left(\frac{m w_{isl}}{\Omega} \right)^2 \right)$$

Perte du mode m

$$l$$



Influence de la modulation

Perte due à la modulation du mode m: $M(1-\cos w_M t)$

$$\rightarrow e^{i(w_p + m w_{isl})t} M \left(1 - \frac{1}{2} e^{i w_M t} - \frac{1}{2} e^{-i w_M t} \right)$$

$$- e^{i w_p t} M \left(\frac{1}{2} e^{i(w_M + m w_{isl})t} - e^{i m w_{isl} t} + \frac{1}{2} e^{i(-w_M + m w_{isl})t} \right)$$

Si $w_M = w_{isl}$

$$- e^{i w_p t} M \left(\frac{1}{2} e^{i(m+1)w_{isl}t} - e^{i m w_{isl} t} + \frac{1}{2} e^{i(m-1)w_{isl}t} \right)$$



Injecte le mode m+1

Injecte le mode m-1



D'où l'équation d'évolution des modes couplés

$$E_{n+1}^{(m)} = E_n^{(m)} + E_n^{(m)} G_p \left(1 - \left(\frac{m w_{isl}}{\Omega} \right)^2 \right) - E_n^{(m)} l + M \left(\frac{1}{2} E_n^{(m+1)} - E_n^{(m)} + \frac{1}{2} E_n^{(m-1)} \right)$$

modes couplés

Condition de stationnarité

$$E^{(m)} G_p \left(1 - \left(\frac{m w_{isl}}{W} \right)^2 \right) - E^{(m)} l + M \left(\frac{1}{2} E^{(m+1)} - E^{(m)} + \frac{1}{2} E^{(m-1)} \right) = 0$$

Équation de modes couplés

On pose $E^{(m)} = \tilde{E}(w) = \tilde{E}(w_p + m w_{isl})$

$$E^{(m+1)} - 2E^{(m)} + E^{(m-1)} \xrightarrow{w_M^2 \frac{d^2}{dw^2} \tilde{E}}$$



Équation du mode-lock actif: domaine fréquentiel

$$\left[G_p \left(1 - \left(\frac{\mathbf{w}}{W} \right)^2 \right) - l \right] \tilde{E}(\mathbf{w}) + \frac{M}{2} \mathbf{w}_M^2 \frac{d^2}{d\mathbf{w}^2} \tilde{E}(\mathbf{w}) = 0$$

Rétrécissement fréquentiel

Elargissement fréquentiel

Solution: $\tilde{E}(\mathbf{w}) = A e^{-\mathbf{w}^2 t^2 / 2}$ si $\left[G_p \left(1 - \left(\frac{\mathbf{w}}{\Omega} \right)^2 \right) - l \right] + \frac{M}{2} \mathbf{w}_M^2 \left(-t^2 + \mathbf{w}^2 t^4 \right) = 0$

$$t = \left(\frac{2G_p}{M \mathbf{w}_M^2 \Omega^2} \right)^{1/4}$$

$$G_p - l = \frac{1}{2} \frac{(2G_p M \mathbf{w}_M^2)^{1/2}}{\Omega}$$

Pulse gaussien $E(t) = A e^{-t^2 / 2t^2}$

τ minimum -> Ω maximum

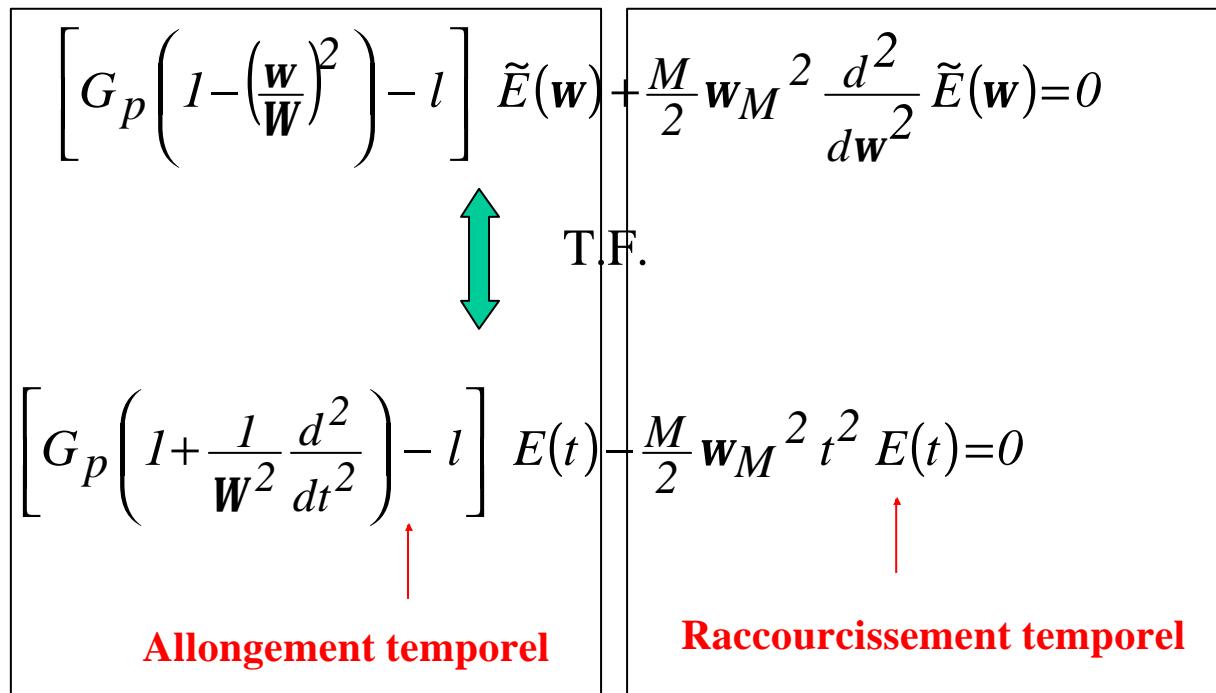
Gain supplémentaire nécessaire



Équation du mode-lock actif: domaine temporel

$$TF\left(w^2 \tilde{f}(w)\right) = -\frac{d^2}{dt^2} TF(\tilde{f}(w)) \quad TF\left(\frac{d^2}{dw^2} \tilde{f}(w)\right) = -t^2 TF(\tilde{f}(w))$$

Domaine fréquentiel





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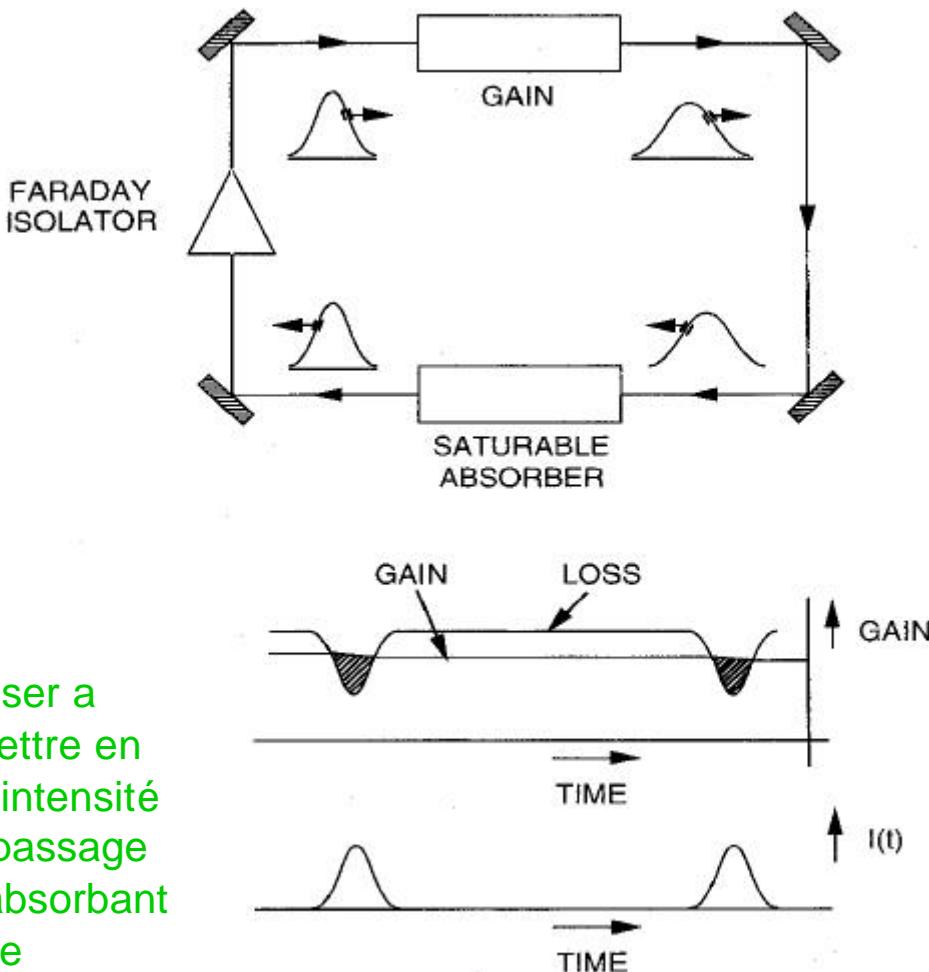
Impulsions relativistes

Accélération de particules



PASSIVE MODE LOCKING

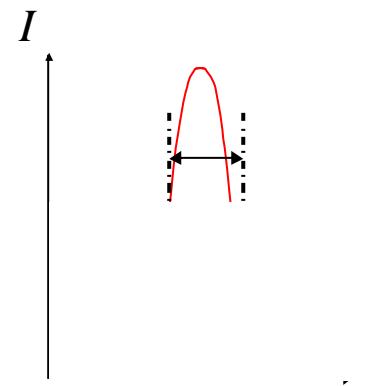
L'énergie laser a intérêt à se mettre en paquet de forte intensité pour forcer le passage au travers de l'absorbant saturable



Compétition entre:

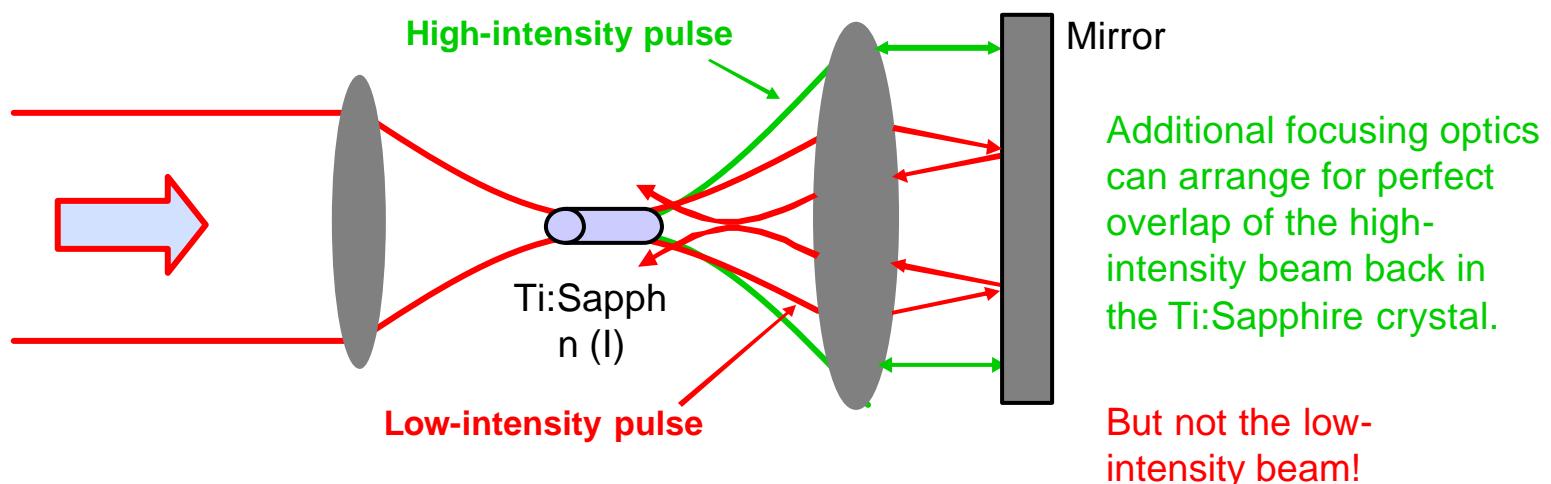
Elargissement par le gain

Rétrécissement par absorbant saturable





Exemple de saturation d'absorption: lentille de Kerr (1)

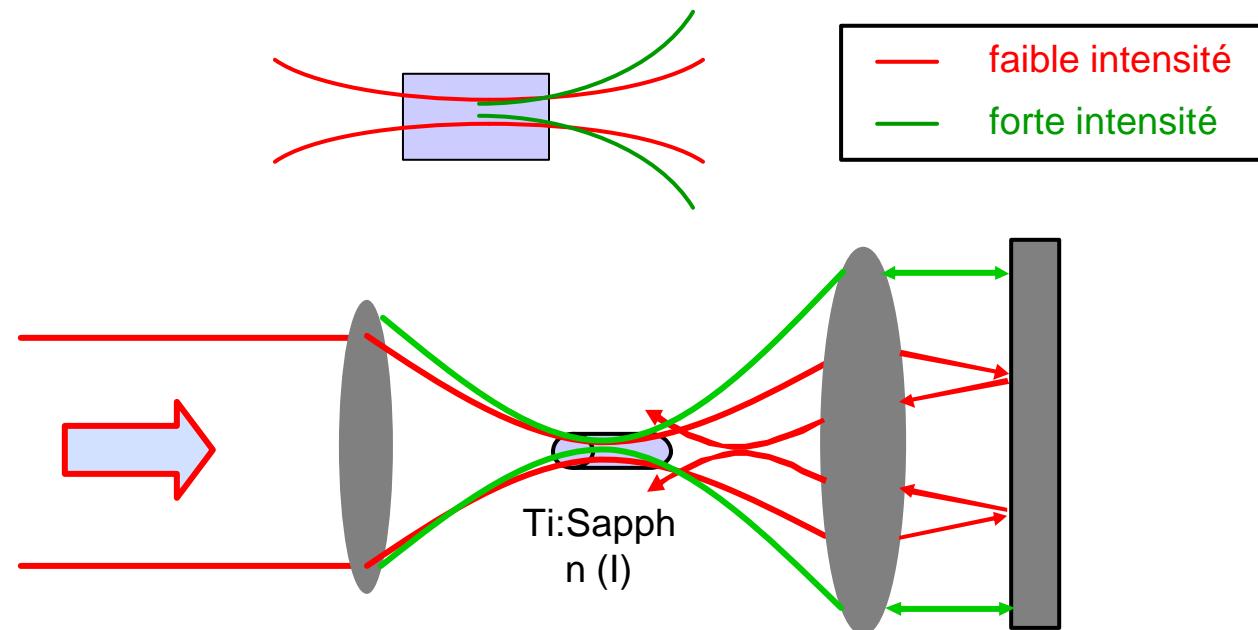


C'est un premier exemple d'absorbant saturable
“MAGIC MODE LOCKING”



Exemple de saturation d'absorption: lentille de Kerr (1)

Effet Kerr: l'indice $n(I)$ augmente avec l'intensité du signal optique $n(I) = n_1 + n_2 I$

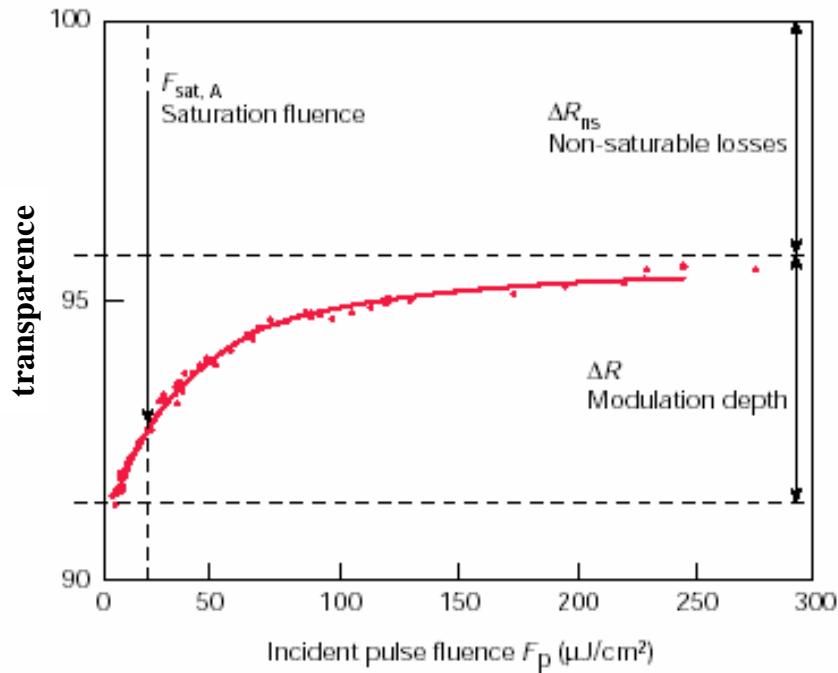


Le montage priviliege les fortes intensités

C'est un premier exemple d'absorbant saturable
“MAGIC MODE LOCKING”

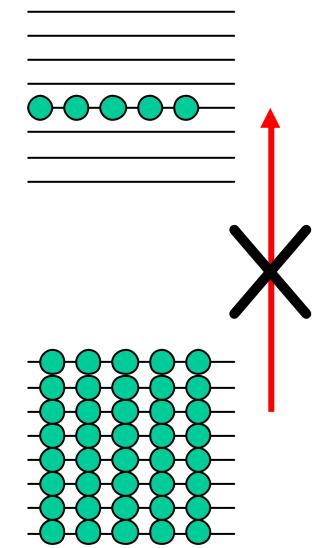


Exemple de saturation d'absorption: SESAM (2)



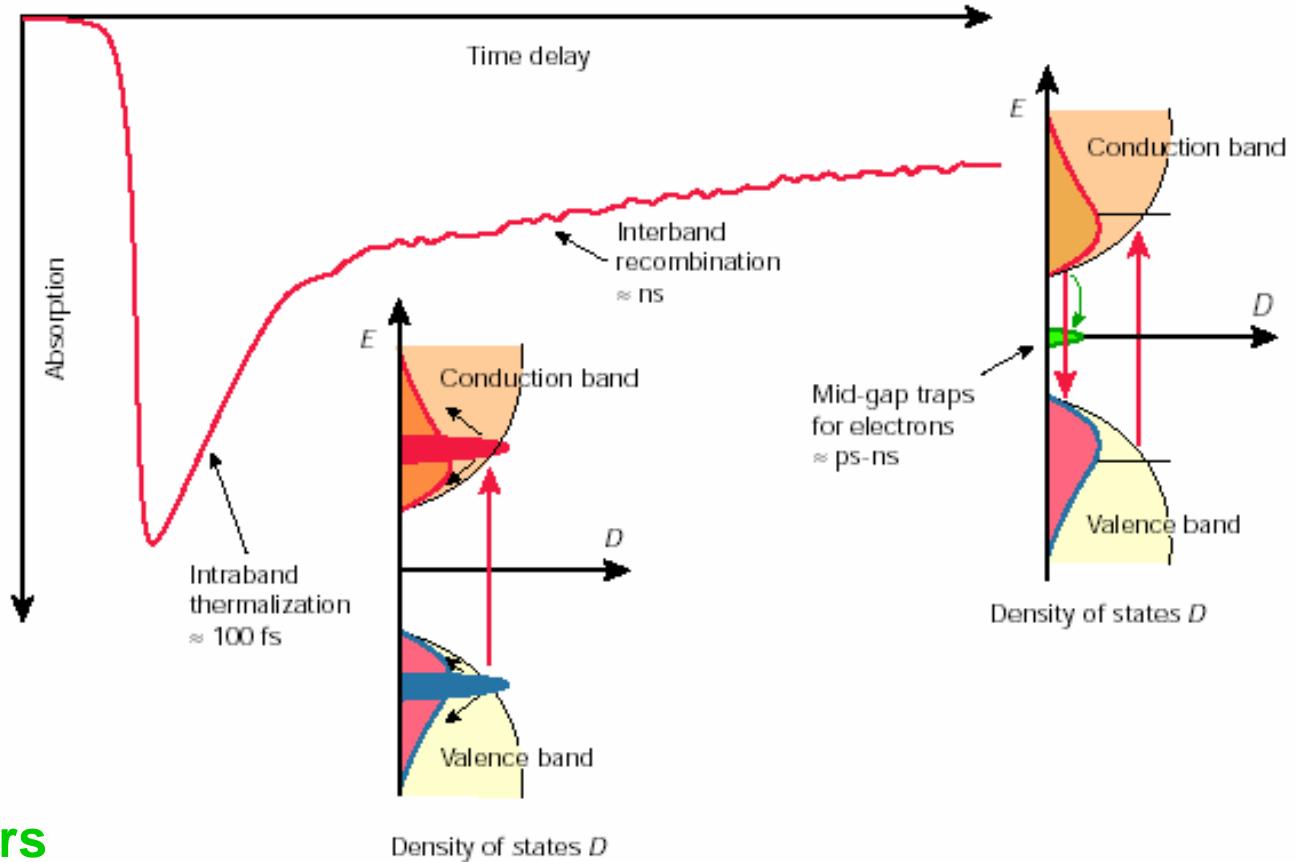
**Saturation
d'absorption
dans les
semiconducteurs**

U. Keller Nature





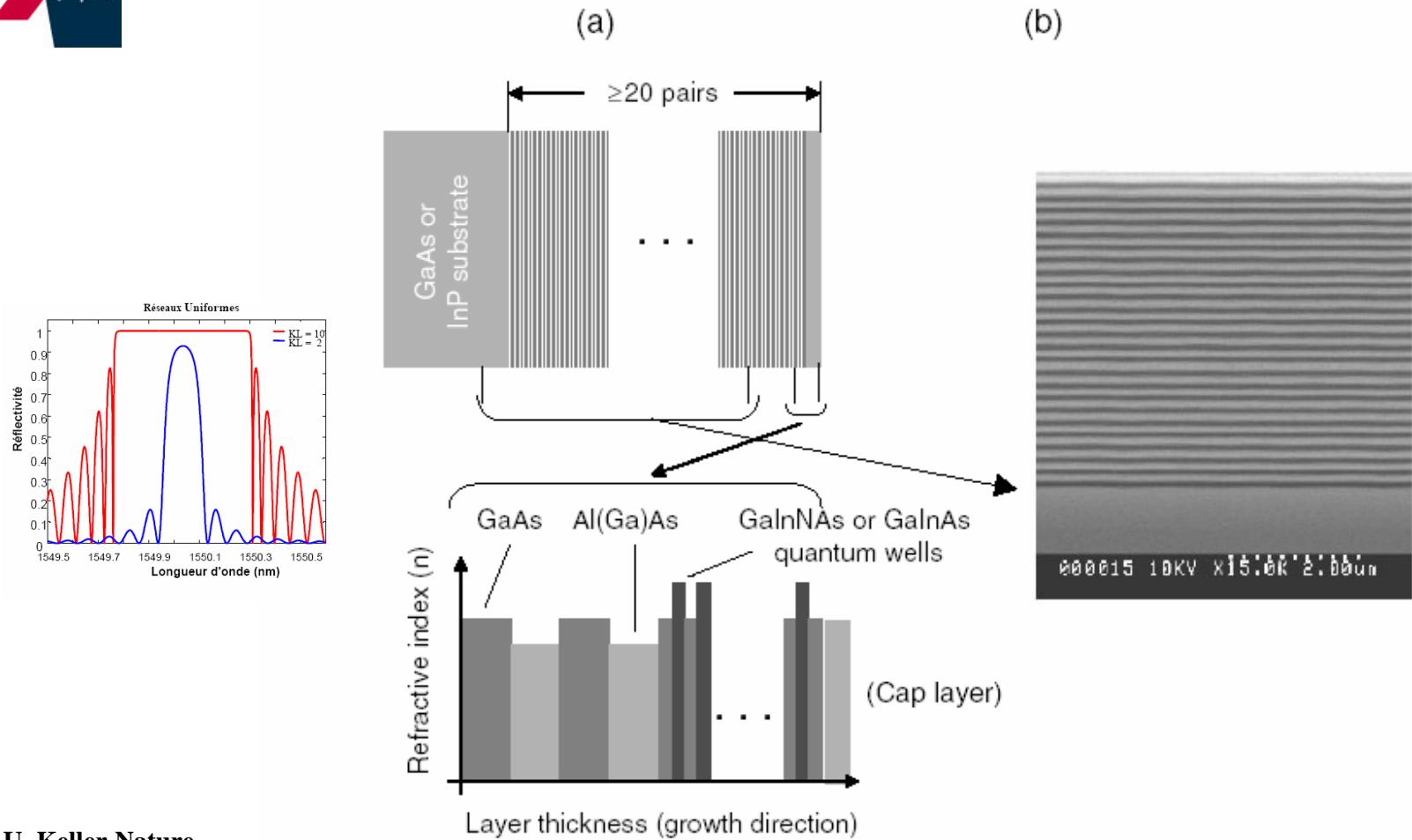
Exemple de saturation d'absorption: SESAM (2)



**Saturation
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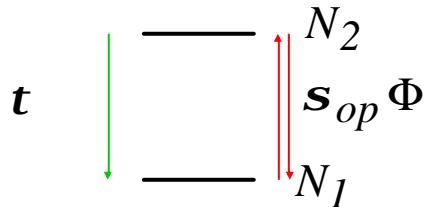


Exemple de saturation d'absorption: SESAM (2)





MODELE ULTRA-SIMPLE DE SATURATION D'ABSORPTION



$$\frac{d}{dt}N_1 = +\frac{N_2}{t} + N_2 s_{op} \Phi - N_1 s_{op} \Phi$$

$$N_1 + N_2 = N$$

A l'état stationnaire:

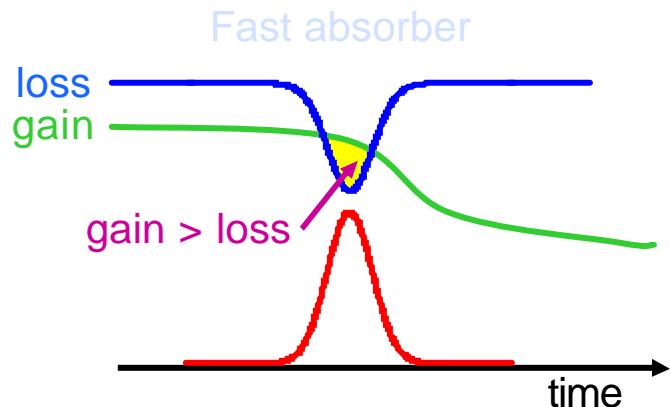
$$\left\{ \begin{array}{l} \frac{N_2}{t} = s_{op} \Phi \Delta N \\ N_2 = \frac{N - \Delta N}{2} \end{array} \right. \quad \rightarrow \quad \Delta N = \frac{N}{1 + 2 s_{op} t \Phi}$$

$$\left. \begin{array}{l} \mathbf{a} = s_{op} \Delta N \\ \mathbf{a}_0 = s_{op} N \\ \Phi_{sat} = 1/2 s_{op} t \end{array} \right\}$$

$$\mathbf{a} = \frac{\mathbf{a}_0}{1 + \Phi / \Phi_{sat}}$$



Mode lock passif: absorbant rapide



$$\mathbf{a}(E) = \frac{\mathbf{a}_0}{1 + \frac{|E|^2}{I_{sat}}} \approx \mathbf{a}_0 \left(1 - \frac{|E|^2}{I_{sat}} \right)$$

avec $\mathbf{g}_a = \frac{\mathbf{a}_0 L_a}{I_{sat}}$

$$e^{-\mathbf{a} L_a} \approx 1 - \mathbf{a} L_a = 1 - \underbrace{\mathbf{a}_0 L_a}_{l \text{ saturation}} + \underbrace{\mathbf{g}_a |E|^2}_{l \text{ saturation}}$$

$$\left[G_p \left(1 + \frac{1}{W^2} \frac{d^2}{dt^2} \right) - l \right] E(t) + \mathbf{g}_a |E|^2 E(t) = 0$$

Ginzburg-Landau

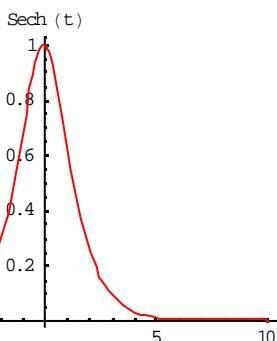


$$\left[G_p \left(1 + \frac{1}{W^2} \frac{d^2}{dt^2} \right) - l \right] E(t) + g_a |E|^2 E(t) = 0$$

Solution $E(t) = E_0 \operatorname{sech} \left(\frac{t}{\Omega} \right)$ avec $\operatorname{sech}(x) = \frac{1}{\cosh(x)}$

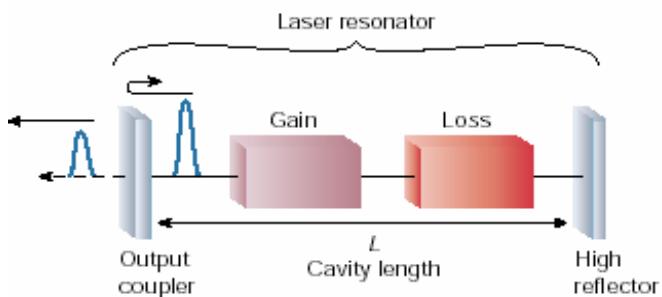
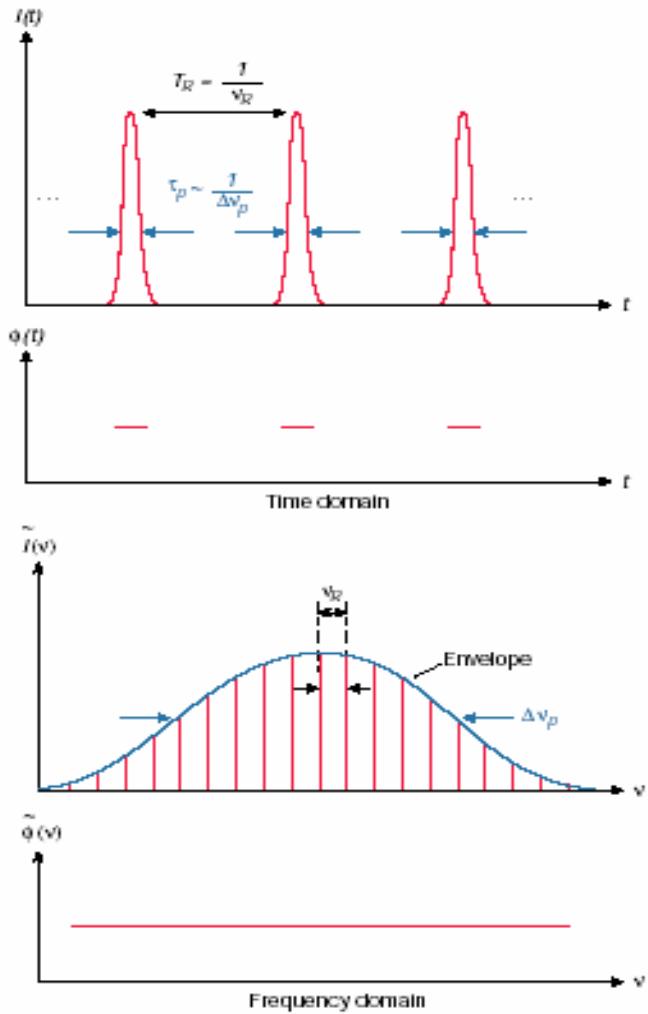
$$\frac{d^2}{dx^2} \operatorname{sech}(x) = \operatorname{sech}(x) - 2 \operatorname{sech}^3(x)$$

$$[G_p - l] E_0 \operatorname{sech} \left(\frac{t}{\Omega} \right) + \frac{G_p E_0}{\Omega^2} \left(\operatorname{sech} \left(\frac{t}{\Omega} \right) - 2 \operatorname{sech}^3 \left(\frac{t}{\Omega} \right) \right) + g_a E_0^3 \operatorname{sech}^3 \left(\frac{t}{\Omega} \right) = 0$$

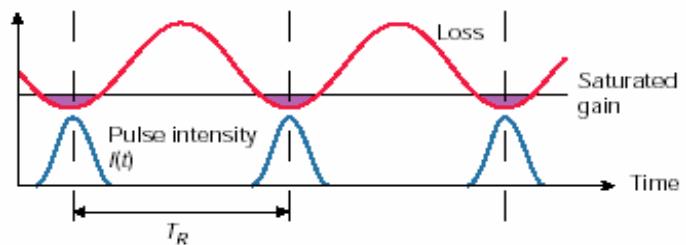


$$g_a |E_0|^2 = \frac{2G_p}{W^2 \Omega^2} \quad G_p - l + \frac{G_p}{W^2 \Omega^2} = 0$$

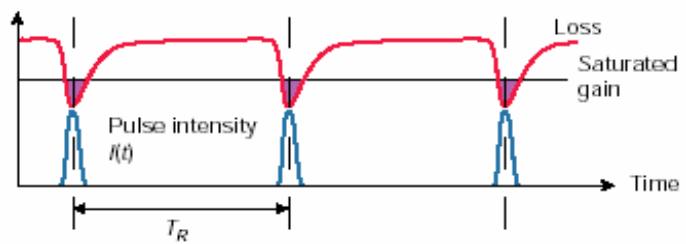
$t \approx 1/\Omega$ \rightarrow Plus court que le mode lock actif !!



Active modelocking



Passive modelocking



ONERA



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Mesure de l'intensité ET de la phase en fonction du temps

Variation temporelle du champ:

$$E(t) = \operatorname{Re} \left\{ I(t)^{1/2} \exp [i\omega_0 t - i f(t)] \right\}$$

↑ Intensité ↑ Phase

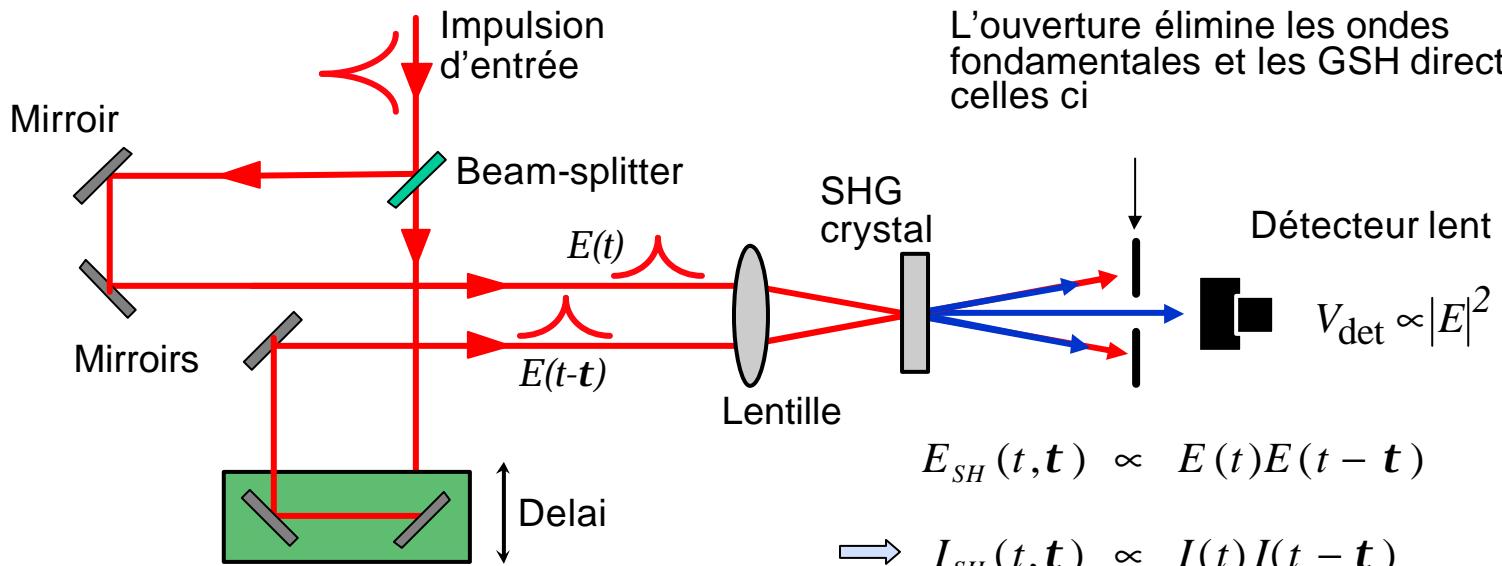
Variation fréquentielle:

La connaissance de l'intensité et la phase temporelle ou le spectre et la phase spectrale détermine totalement l'impulsion



AUTOCORRELATEUR D'INTENSITE TEMPOREL

Recette de l'autocorrélateur en intensité: on prend un signal, on en retarde une partie, on somme les deux dans un cristal non linéaire et on détecte l'intensité de la seconde harmonique



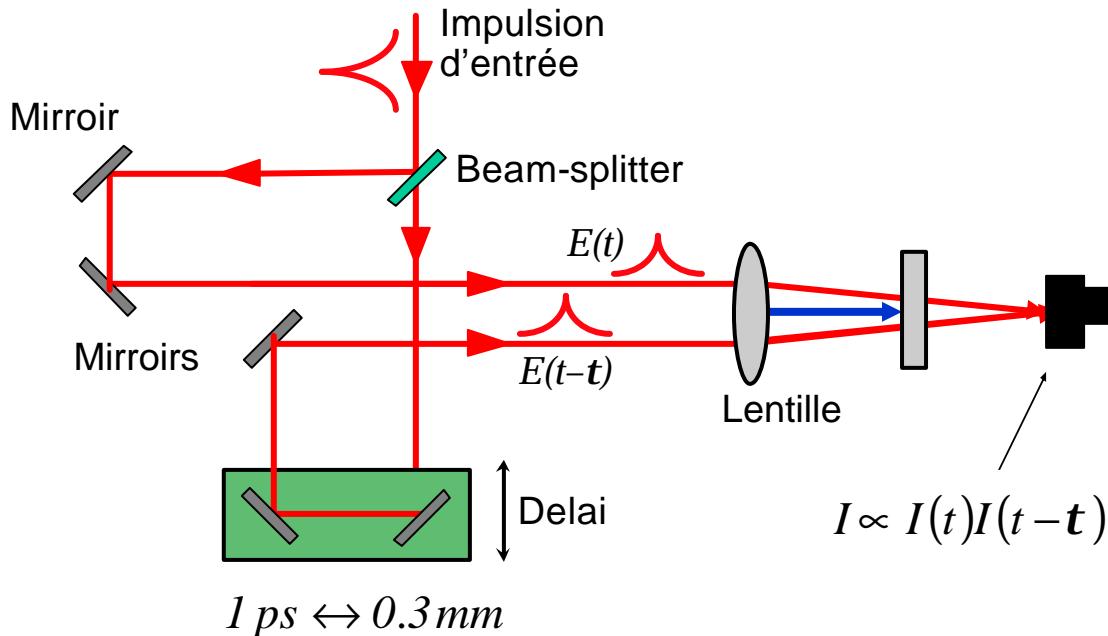
$$A^{(2)}(t) \equiv \int_{-\infty}^{\infty} I(t)I(t - t) dt$$

Autocorrélation en intensité

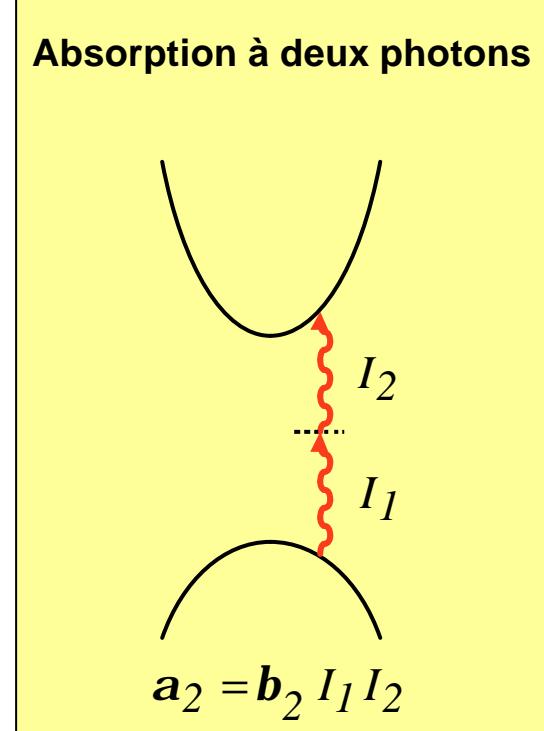


AUTOCORRELATEUR D'INTENSITE TEMPOREL

Encore plus simple

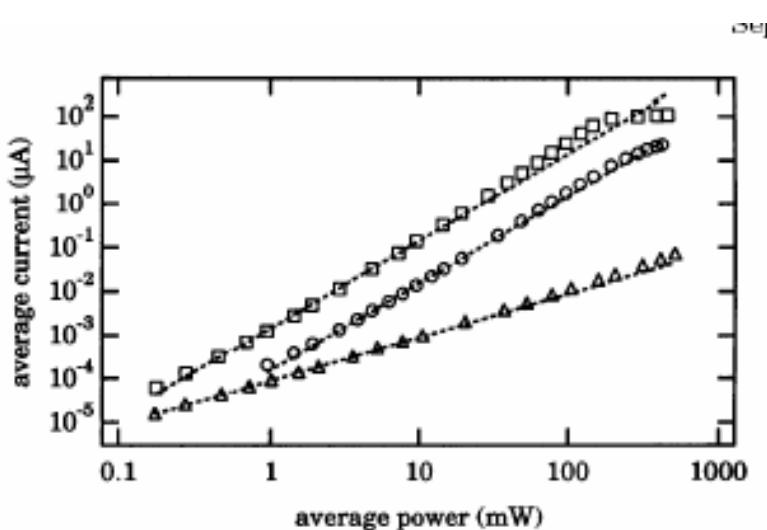


$$I \propto I(t)I(t-t)$$





GRENOUILLE AT A GLANCE



RESULTATS EXPERIMENTAUX ET START-UP

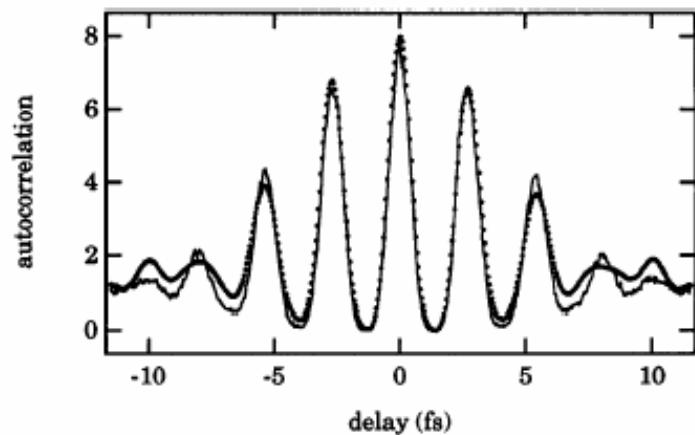


Fig. 5. Interferometric autocorrelation measurement of a 6-fs pulse with a GaAsP photodiode (circles) and a 15- μm BBO crystal (curve).

Ranka et

OPTICS LETTERS / Vol. 22, No. 17 / September 1, 1997

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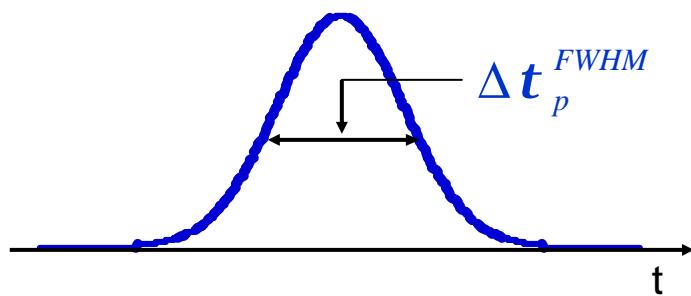
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Autocorrelation d'une impulsion gaussienne

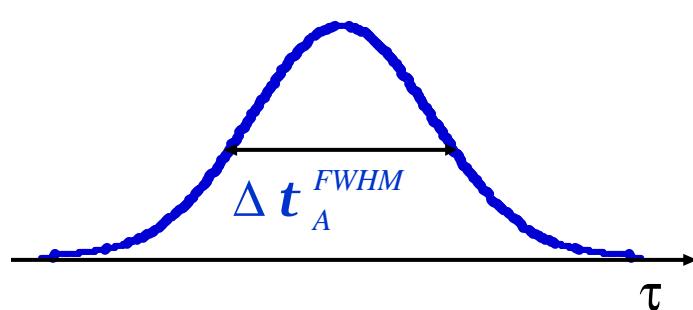
Pulse

$$I(t) = \exp \left[-\left(\frac{2\sqrt{\ln 2}t}{\Delta t_p^{FWHM}} \right)^2 \right]$$



Autocorrelation

$$A^{(2)}(t) = \exp \left[-\left(\frac{2\sqrt{\ln 2}t}{\Delta t_A^{FWHM}} \right)^2 \right]$$



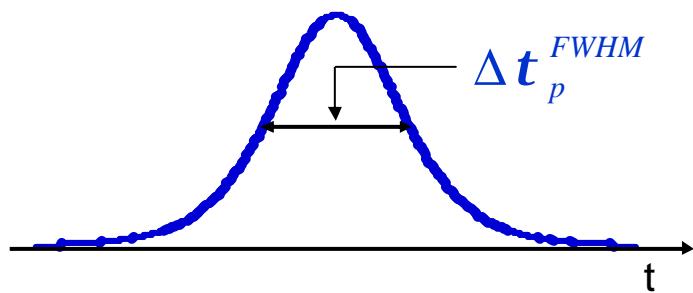
$$\Delta t_A^{FWHM} = 1.41 \Delta t_p^{FWHM}$$



Autocorrelation d'une impulsion sécante

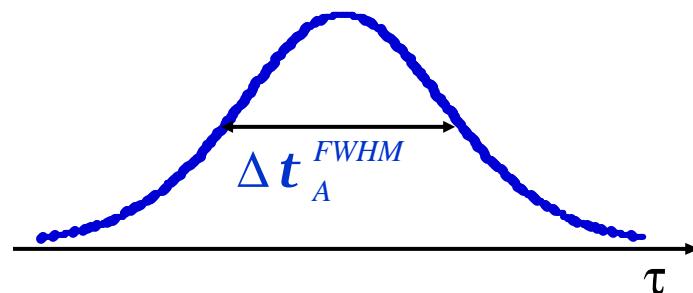
Pulse

$$I(t) = \operatorname{sech}^2\left[\frac{1.7627 t}{\Delta t_p^{FWHM}}\right]$$



Autocorrelation

$$A^{(2)}(t) = \frac{3}{\sinh^2\left(\frac{2.7196 t}{\Delta t_A^{FWHM}}\right)} \left[\frac{2.7196 t}{\Delta t_A^{FWHM}} \coth\left(\frac{2.7196 t}{\Delta t_A^{FWHM}}\right) - 1 \right]$$



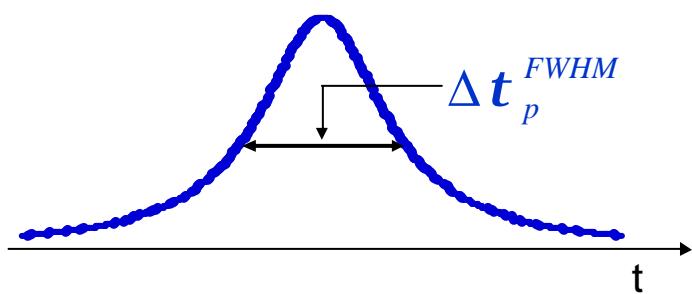
$$\Delta t_A^{FWHM} = 1.54 \Delta t_p^{FWHM}$$



Autocorrelation d'une impulsion lorentzienne

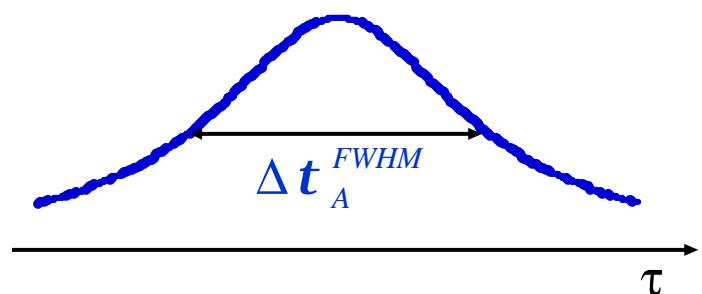
Pulse

$$I(t) = \frac{1}{1 + (2t/\Delta t_p^{FWHM})^2}$$



Autocorrelation

$$A^{(2)}(t) = \frac{1}{1 + (2t/\Delta t_A^{FWHM})^2}$$

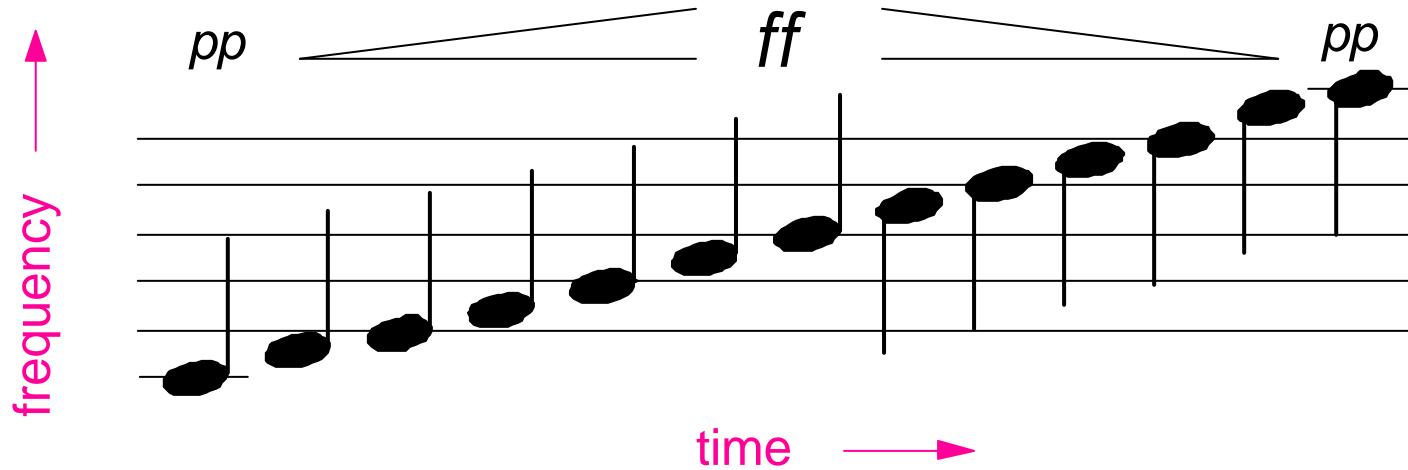


$$\Delta t_A^{FWHM} = 2.0 \Delta t_p^{FWHM}$$



SPECTROGRAMME

Exemple typique: la portée musicale



C'est un tracé de la fréquence en fonction du temps avec des indications d'intensité
C'est un tacé de temps-fréquence



DEFINITION MATHEMATIQUES DU SPECTROGRAMME

Soit $E(t)$ un signal: son spectrogramme est

$$Sp_E(w, t) \equiv \left| \int_{-\infty}^{\infty} E(t) g(t - t') \exp(-iw t') dt' \right|^2$$

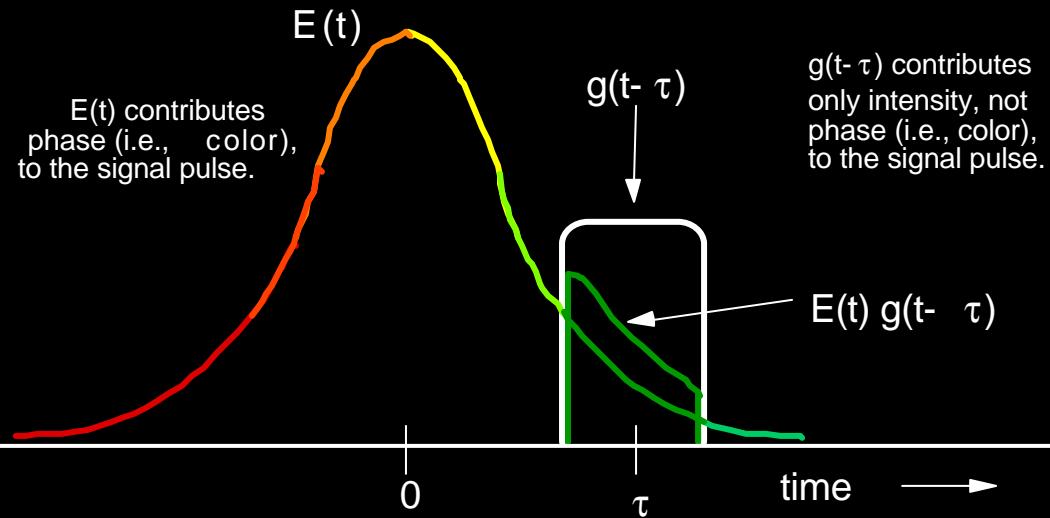
où $g(t-t')$ est une fonction d'échantillonage à délai τ variable.

Sans $g(t-t')$, $Sp_E(\omega, \tau)$ serait simplement le spectre de $E(t)$



The Spectrogram of a waveform $E(t)$

We must compute the spectrum of the product: $E(t) g(t - \tau)$

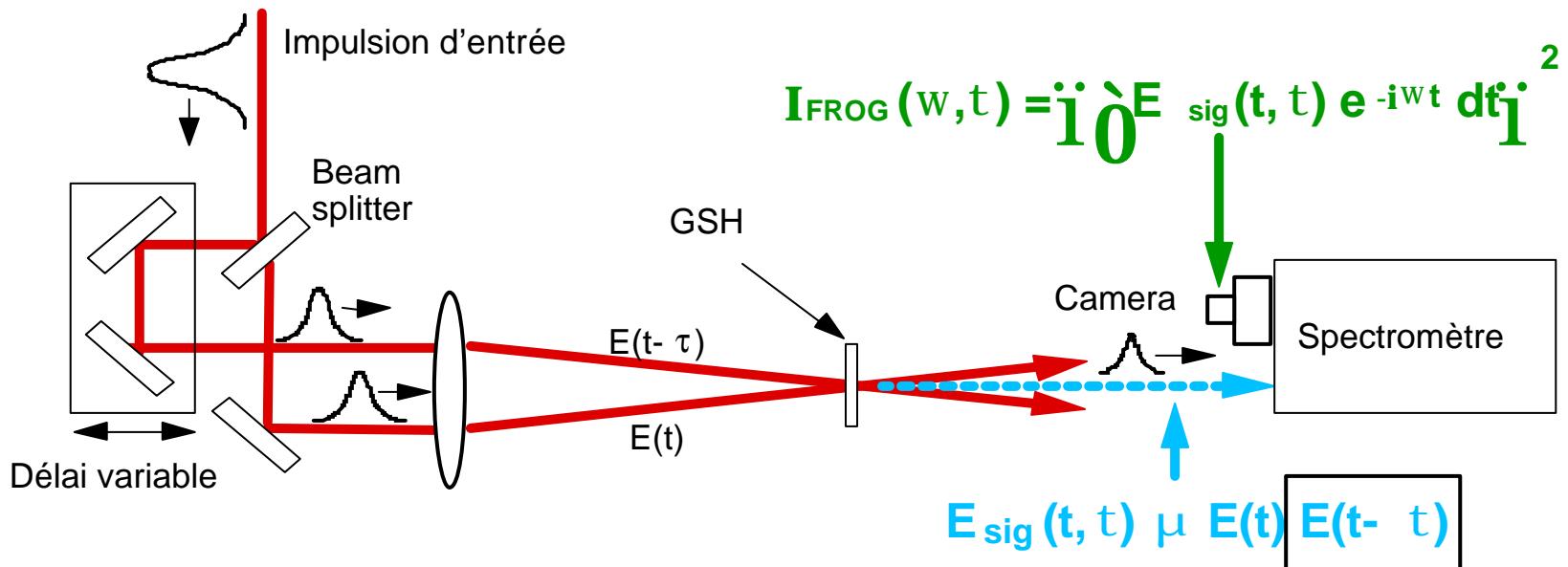


The spectrogram tells the color and intensity of $E(t)$ at the time τ .



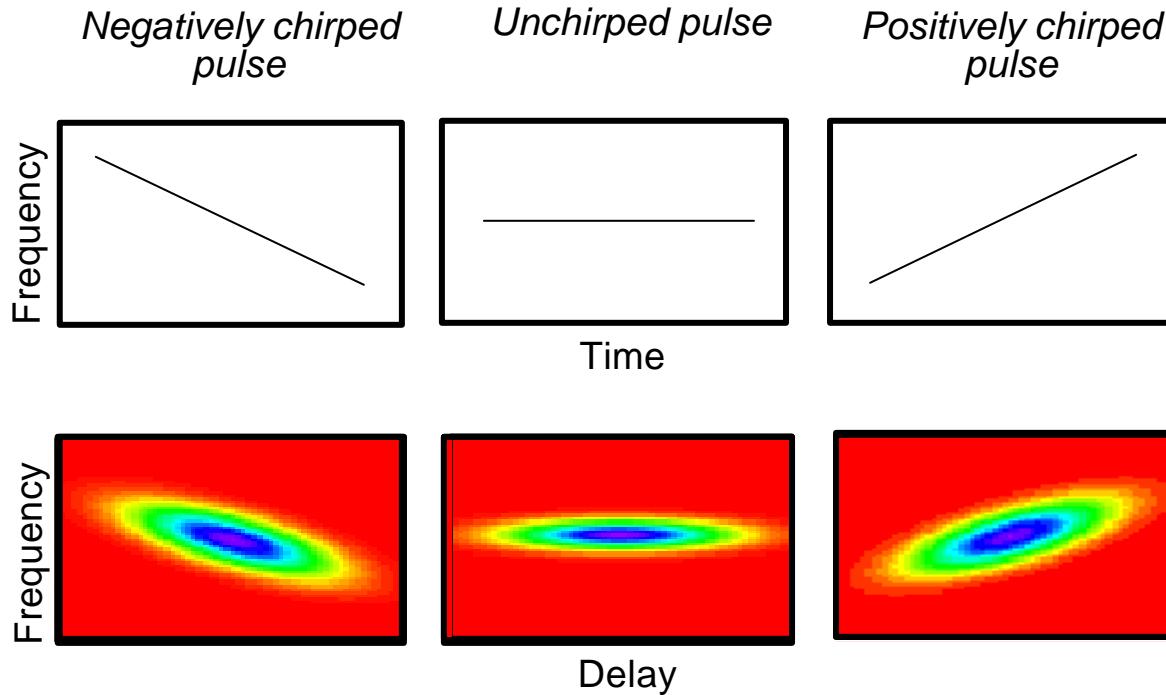
Frequency-Resolved Optical Gating (FROG)

On rajoute au montage d'autocorrelation en intensité une analyse spectrale.
La porte temporelle est le signal décalé: le signal s'analyse lui-même!





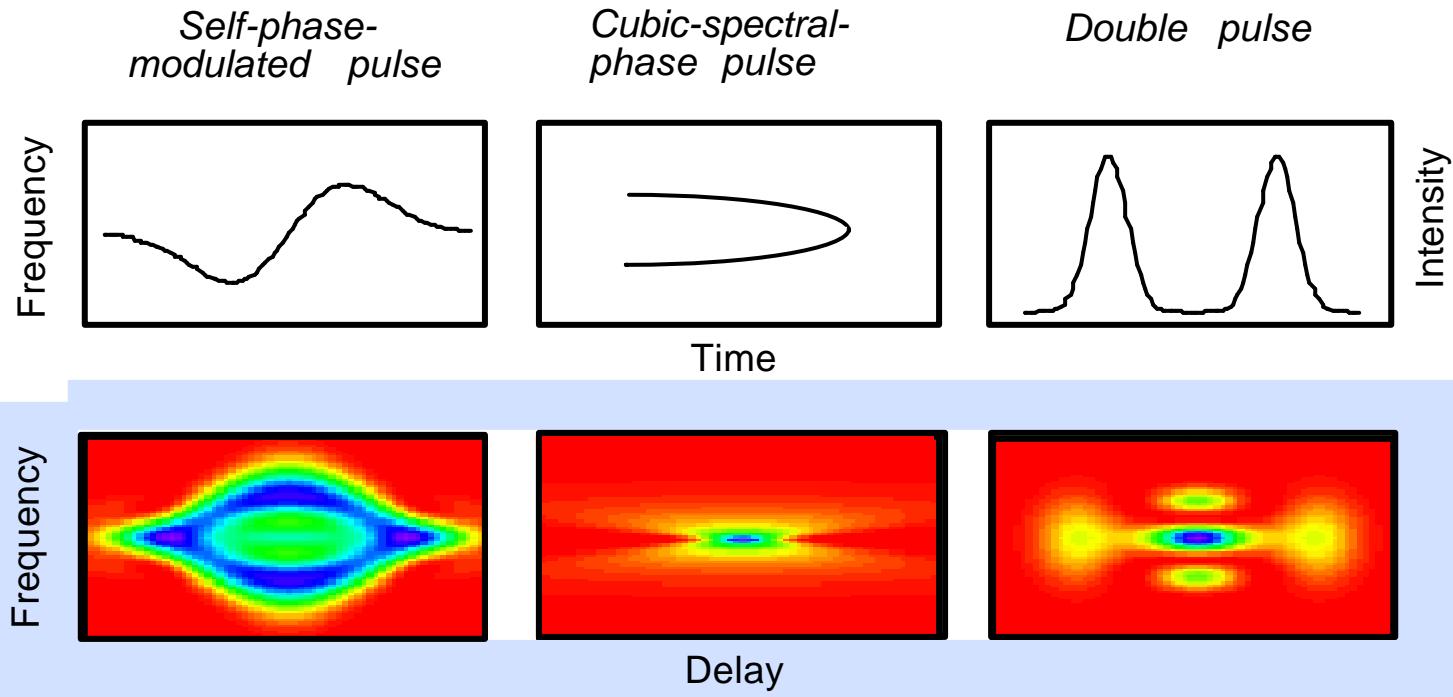
Résultats de FROG: impulsion gaussienne



The FROG trace visually displays the frequency vs. time.



Résultats de SHG-FROG: impulsions complexes



SHG FROG traces are symmetrized PG FROG traces.



FemtoPhysique

A: Impulsions ultra-courtes

A travers les ans

Bloquage de modes

B: Blocage actif

Équation des modes couplés

Impulsions gaussiennes

C: Blocage passif

Absorbants saturables

Equations de Siegmann-Hauss

Impulsions sécantes

Solitons

D: Caractérisation des impulsions

Autocorrélation

FROG

E: Physique avec des impulsions
ultra-courtes

Contrôle cohérent

Génération d'harmoniques
élevées (UV, X)

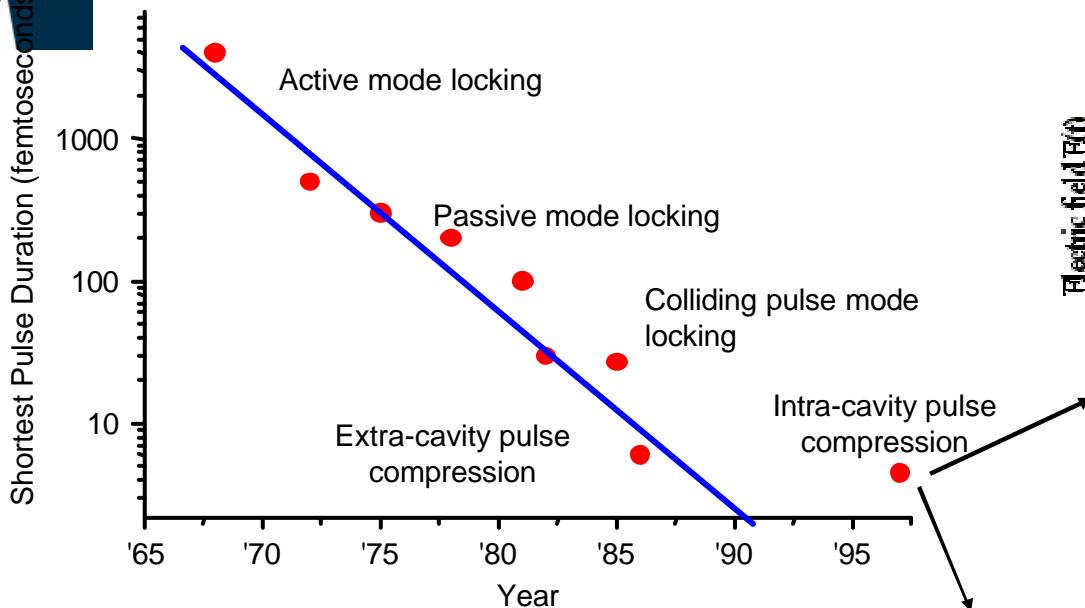
Lidar TeraWatt

Impulsions relativistes

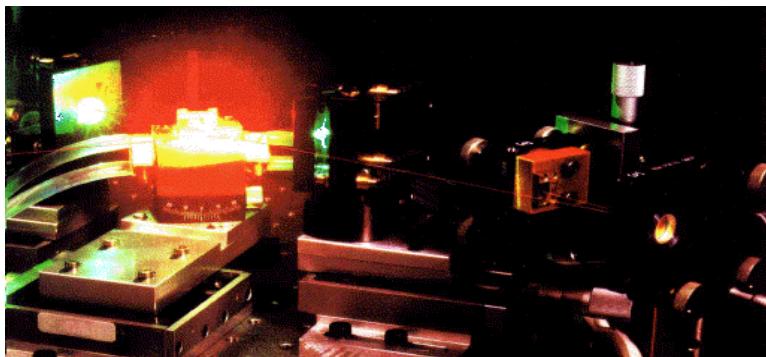
Accélération de particules



Ultrafast Lasers

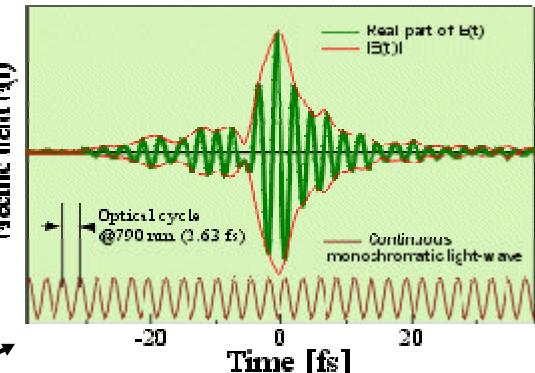


Ultrafast Ti:sapphire laser



Rick Trebino

A 4.5-fs pulse...



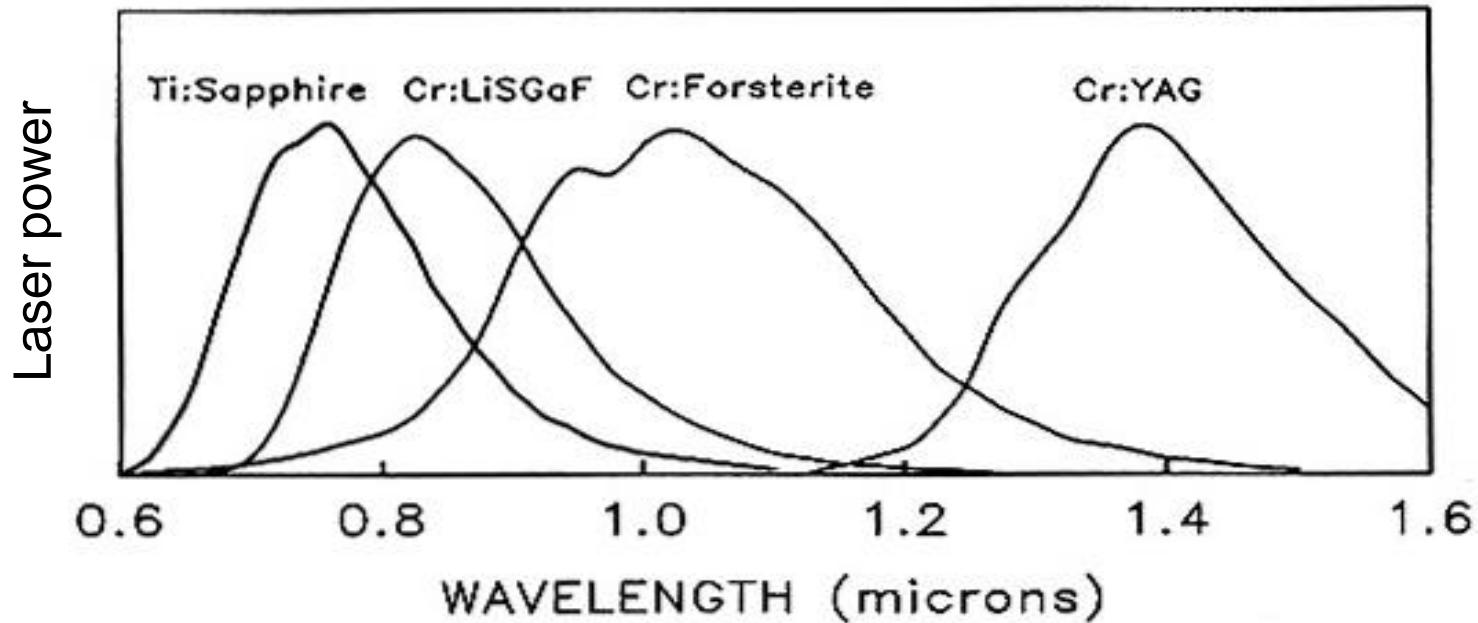
Current record:
0.8 fs
2004

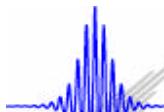
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MILIEU LASERS ULTRA-RAPIDES

Milieux dans lesquels la largeur de gain est très importante

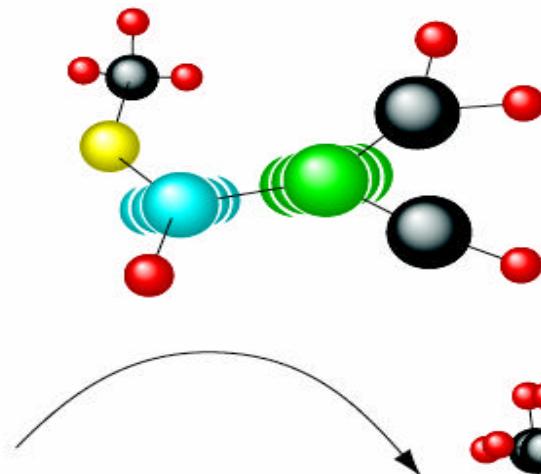
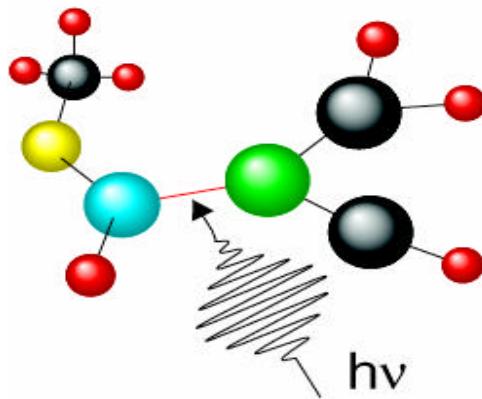




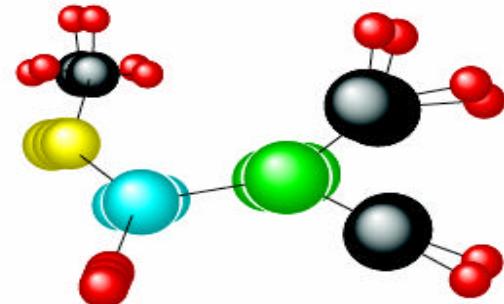
Intramolecular vibrational redistribution

Department of Physics, University of Würzburg, Germany

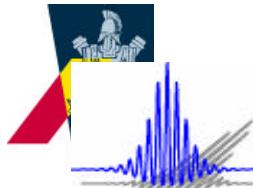
Excite one bond



A few fs later, the entire molecule is vibrating.

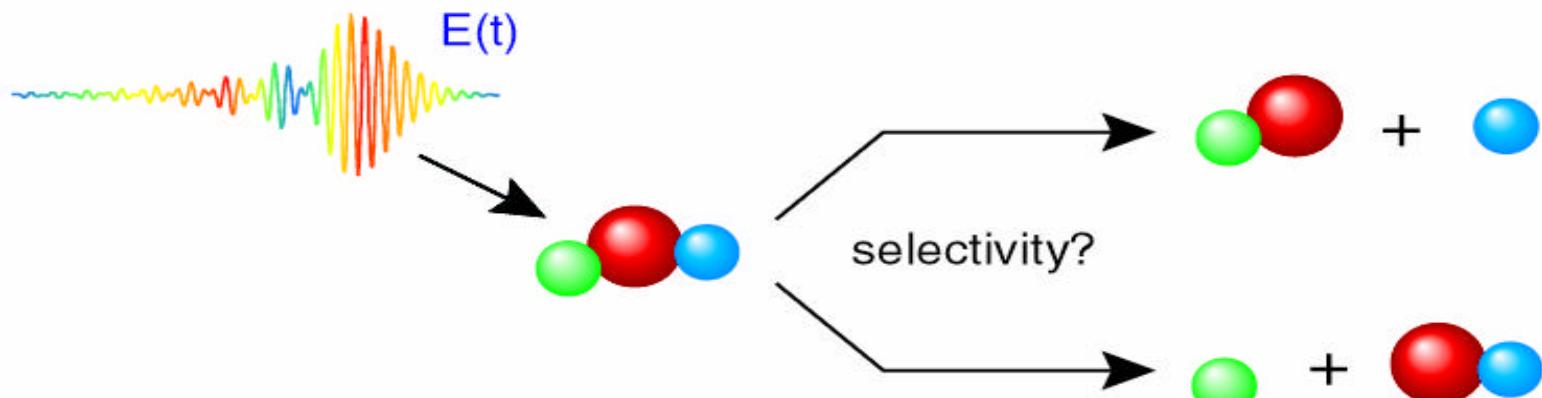


IVR occurs on a few-fs time scale, so long pulses excite entire molecule, and the weakest bond breaks.



Optical control of chemical reactions

Department of Physics, University of Würzburg, Germany

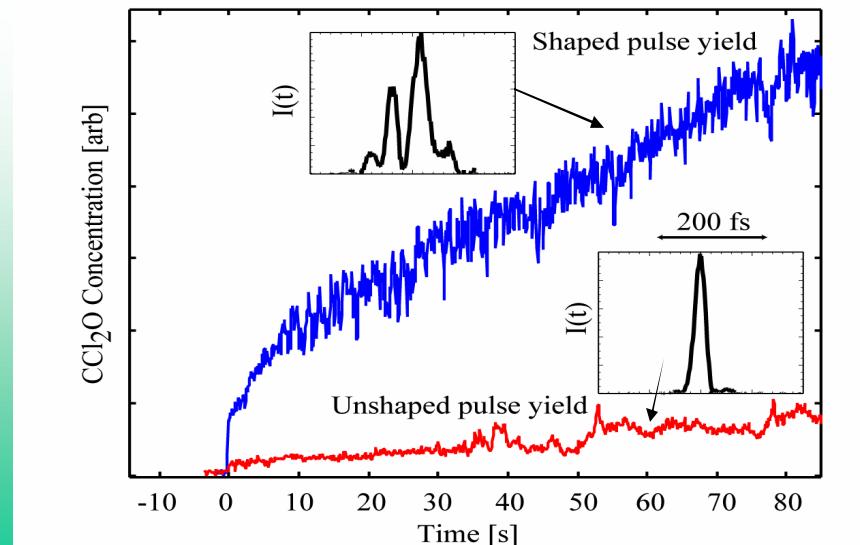
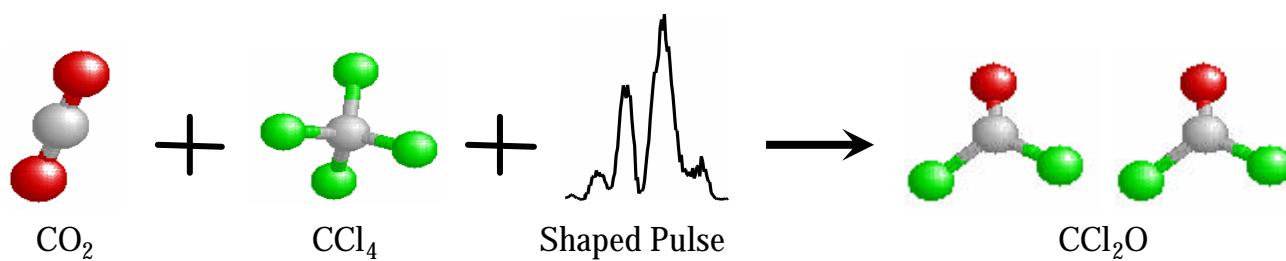


electric control field $E(t)$:
which one to use?
how to generate it?



Coherent Control of a Simple Reaction

Reaction Under Study

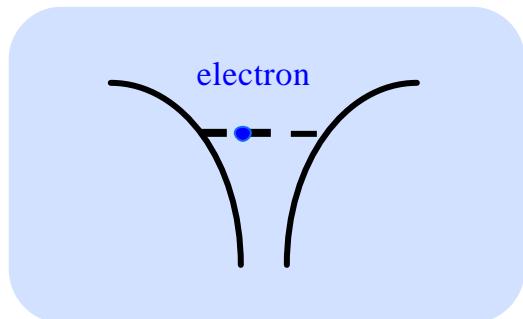


Murnane and
Kapteyn, University of
Colorado



Génération d'harmoniques élevées

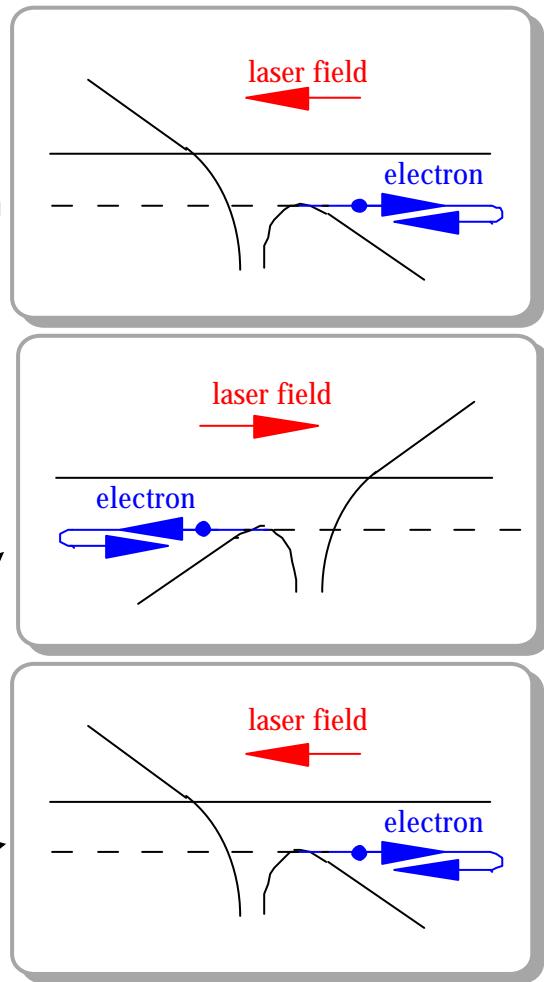
The potential due to the nucleus in the absence of the intense laser field:



$$E \text{ V/cm} = 27.5 \sqrt{P \text{ W/cm}^2}$$

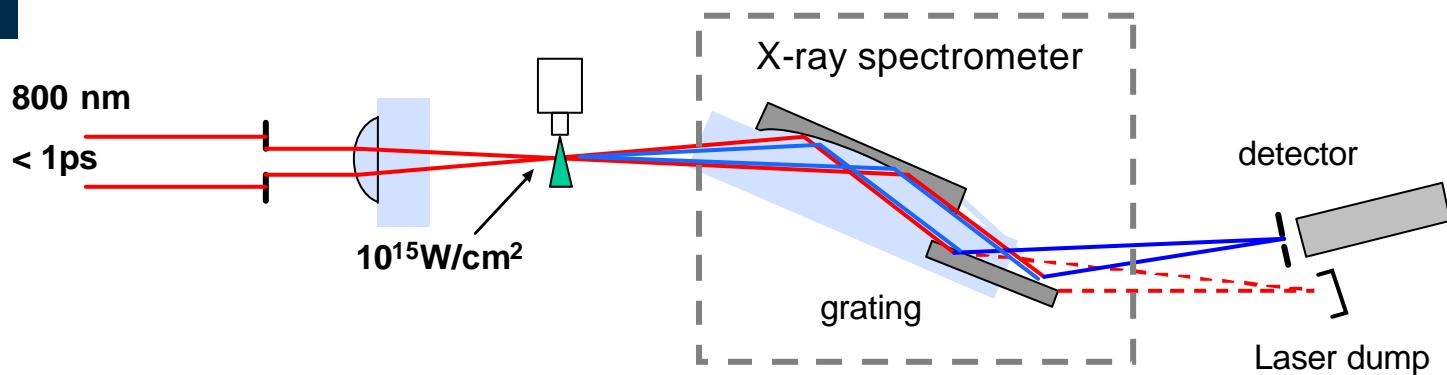
But the laser field is so intense
that it highly distorts the potential!

$$U(x) = \frac{-e^2}{4\pi\epsilon_0|x|} - eEx \approx GV/\text{cm}$$

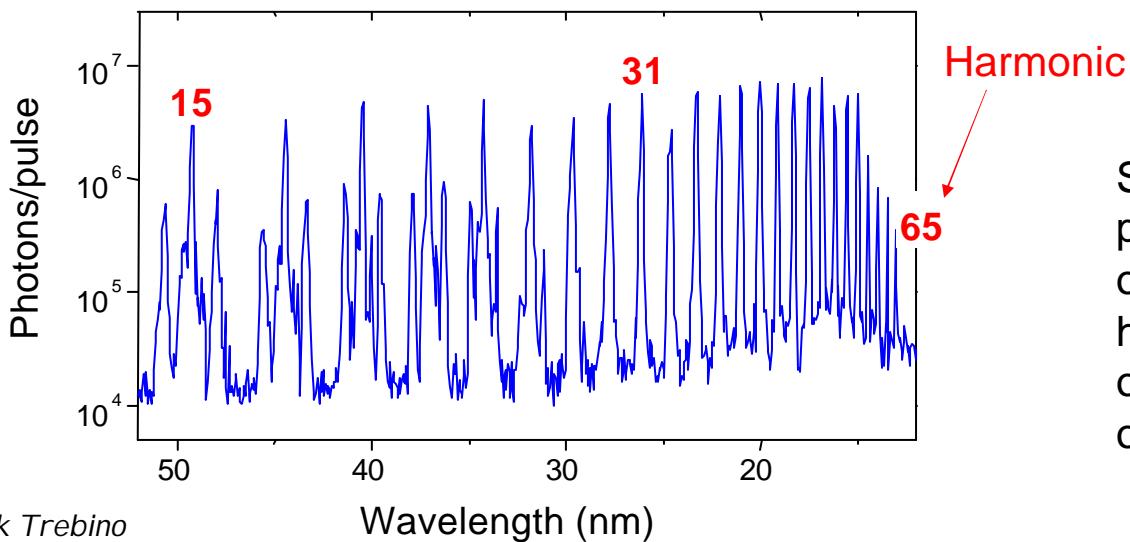




High Harmonic Generation in a gas



HHG in neon



Rick Trebino

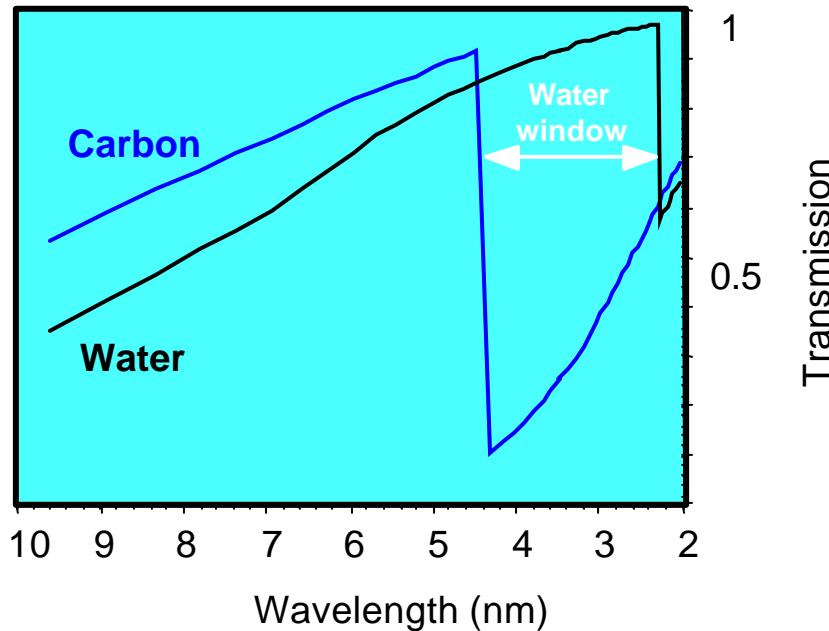
Symmetry issues prevent HHG from occurring at even harmonics. But it yields odd harmonics and lots of them!

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X-ray wavelengths between 2.2 and 4.5 nm have major biological applications.

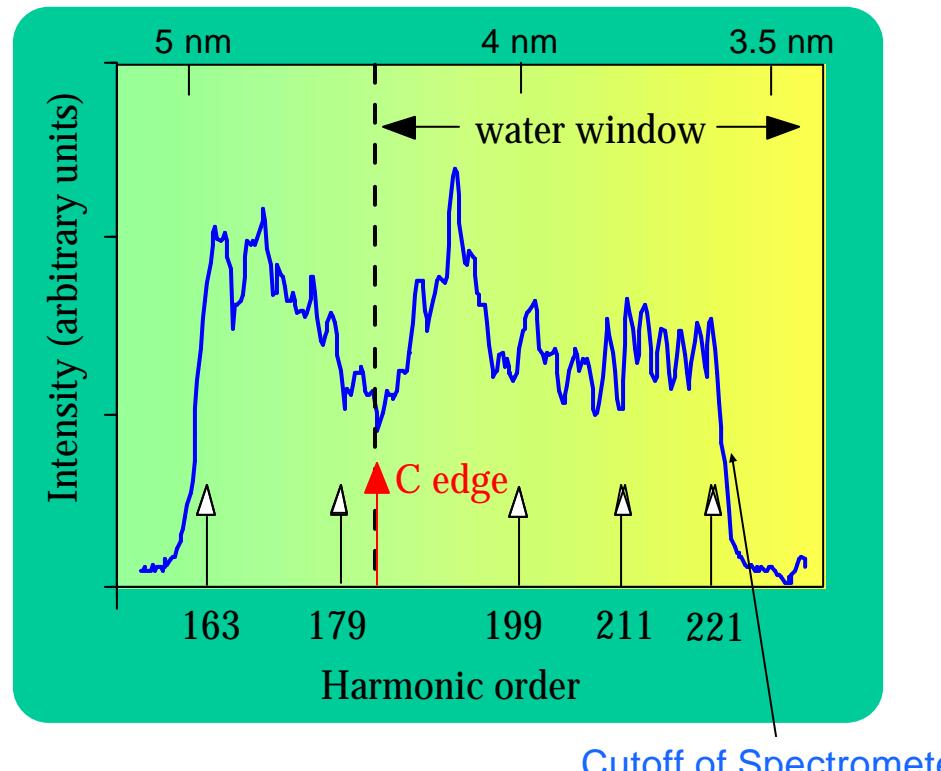


Carbon absorbs these wavelengths, but water doesn't.
This is the “water window.”



In He, it's possible to generate x-rays in the water window.

Coherent < 10fs x-ray generation in He to 2.7 nm



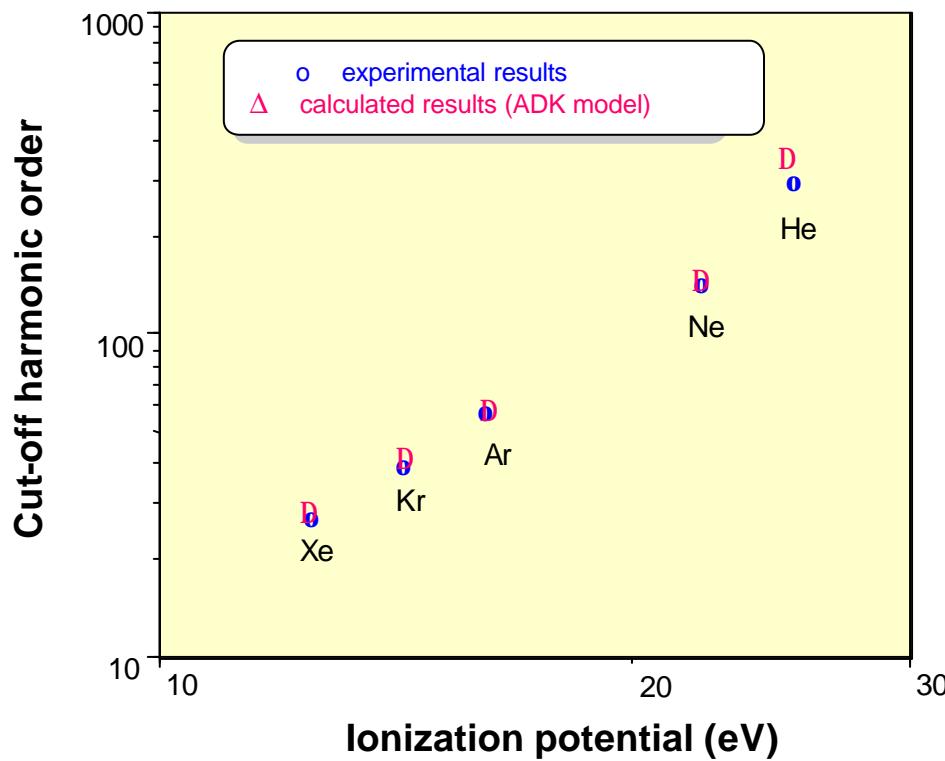
Rick Trebino

Z. Chang et al, Phys. Rev. Lett. 79, 2967 (1997)

C. Spielmann et al, Science 278, 661 (1997)



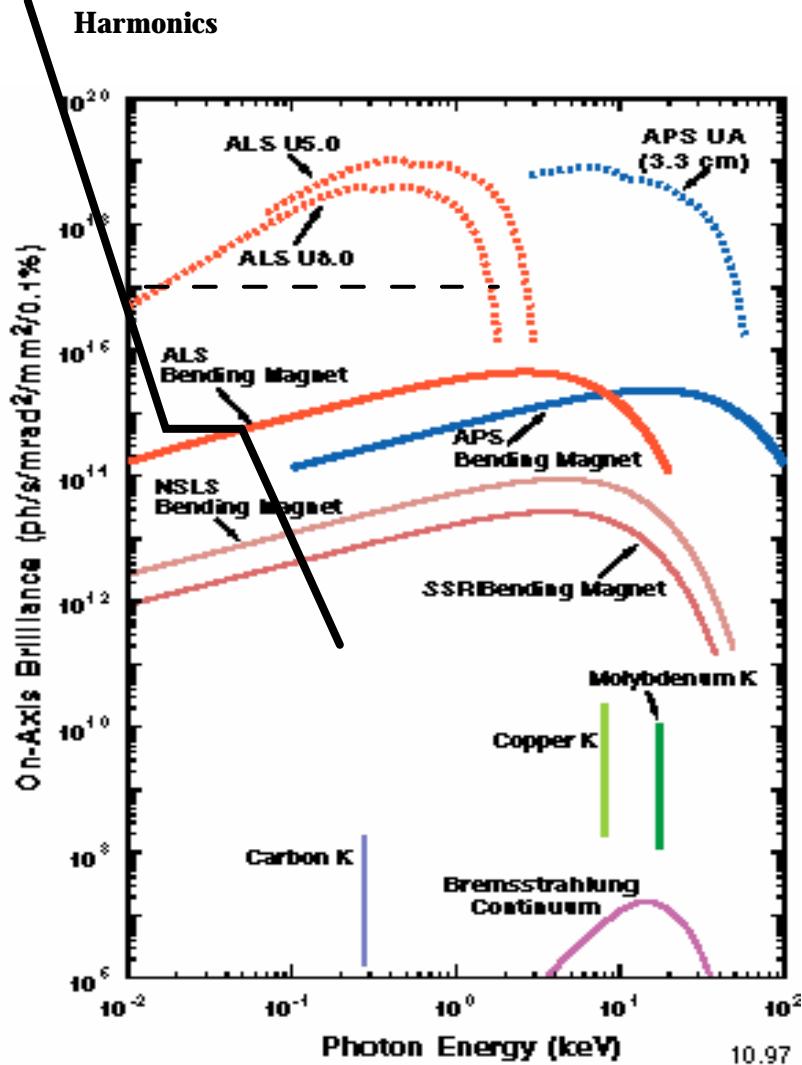
The cut-off wavelength depends on the medium.



$$h\nu_{cutoff} = I_p + 3.2 U_p$$

↑
ionization potential of atom

$U_p \mu I_p^{1/2}$
quiver energy of e^-



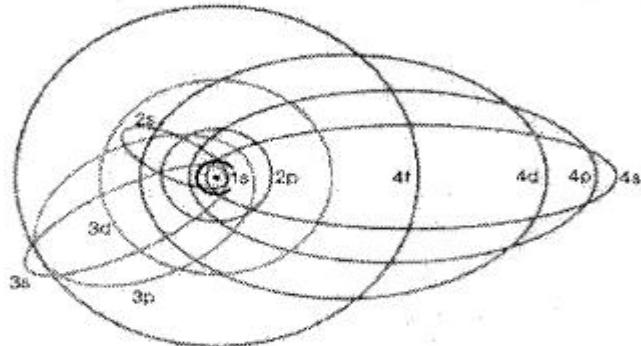
Average brilliance: HHG vs. other x-ray sources

High harmonics are weaker, but they're ultrafast and spatially coherent



Why try to make attosecond pulses?

Tracing the Motion of Electrons in Atoms?



Bohr-model:

It takes

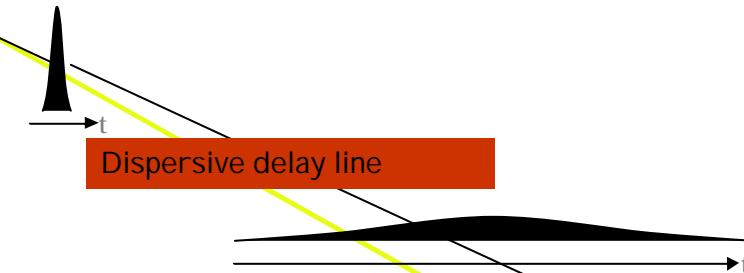
$T_{\text{orbit}} \approx 152$ attoseconds
for the electron to circle
around the proton in the
ground state of the
hydrogen atom.

- ☒ Requires measurement of time within a fraction of light oscillation



Chirped-Pulse Amplification

Short pulse oscillator



Chirped-pulse amplification involves stretching the pulse before amplifying it, and then recompressing it later.

CPA is THE big development.

G. Mourou and coworkers 1983

Pulse compressor

We can stretch the pulse by a factor of 10,000, amplify it, and then recompress it!

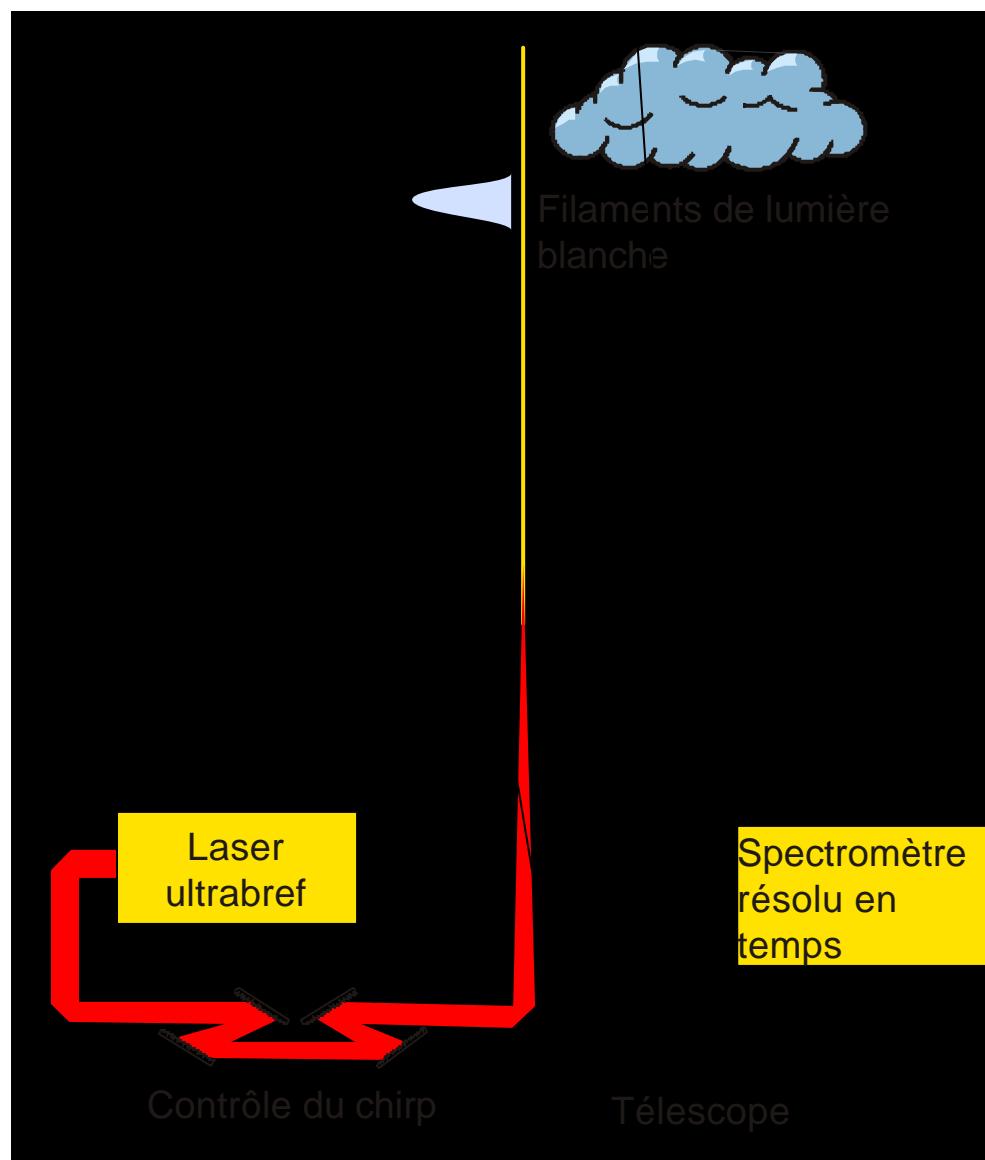
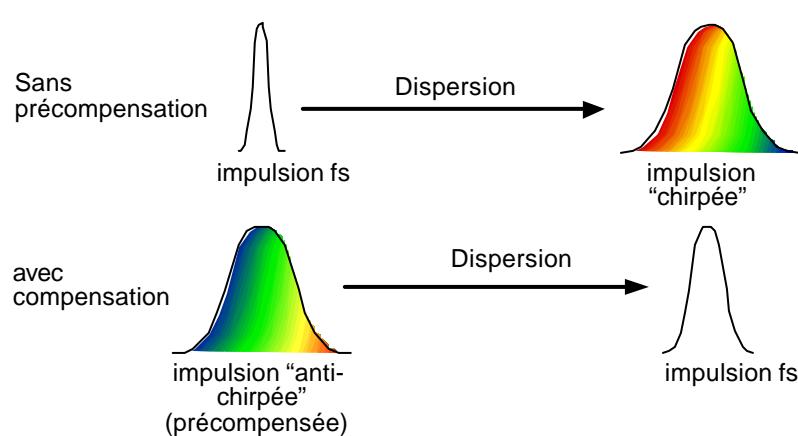
Rick Trebino

O N E R

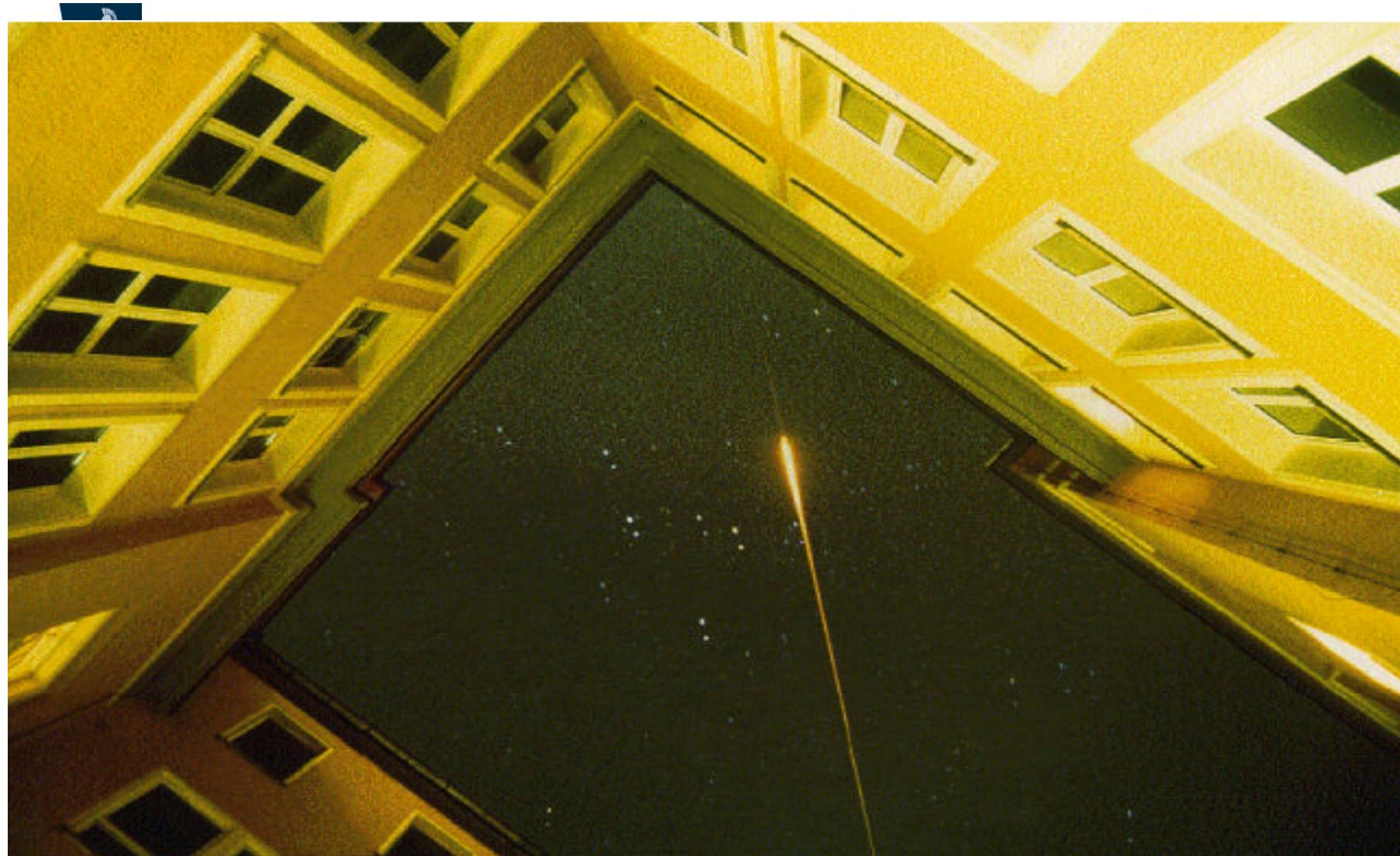
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Principe du Lidar non-linéaire



J.P. Wolf

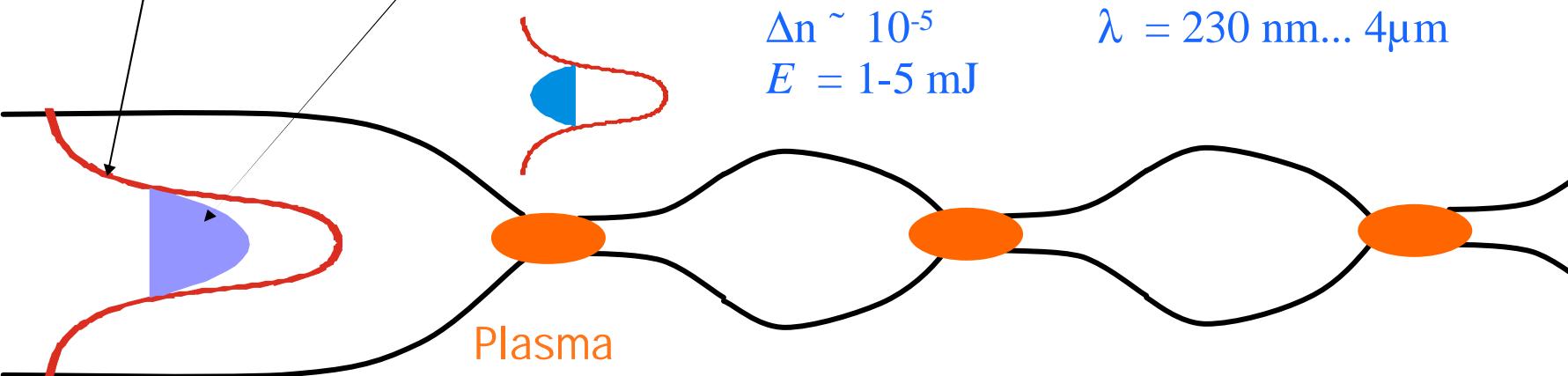




Propagation auto-guidée

Profil d'intensité

« Lentille » de Kerr



$$F = 100 \mu\text{m}$$

$$L > 300 \text{ m}$$

$$\Delta n \sim 10^{-5}$$

$$E = 1-5 \text{ mJ}$$

$$I = 10^{14} \text{ W/cm}^2$$

$$\rho = 10^{15} \text{ cm}^{-3}$$

$$\lambda = 230 \text{ nm... } 4\mu\text{m}$$

Que se passe-t'il pour :

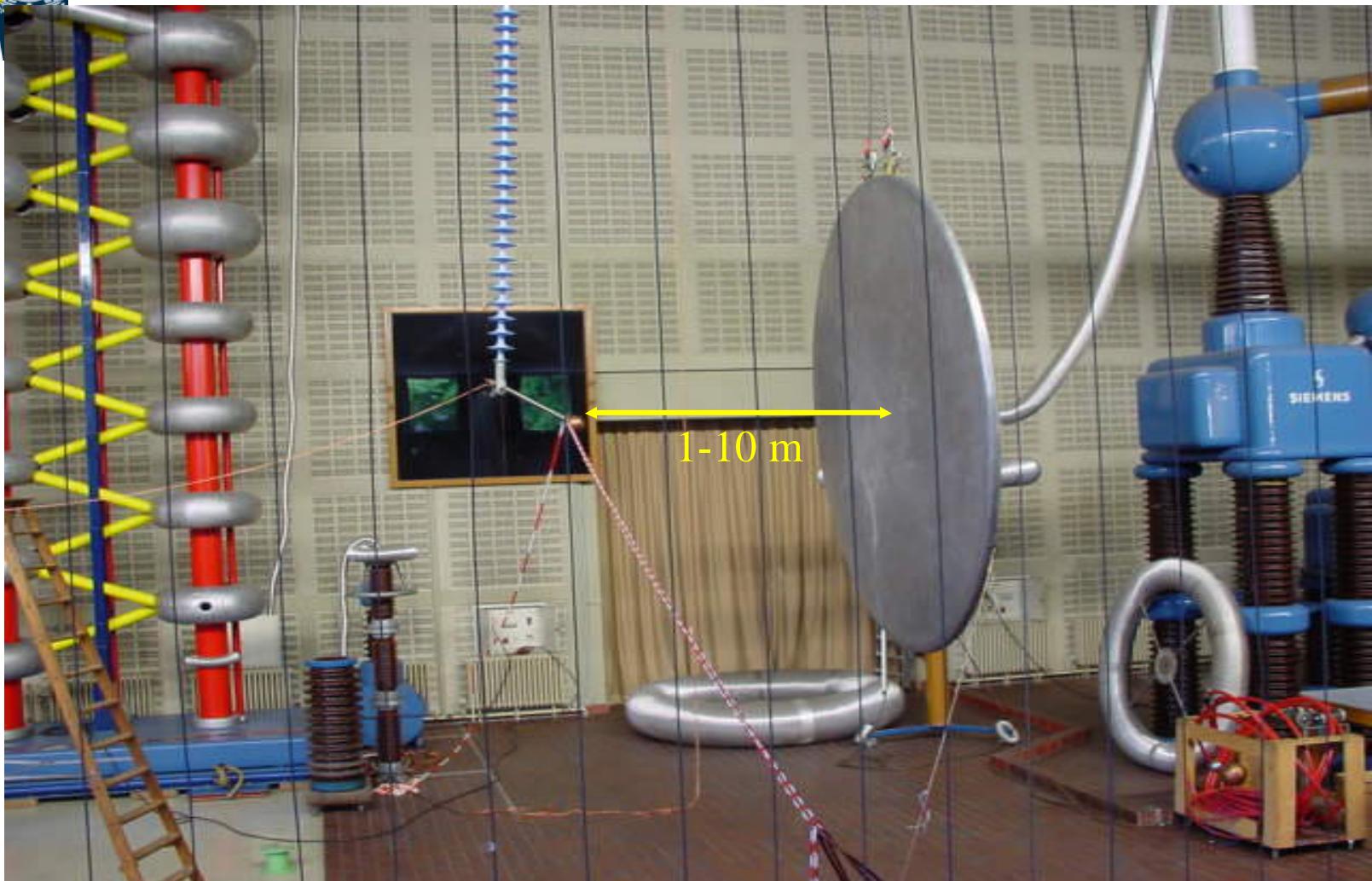
- un faisceau puissant et étendu (multifilamentation) ?
- très longues distances ?
- un profil de faisceau « sale » ?
- contrôler le processus ?

J.P. Wolf



Contrôle laser de décharges haute tension

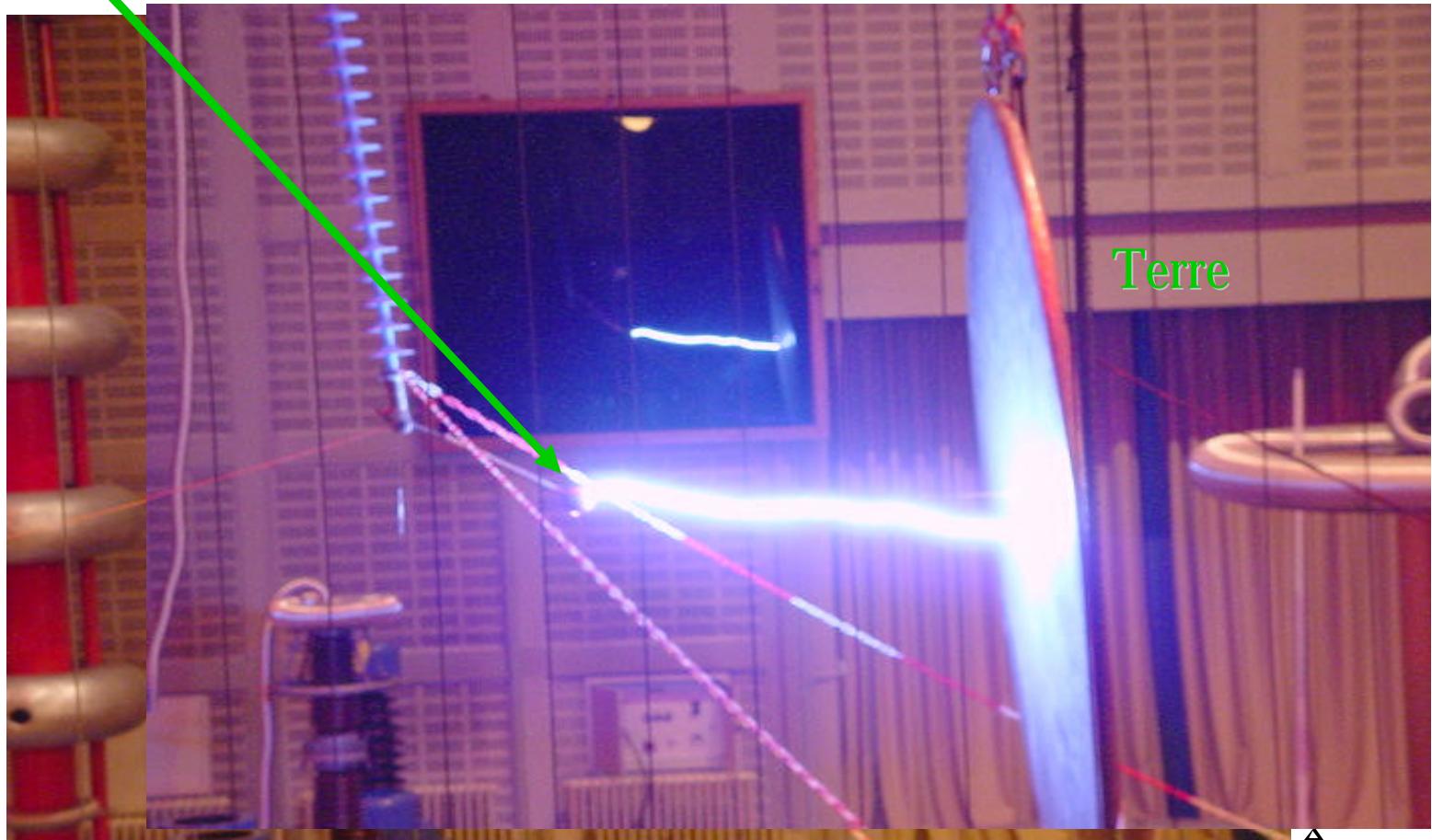
J.P. Wolf





« Nuage » : -1 MV, 1,2 μ s

J.P. Wolf

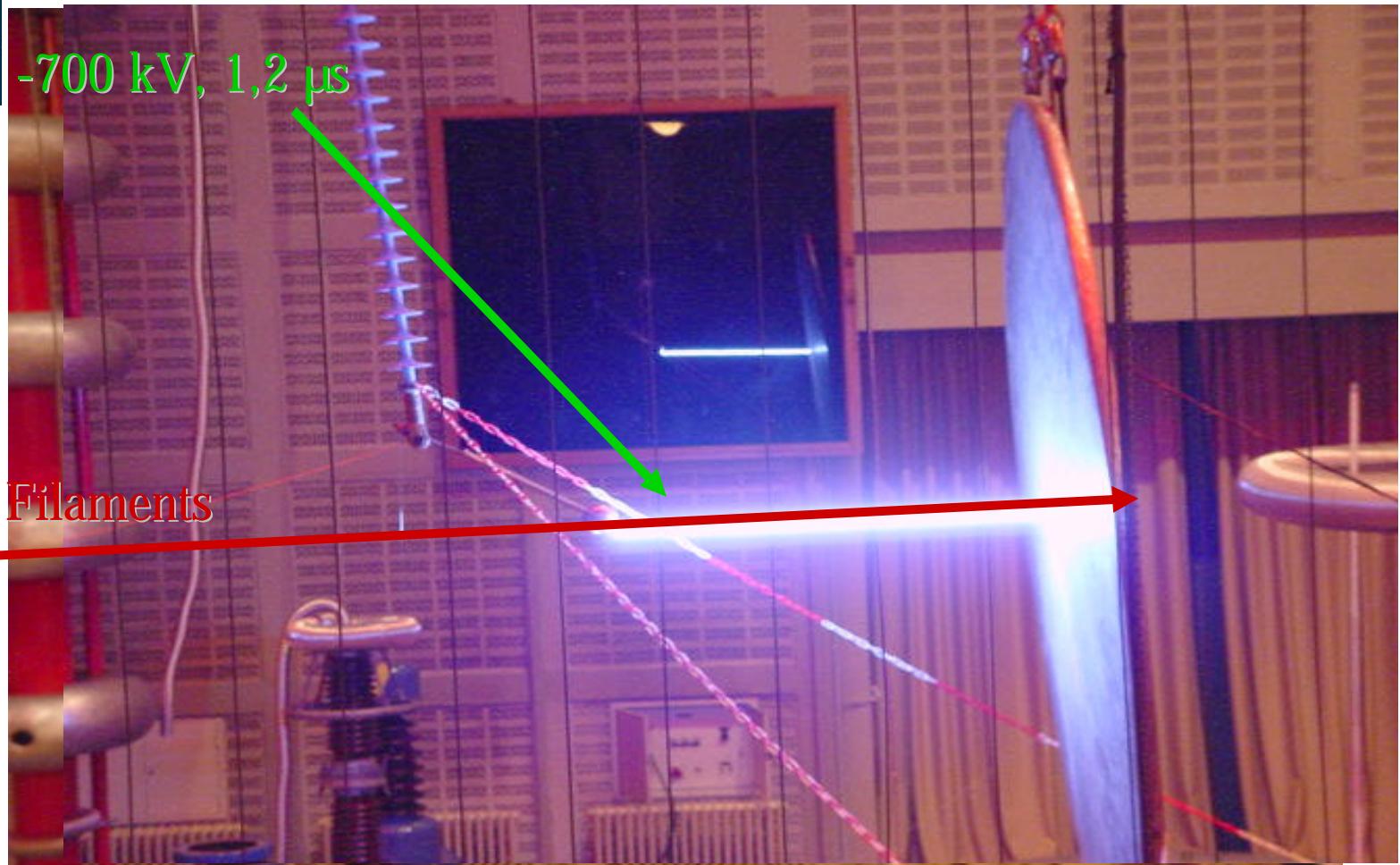


CERN

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J.P. Wolf



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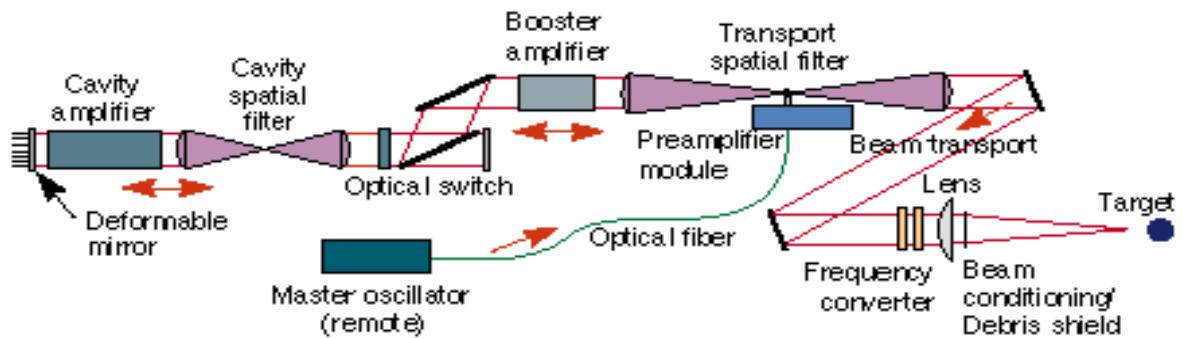


Even Higher Intensities!



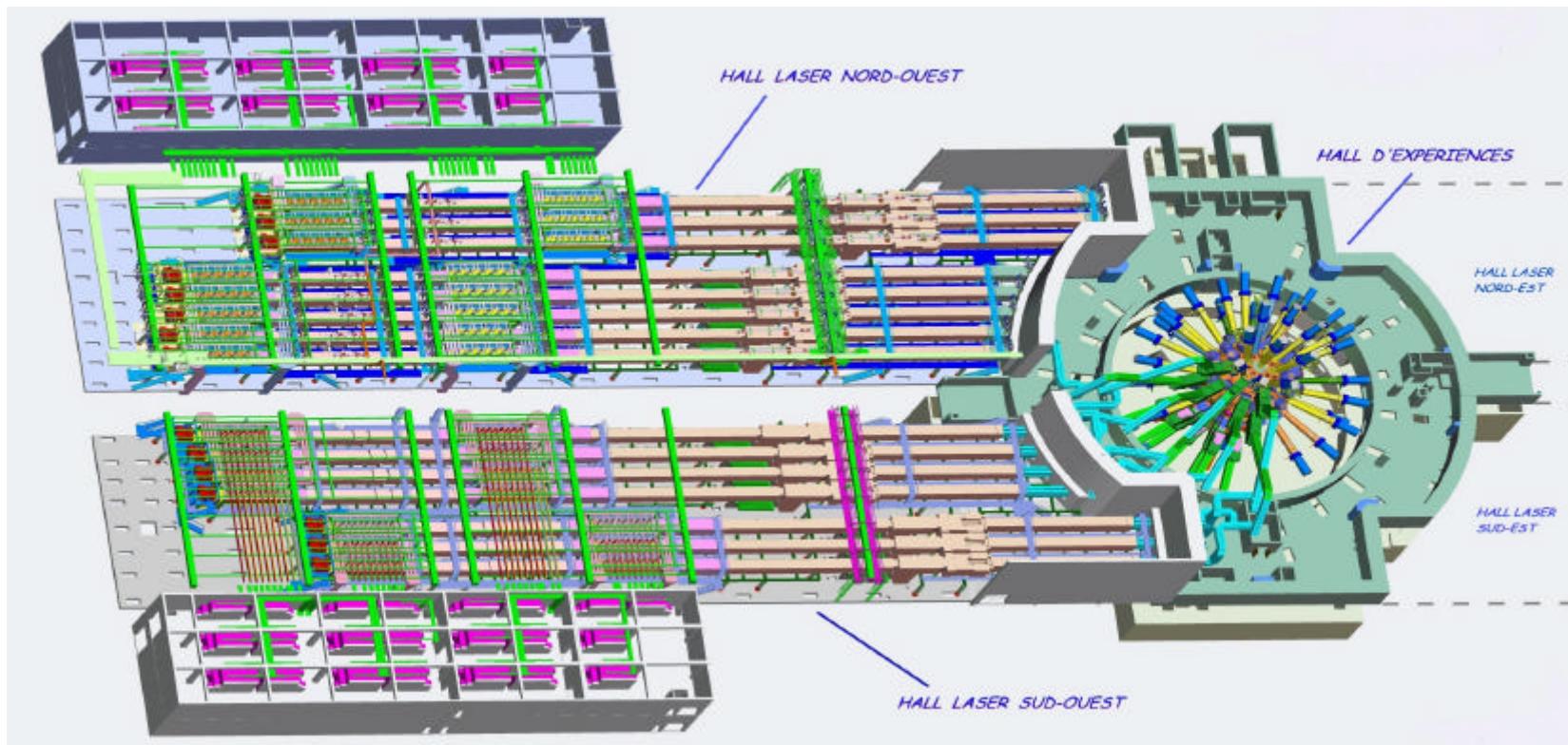
National Ignition Facility
(under construction)

192 shaped pulses
1.8 MJ total energy!!!
Sub-ns pulses





Laser MégaJoule du DEA-DAM: Halls laser NO et SO et hall d'expériences du LMJ





Laser MégaJoule du DEA-DAM: LA SALLE EXPÉRIENCES

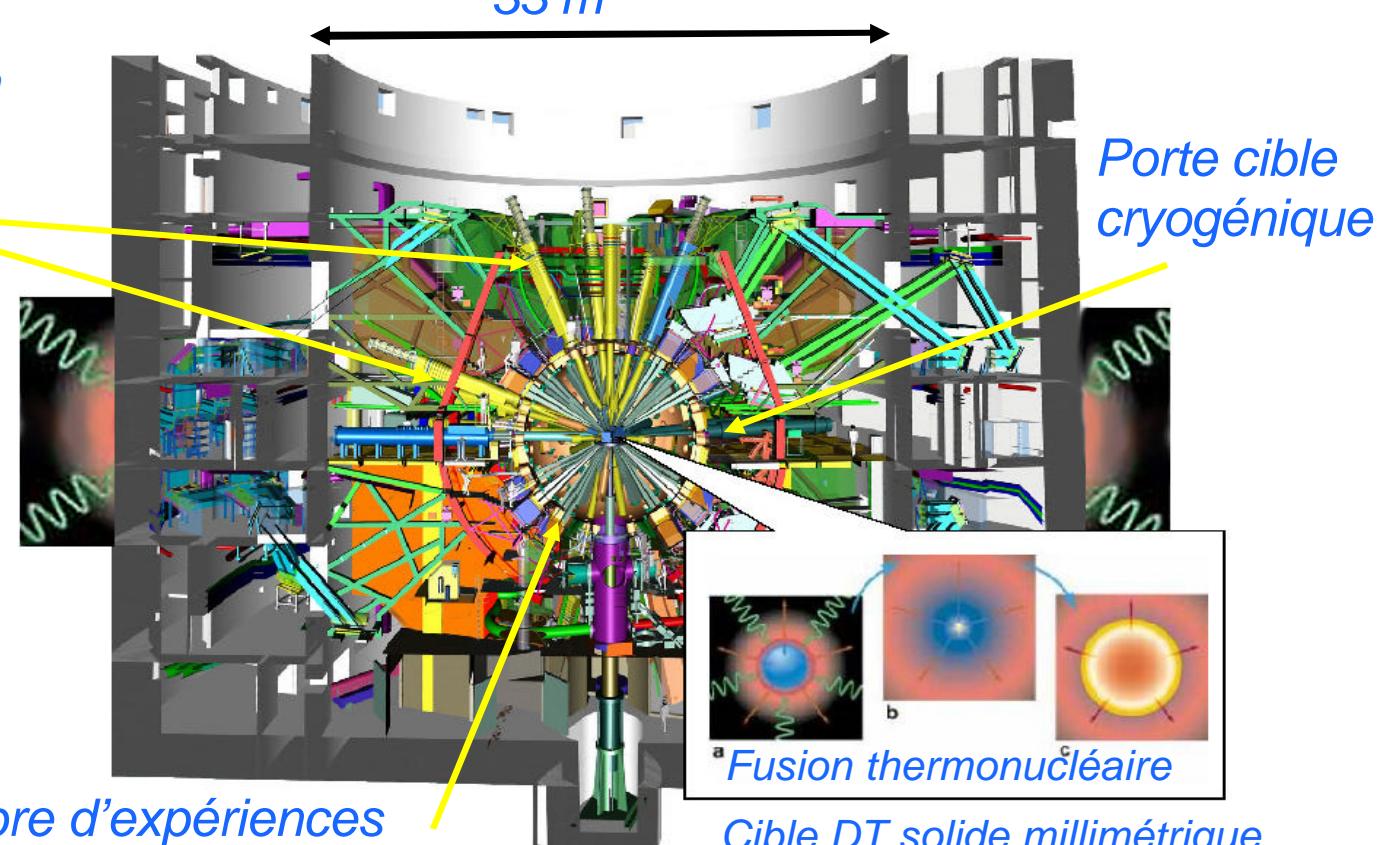
Tubes d'insertion
des diagnostics

Energie
Laser

1.8 MJ

Chambre d'expériences
10 m de diamètre

33 m



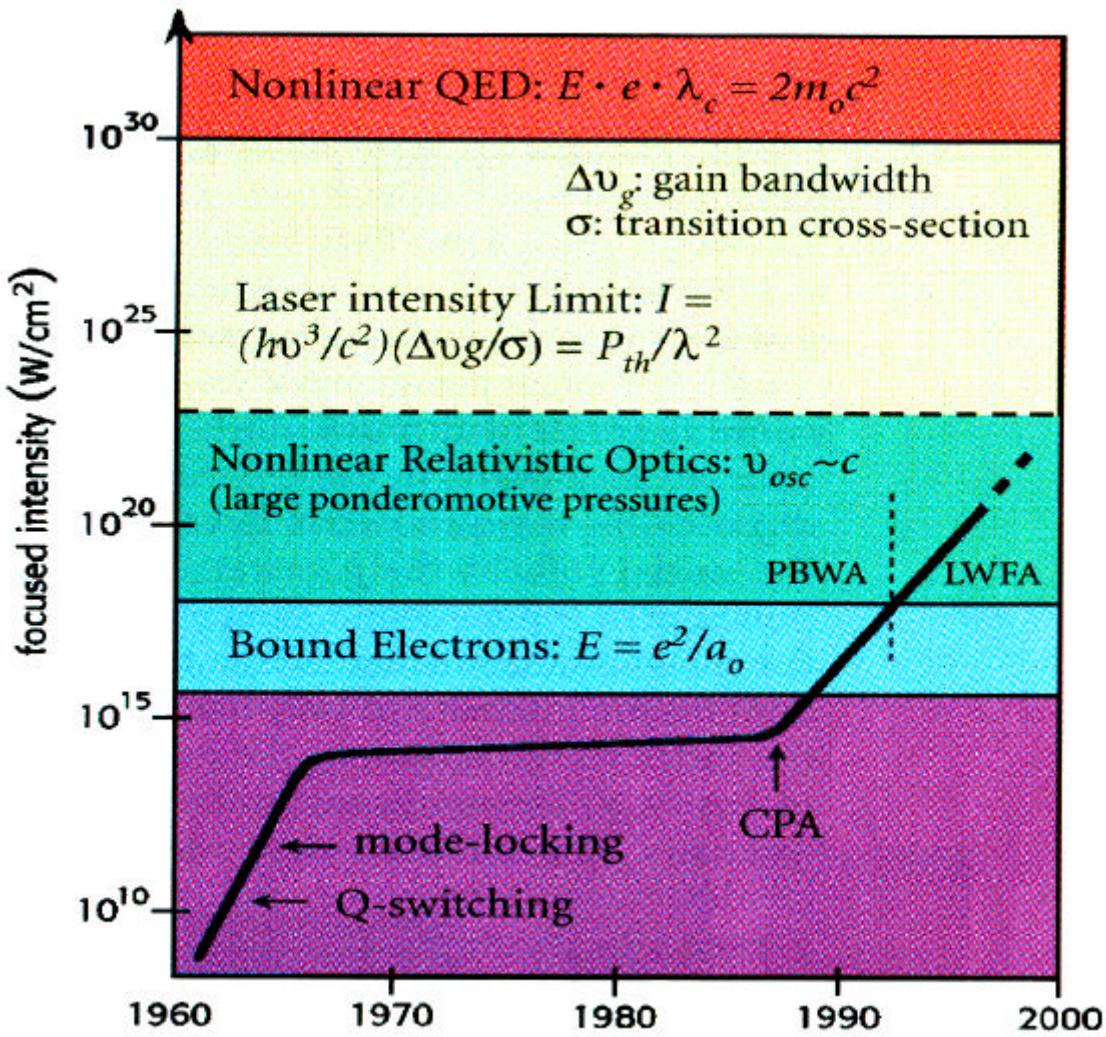
Fusion thermonucléaire
Cible DT solide millimétrique
20 MJ

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What to do with such high intensities



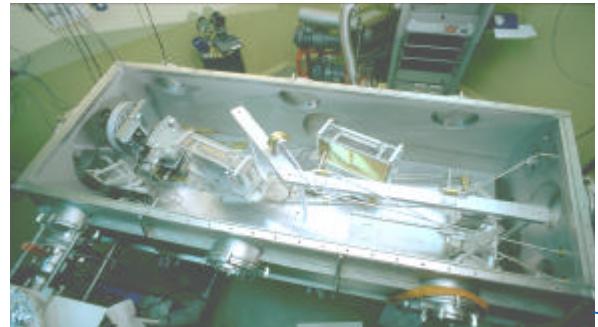


ACCELERATION DE PARTICULES PAR LASER



F. Amiranoff

*Laboratoire pour l'Utilisation des Lasers Intenses : LULI
Unité mixte CNRS - CEA - Ecole Polytechnique - Université Paris 6*





QUELQUES FORMULES TRIVIALES...

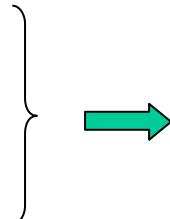
Energie électromagnétique

$$P = \frac{1}{2Z_0} F^2$$

Poynting

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377 \Omega$$

Impédance du vide



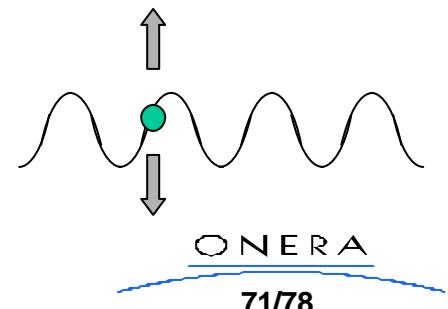
$$F \text{ V/cm} = 27.5 \sqrt{P \text{ W/cm}^2}$$

Energie de tremblement (*quivering*)

$$m \ddot{x} = q F e^{i \omega t} \rightarrow x = -\frac{q}{m \omega^2} F e^{i \omega t} \rightarrow E_q = \frac{1}{2} m \dot{x}^2 = \frac{1}{2} \frac{q^2 F^2}{m \omega^2} \quad (\text{non relativiste})$$

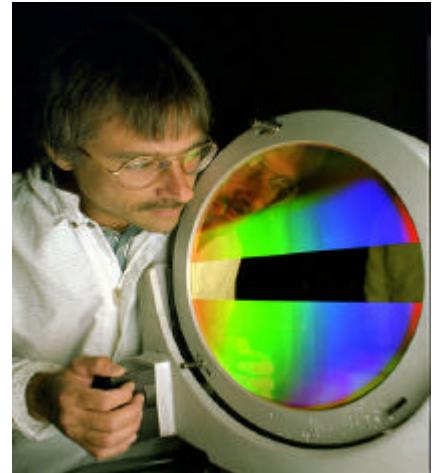
$$\rightarrow E_q = \frac{Z_0 q^2}{m} \frac{P}{\omega^2}$$

$$E_q (\text{eV}) = 210^{-13} P \text{ W/cm}^2 (l_{\mu\text{m}})^2$$





Le laser Petawatt à Livermore



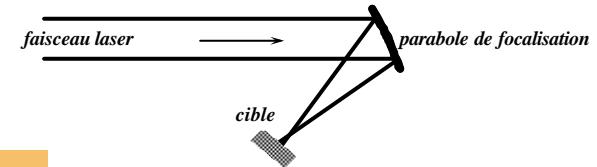
**Le kilojoule en moins d'une
picoseconde**



Les lasers ultra-intenses



Intensité : 10^{16} W/cm^2 à 10^{20} W/cm^2



$$E [\text{V/m}] = 3.10^3 I^{1/2} [\text{W/cm}^2]$$

Champ électrique : **300 GV/m à 30 TV/m (3.10^{13} V/m)**

> champ intra-atomique $\sim 100 \text{ GV/m}$

Energie d'oscillation d'un électron : **$250 \text{ keV} * I / 4.10^{18} \text{ W/cm}^2$**

Les électrons oscillent à des vitesses relativistes

Comment transformer ces accélérations radiales en transversales ???

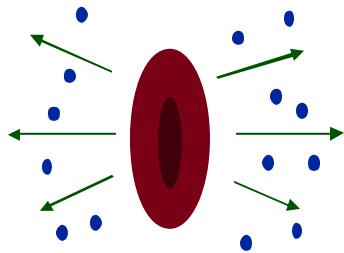
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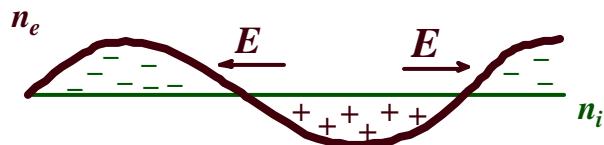
Accélération laser de particules

LEADER

Point n°1 : une impulsion laser repousse les électrons
vers les zones de champ faible



Point n°2 : dans un plasma, une séparation de charges électrons - ions
est associée à un champ électrique très élevé



$$E \text{ [GV/m]} = 30 \left[n_e / 10^{17} \text{ cm}^{-3} \right]^{1/2} d$$

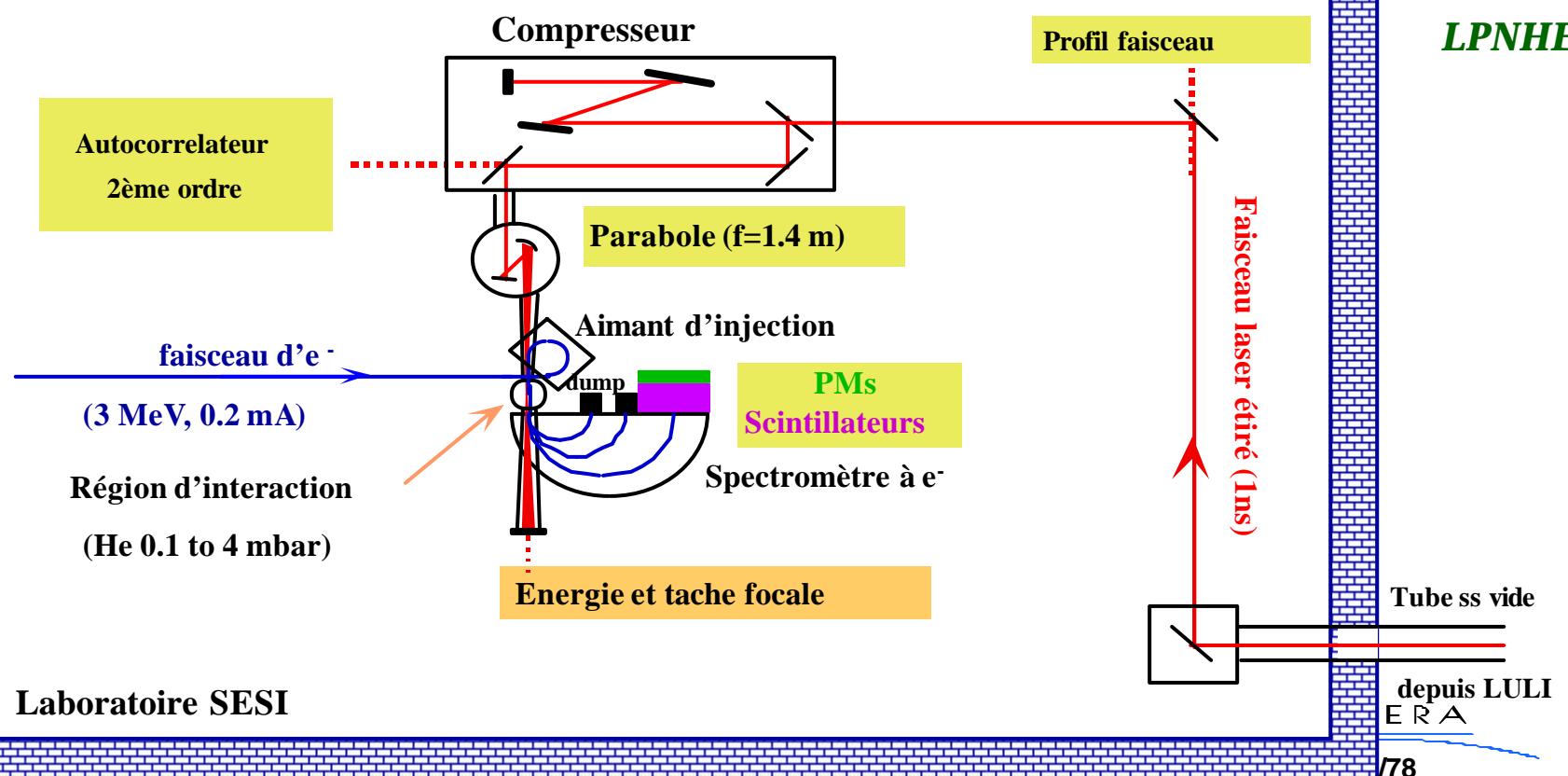
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Sillage laser : schéma expérimental



LSI

LPNHE





Sillage laser :

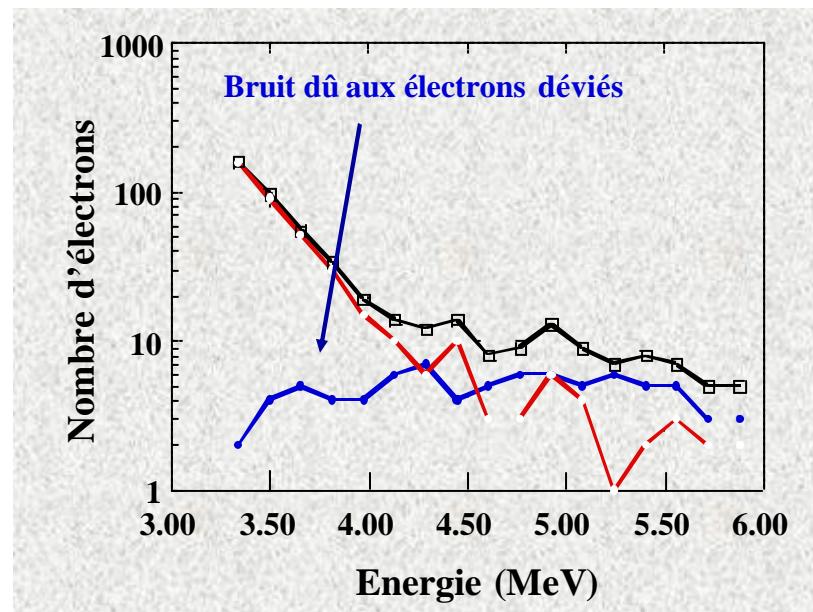
LPNHE

LSI

Acceleration dans un champ de 1.5 GV/m et effets radiaux



Les électrons de 3-MeV sont accélérés jusqu'à \sim 4.5 MeV
Dans un champ maximum de 1.5 GV/m



2.5 J 350 fs 10^{17} W/cm² 0.5 mbar He

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Conclusion et futur sur l'accélération laser de particules



- L'accélération laser de particules a été démontrée
 - Gains d'énergie de 1 MeV à 100 MeV
 - Champs E de 1 GV/m à 100 GV/m
 - Gains du GeV espérés
- Sources d'électrons jusqu'à ~ 1 GeV (nC, <1 ps)
 - La qualité doit être mesurée et améliorée
- Gains d'énergie élevés
 - La qualité du faisceau doit être mesurée
- Des gains plus élevés nécessitent un guidage laser
 - Plusieurs schémas sont en cours de tests