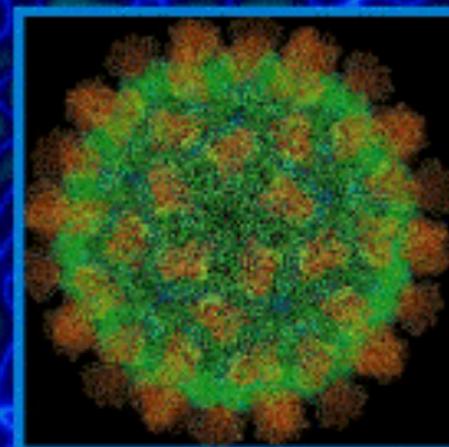


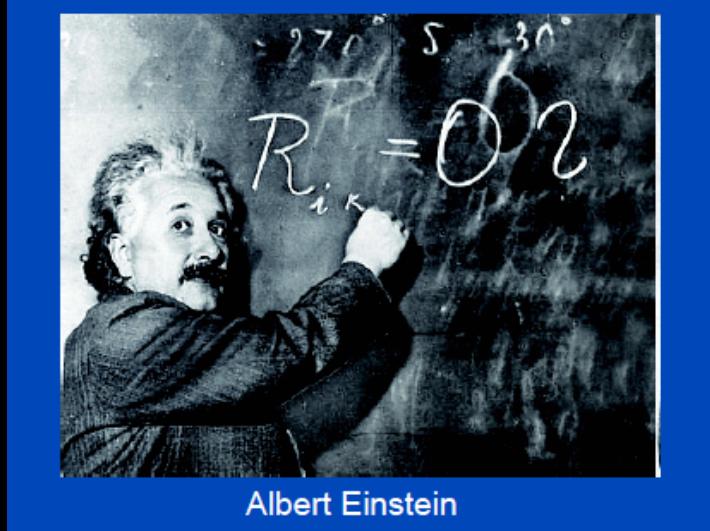
Il fascino discreto della luce laser

Massimo.Ferrario@LNF.INFN.IT

Anno Internazionale della Luce 2015
LNF – Mercoledi' 29 Aprile



1 – Absorption, Spontaneous and Stimulated Emission of Radiation - 1917



$$0 = A_{21}n_2 + B_{21}n_2\rho(\nu) - B_{12}n_1\rho(\nu)$$

Physik Zeitschr. XVIII, 1917. Einstein, Zur Quantentheorie der Strahlung. 124

	$\beta = 1$	6	12	kg/cm^2
Höllmesser der Röhrenfeder	$t_0 = 5,50$	$5,16$	$5,55$	cm
Größe Hallbachse d. Ellipse	$a = 1,138$	$0,847$	$0,726$	-
Kleine	$b = 0,93$	$0,743$	$0,711$	-
Wandsstärke	$R = 0,021$	$0,018$	$0,015$	-
Bogenlänge der Röhrenfeder	$x = 270^\circ$	270°	270°	-
Aufbiegung nach Venuoch	$A_x = 4,575$	$0,895$	$0,454$	-
Gl. (25a)	$A_x : \beta = 0,912$	$0,766$	$0,378$	-

Mit Rücksicht auf die nur unvollkommenen Erfassungsgegenstände und die Merkmalskurven sowie auf die Verbindung des Enden, welche zweifellos die der Theorie zugrunde liegende Achsenymmetrie um ZZ beeinträchtigt, kann man die Abweichungen der berechneten und gefundenen Aufbiegungen an der 6 kg- und 12 kg-Röhrenfeder als zufällig ansehen, zumal sie entgegengesetztes Vorzeichen besitzen. Bei der schwachen 1 kg Feder dagegen reicht dies zur Erklärung einer 4-fachen Aufbiegung jedenfalls nicht aus, so daß man hierfür auf die strengere Formel (38) zurückgreifen müßte. Außerdem ist es nicht unwahrscheinlich, daß in diesem Falle die Doppelymmetrie bei der Formänderung verloren gegangen ist, ein Umstand, dem man in Gl. (8) näherungsweise durch Hinzufügung eines oder mehrerer Terme mit geraden Vielfachen von φ genügen könnte.

Danzig-Langfuhr, Techn. Hochschule,
(Eingegangen 26. Februar 1917)

Zur Quantentheorie der Strahlung.
Von A. Einstein.

Die formale Ähnlichkeit der Kurve der charakteristischen Verteilung der Temperaturstrahlung mit Maxwell'schen Geschwindigkeitsverteilungsgesetzen ist zu fragen, ob daß sie lange hätte verborgen bleiben können. In der Tat wurde bereits W. Wien in der wichtigen theoretischen Arbeit, in welcher er sein Verschiebungsgesetz ableitete, durch diese Ähnlichkeit auf eine weitergehende Bestimmung der Strahlungsfomel geführt. Er fand hierbei bekanntlich die Formel

$$\varrho = v^3 f\left(\frac{v}{T}\right) \quad (1)$$

ablesen, durch diese Ähnlichkeit auf eine weitergehende Bestimmung der Strahlungsfomel geführte. Er fand hierbei bekanntlich die Formel

$$\varrho = a v^3 e^{-\frac{av}{kT}} \quad (2)$$

welche als Grenzgesetz für große Werte von v auch heute als richtig angesehen wird (Wien-
1). Zuletzt aufgebrückt in den Mitteilungen der Physikalischen Gesellschaft Zürich, Nr. 85, 1908.

sche Strahlungsfomel). Heute wissen wir, daß bei dieser Betrachtung, welche auf die klassische Mechanik und Elektrodynamik aufgebaut ist, eine brauchbare Strahlungsfomel liefern kann, sondern daß die klassische Theorie sowohl auf die Rayleighsche Formel

$$\varrho = \frac{h}{\lambda} v^2 T \quad (3)$$

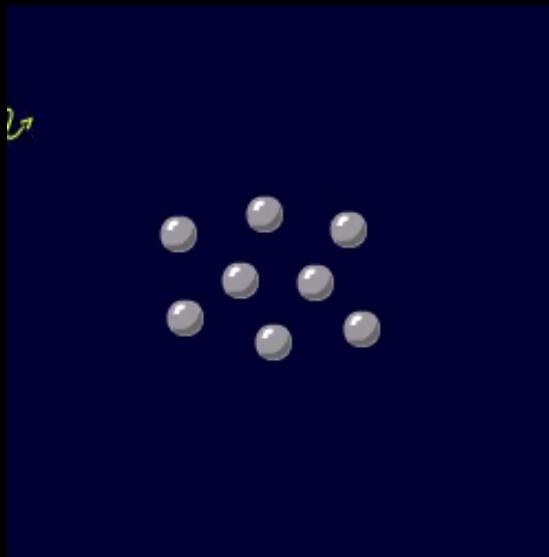
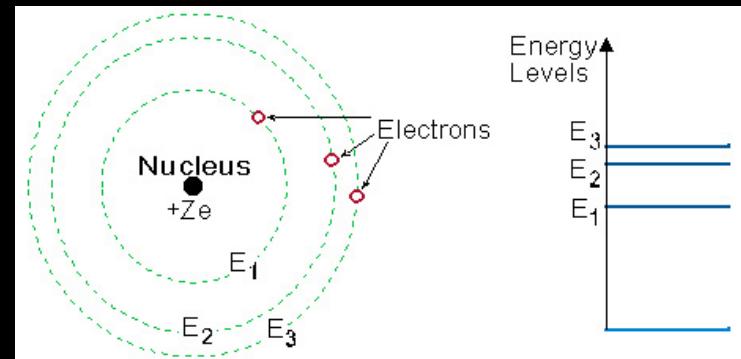
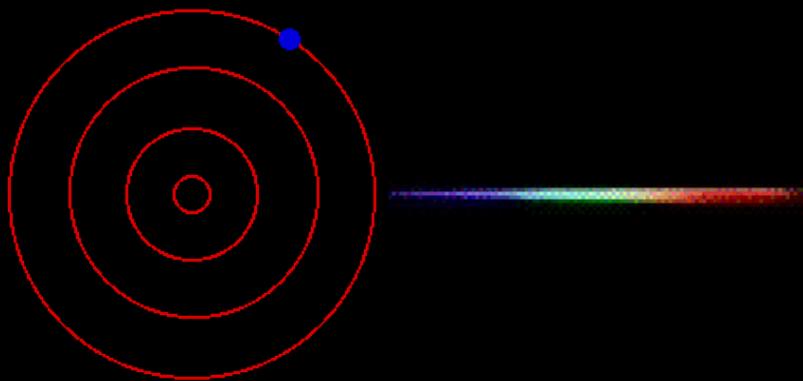
führt. Als dann Planck in seiner grundlegenden Untersuchung seine Strahlungsfomel:

$$\varrho = a v^3 \frac{e^{\frac{av}{kT}}}{e^{\frac{av}{kT}} - 1} \quad (4)$$

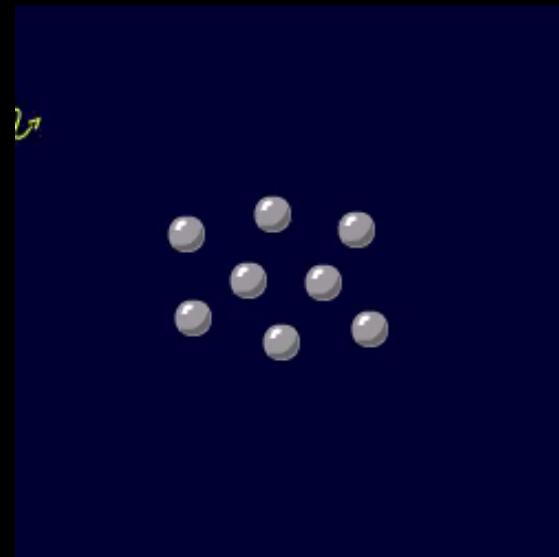
auf die Voraussetzung von diskreten Energieniveaus gegründet hatte, auf welcher sich in rascher Folge die Quantentheorie entwickelte, gewiß jene Wiensche Überlegung, welche zur Gleichung (2) geführt hatte, ausgespielt wieder im Vergessenheit.

Vor kurzem nun fand ich eine der ursprünglichen Wienschen Betrachtung¹⁾ verwandt, auf die Grundvorstellung der Quantentheorie sich stützende Ableitung der Planckischen Strahlungsfomel, in welcher die Beziehung der Maxwell'schen Kurve zu der charakteristischen Ver-
teilungskurve zur Gelung kommt. Diese Ableitung verdient nicht nur wegen ihrer Einfachheit Beachtung, sondern besonders deshalb, weil sie über den für uns noch so dunklen Vorgang der Emission und Absorption der Strahlung durch die Materie einige Klarheit zu bringen scheint. Indem ich einige von Standpunkte der Quantentheorie abweichende Hypothesen über die Strahlung-Emission und -Absorption von Molekülen zugrunde legte, zeige ich, daß Moleküle mit im Sinne der Quantentheorie bei Temperaturgleichgewicht verschiedenen Zuständen, im dynamischen Gleichgewicht mit Planckischer Strahlung stehen; es ergibt sich auf diesem Wege die Planckische Formel (4) in verblüffend einfacher und allgemeiner Weise. Sie ergibt sich aus der Bedingung, daß die von der Quantentheorie geforderte Zustandeverteilung der inneren Energie der Moleküle allein durch Absorption

¹⁾ Vier. A. Deutschen physikal. Gesellschaft Nr. 1214, 1908, S. 345. In der vorliegenden Ubersetzung sind die der 1908 übersetzten Abfassung gegebenen Übersetzungen wiederholt.



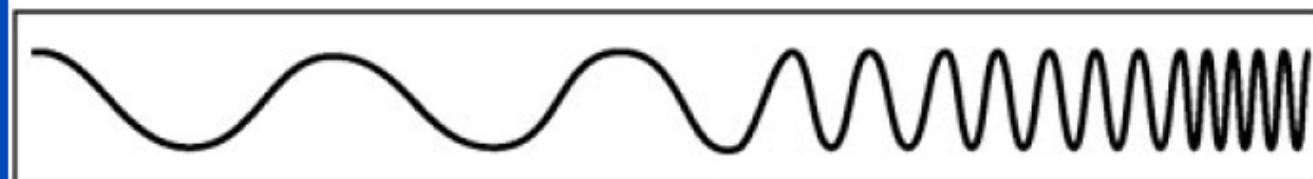
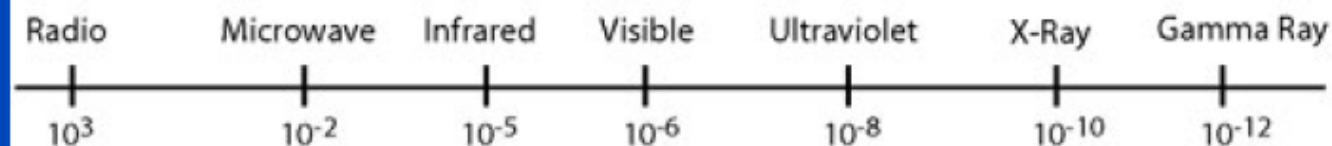
Absorption and Spontaneous Emission



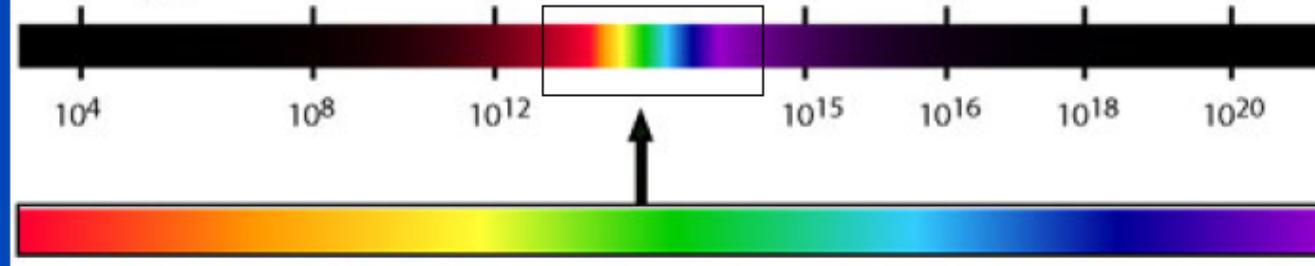
Stimulated Emission

THE ELECTRO MAGNETIC SPECTRUM

Wavelength
(metres)

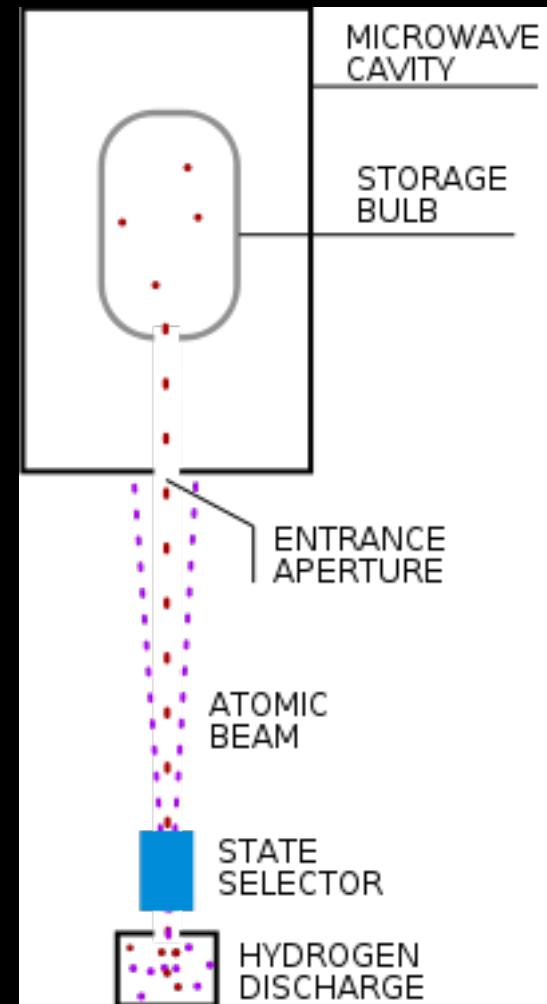
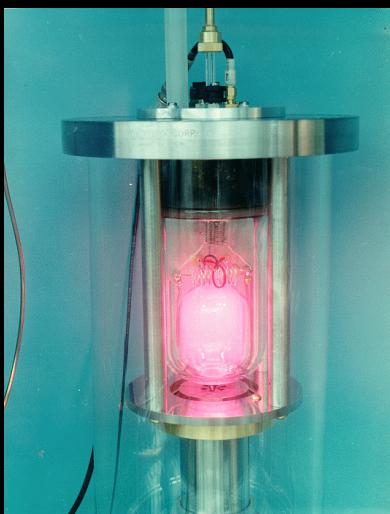
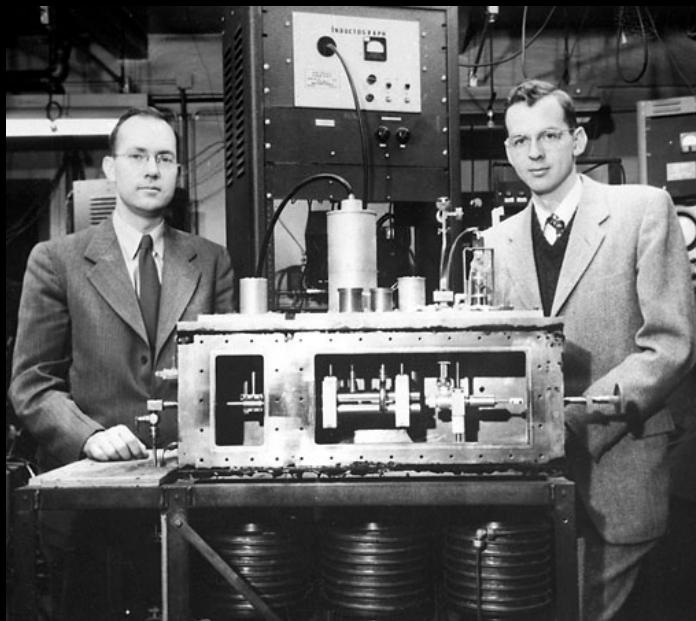


Frequency
(Hz)

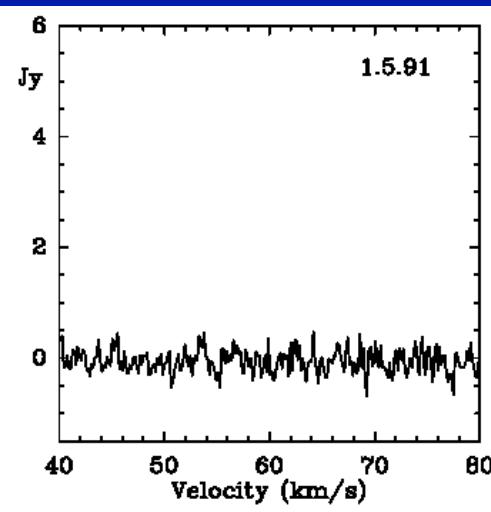
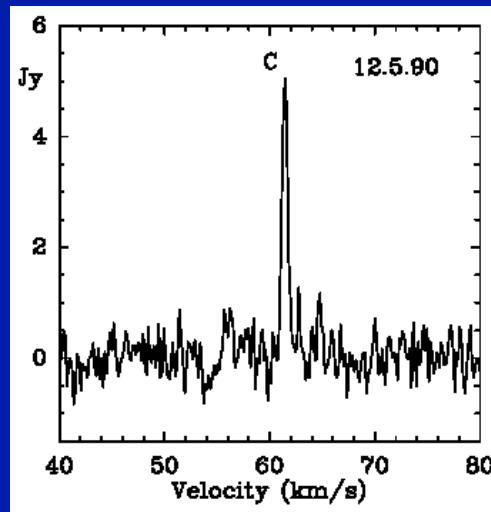
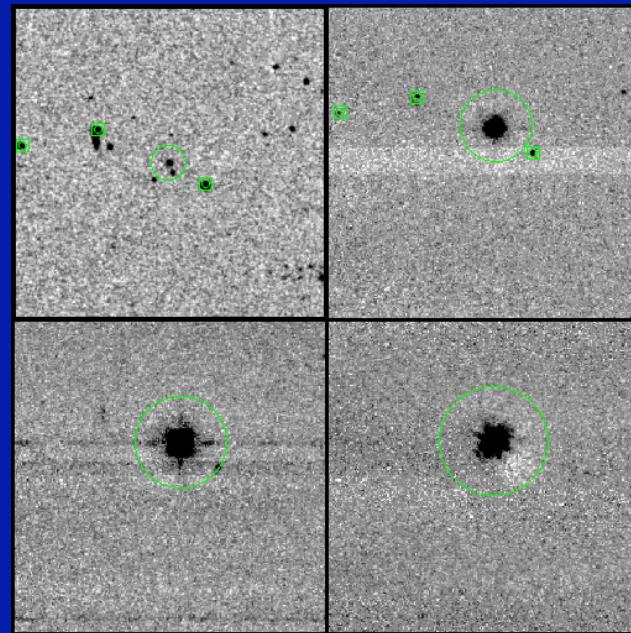


visible spectrum: $\lambda = 400 - 700 \text{ nm}$, $\nu = 7,5 - 4 \cdot 10^{14} \text{ Hz}$

Schawlow & Townes - H-MASER – 1953 – 1.5 GHz, ~ pW



Cosmic MASER 1963 – 20 - 90 GHz



Gordon Gould in 1957



14

Jack Gould

Some rough calculations on the feasibility
of a LASER: Light Amplification by Stimulated
Emission of Radiation.

conceive a tube terminated by optically flat

A simple diagram of a rectangular tube representing a laser cavity. The length of the tube is labeled L . The two vertical walls at the ends of the tube are labeled \mathbb{E}^{2R} , representing partially reflecting mirrors.

Jack Gould
Sworn to and subscribed before me
the 3 day of November 1957
Notary Public, State of New York
No. 08-1621510
Qualified in Bronx County
Commission Expires March 30, 1958

JACK GOULD

partially reflecting parallel mirrors. The mirrors
might be silvered or multilayer interference
reflectors. The latter are lossless and may
have an arbitrarily high reflectance
depending on the number of layers. ■ a
practical achievement is 98% in the visible
for a 7-layer ~~reflect~~ reflector. Flats with
closer tolerance than $1/100 \lambda$ are not available
so if a resonant system is desired, higher
reflectance would not be useful. However,
for a nonresonant system, the 99.9% reflectances
which are possible might be useful.

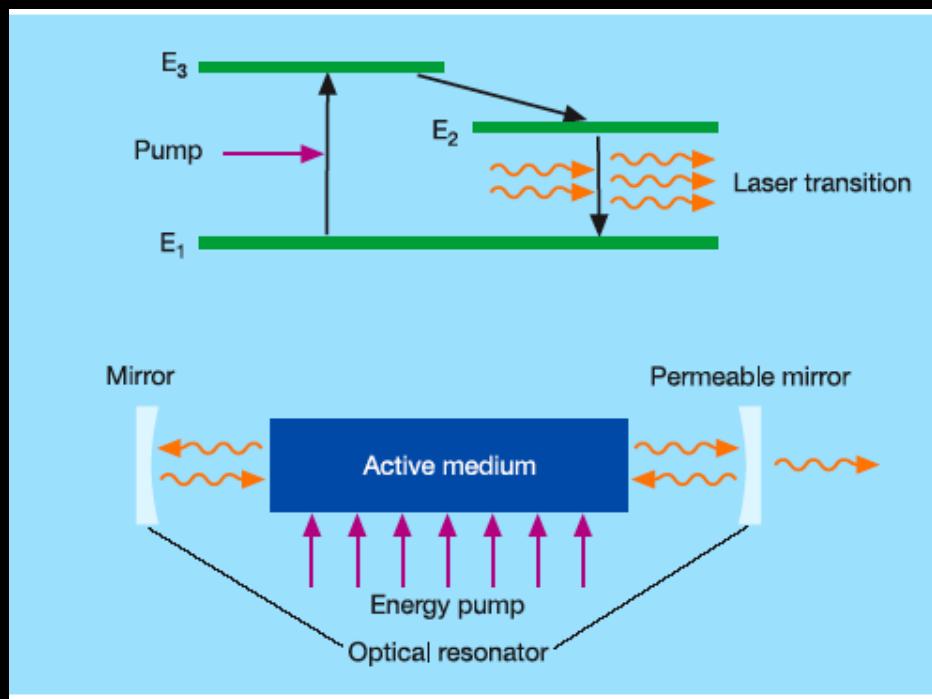
Consider a plane standing wave in the tube. There
is the effect of a closed cavity & since
the laser wavelength is small the diffraction
and hence the lateral loss is negligible.

① O.S. Heavens, "Optical Properties of Thin Solid Films"
(Butterworth Scientific Publications, London, 1955), p.220.

2 – Mirrors and optical cavity



3 - Population inversion



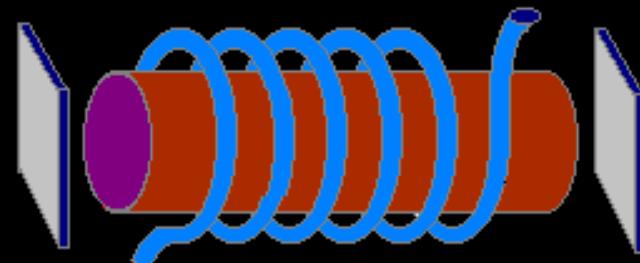
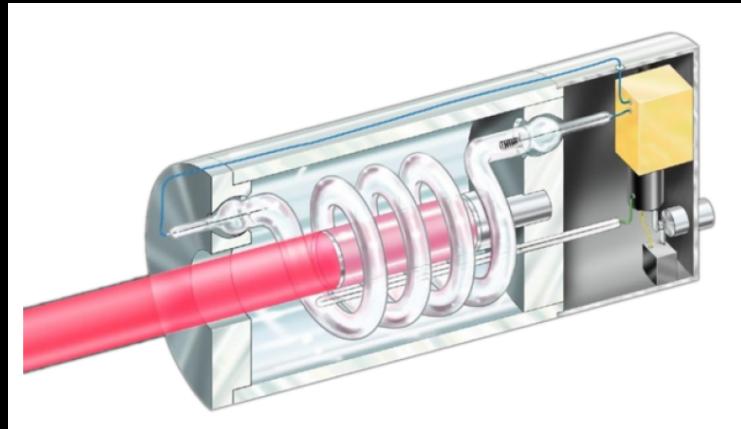
The Maiman Ruby Laser 694,3 nm, 10 kw, $\sim\mu$ s



In 1960 Maiman build the first operational laser device.

It was a ruby laser

In 1984 he awarded with the Nobel prize.



Stimulated Optical Radiation in Ruby

Schawlow and Townes¹ have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan² and Sanders³ have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å.; the active material used was ruby (chromium in corundum).

A simplified energy-level diagram for triply ionized chromium in this crystal is shown in Fig. 1. When this material is irradiated with energy at a wave-length of about 5500 Å., chromium ions are excited to the 3F_2 state and then quickly lose some of their excitation energy through non-radiative transitions to the 3E state⁴. This state then slowly decays by spontaneously emitting a sharp doublet, the components of which at 300° K. are at 6943 Å. and 6929 Å. (Fig. 2a). Under very intense excitation the population of this metastable state (3E) can become greater than that of the ground-state; this is the condition for negative temperatures and consequently amplification via stimulated emission.

To demonstrate the above effect a ruby crystal of 1-cm. dimensions coated on two parallel faces with silver was irradiated by a high-power flash lamp;

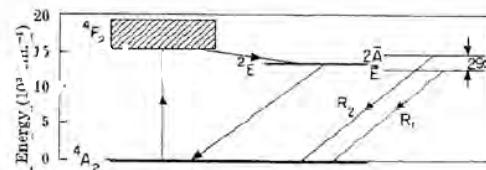


Fig. 1. Energy-level diagram of Cr³⁺ in corundum, showing pertinent processes

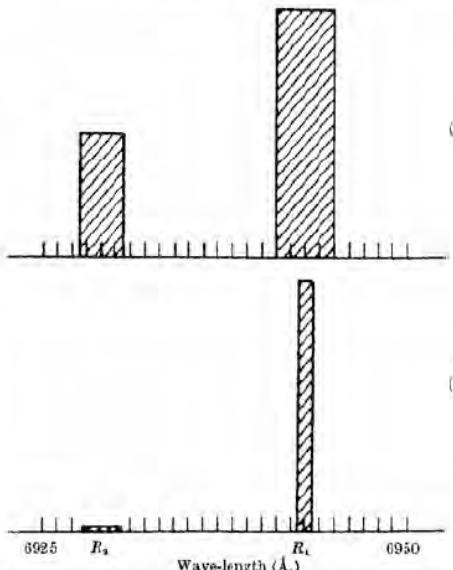


Fig. 2. Emission spectrum of ruby: *a*, low-power excitation; *b*, high-power excitation

the emission spectrum obtained under these conditions is shown in Fig. 2b. These results can be explained on the basis that negative temperatures were produced and regenerative amplification ensued. I expect, in principle, a considerably greater ($\sim 10^4$) reduction in line width when mode selection techniques are used⁵.

I gratefully acknowledge helpful discussions with G. Birnbaum, R. W. Hellwarth, L. C. Levitt, and R. A. Satten and am indebted to I. J. D'Haenens and C. K. Asawa for technical assistance in obtaining the measurements.

T. H. MAIMAN

Hughes Research Laboratories,
A Division of Hughes Aircraft Co.,
Malibu, California.

¹ Schawlow, A. L., and Townes, C. H., *Phys. Rev.*, **112**, 1940 (1959).

² Javan, A., *Phys. Rev. Letters*, **3**, 87 (1959).

³ Sanders, J. H., *Phys. Rev. Letters*, **3**, 86 (1959).

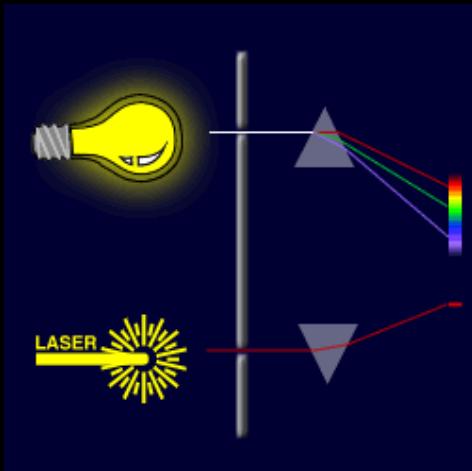
⁴ Maiman, T. H., *Phys. Rev. Letters*, **4**, 564 (1960).

Theodore Maiman Explains the First Ruby Laser

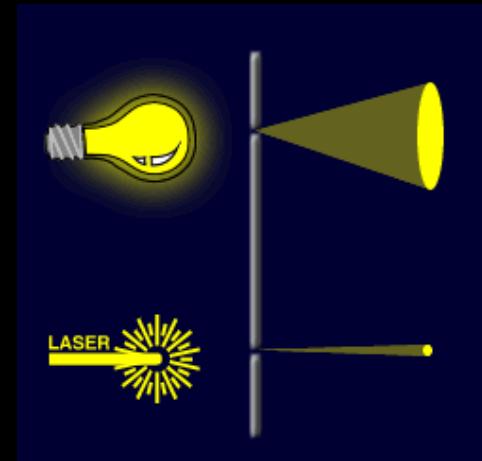


Laser: Solution Looking for a Problem
Loser?

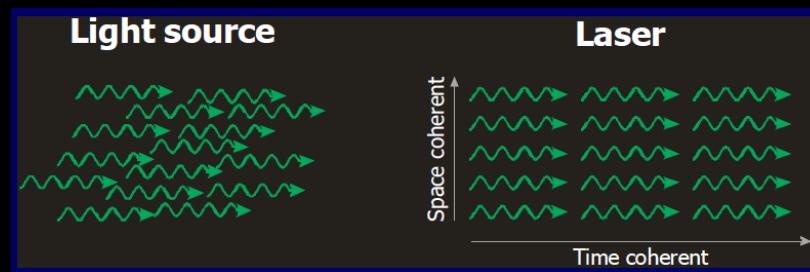
Properties of Stimulated Emission



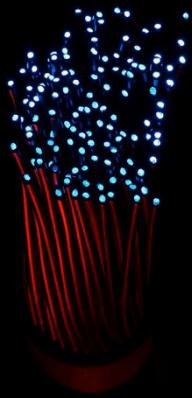
1. Monochromativity.



2. Directionality.



3. Coherence.



Fiber optical communication



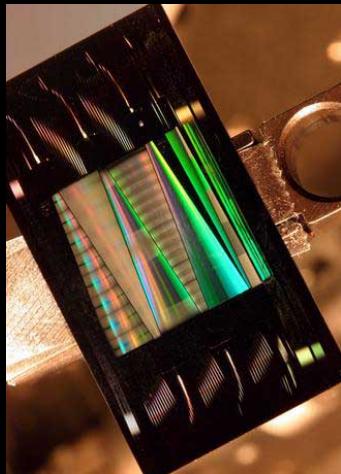
Cutting machines



Bar code scanner



Laser pointer



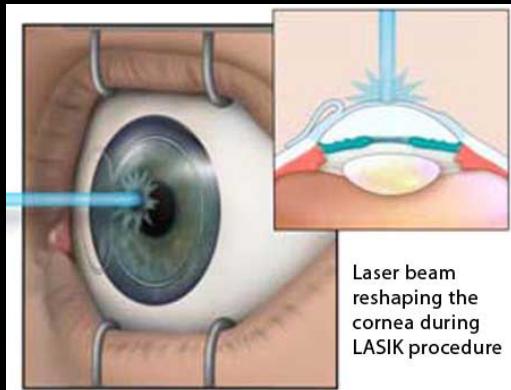
Photolithography



Compact Discs



Light shows



Medicine



Security

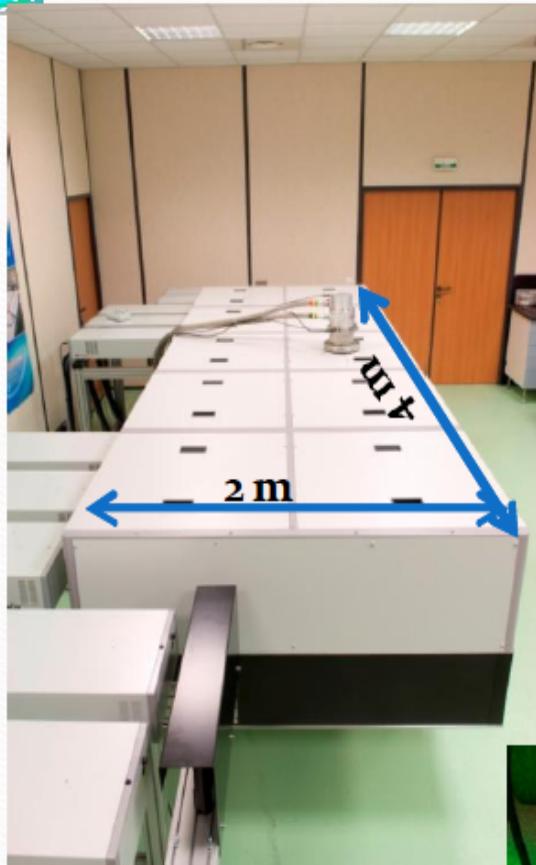


Long Distance measurement



Energy Nuclear Fission

Il laser FLAME



Energia massima: 7 J

Energia massima sul target: ~5 J

Durata minima: 23 fs

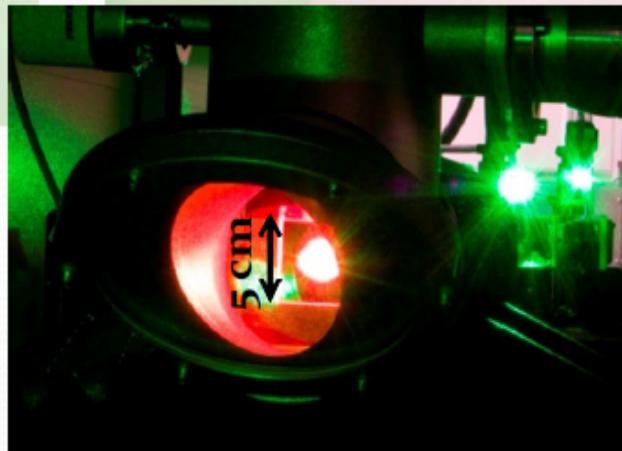
Lunghezza d'onda: 800 nm

Larghezza di banda: 60/80 nm

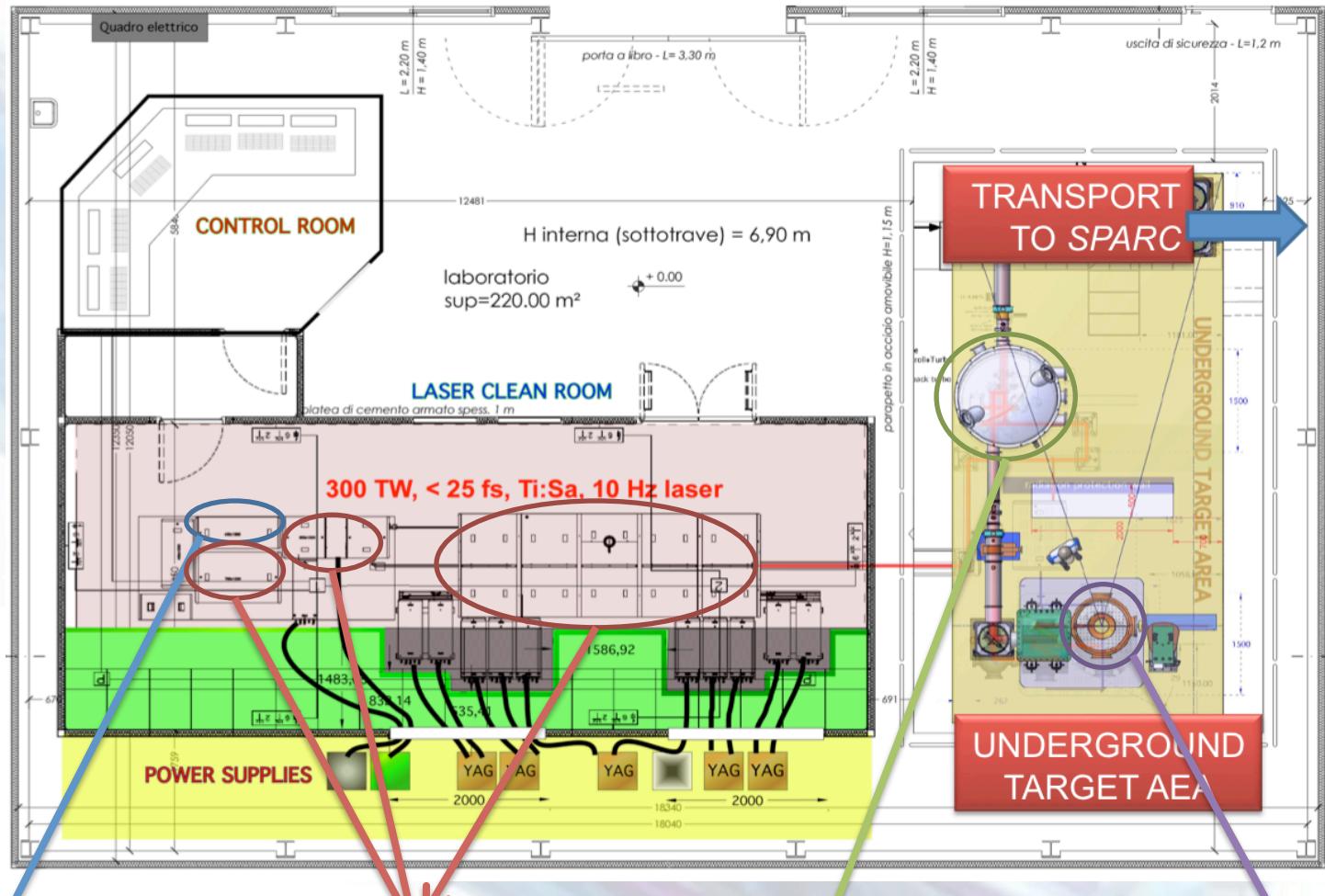
Spot-size @ focus: 10 μ m

Potenza massima: ~300 TW

Contrasto: 10^{10}



Ti:Sa FLAME laser



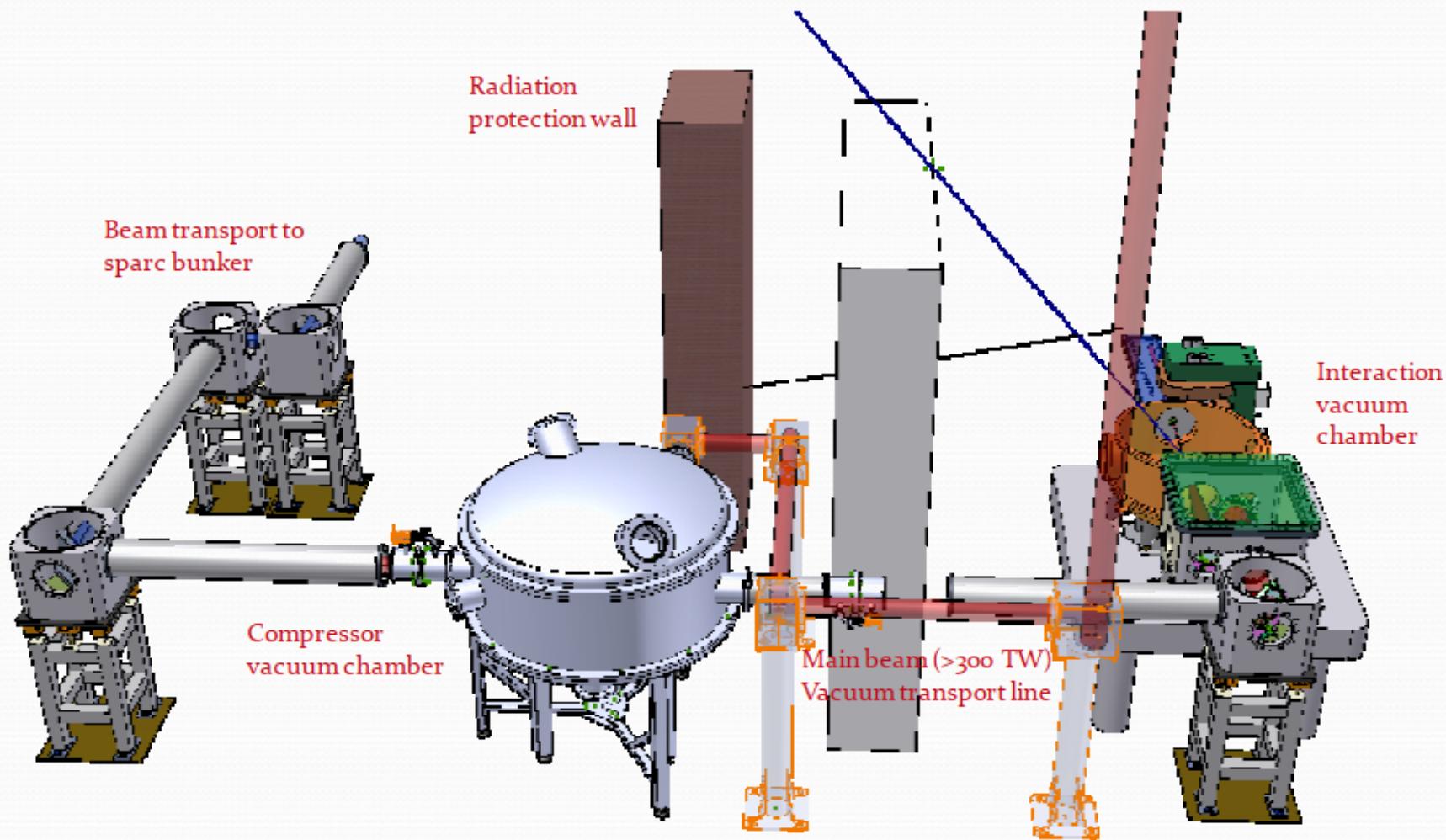
Stretcher

Amplifiers

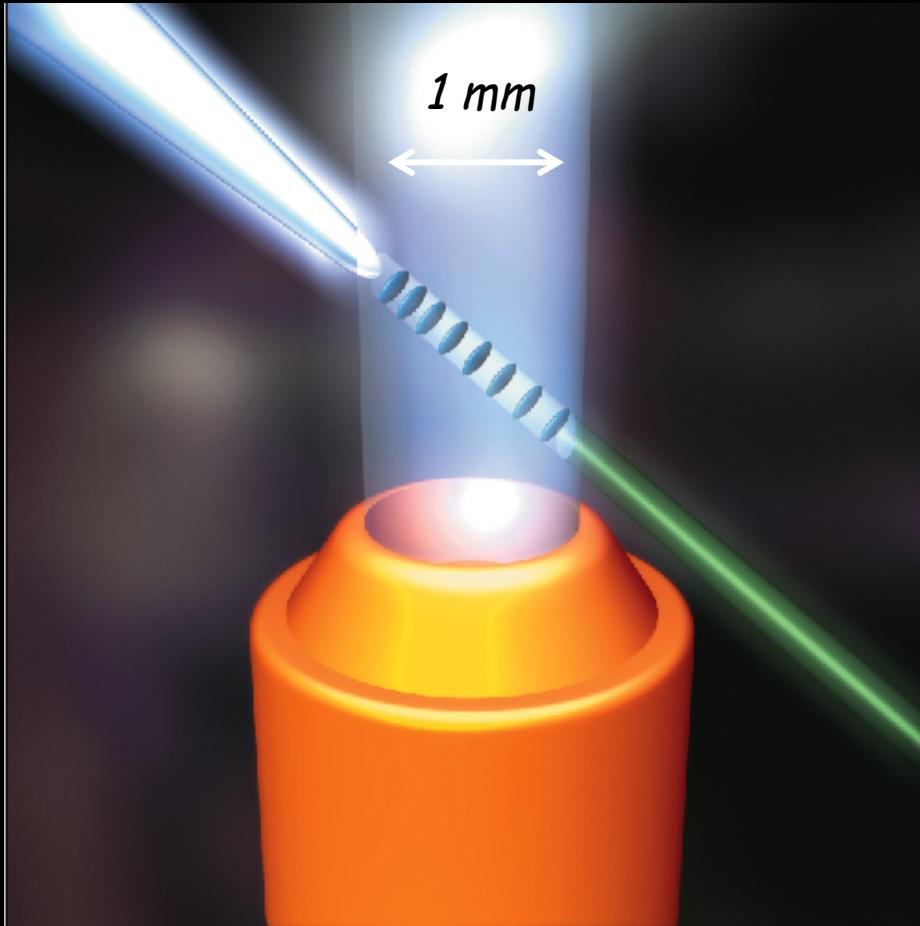
Compressor

LWFA
Electron Self Injection
And
Protons

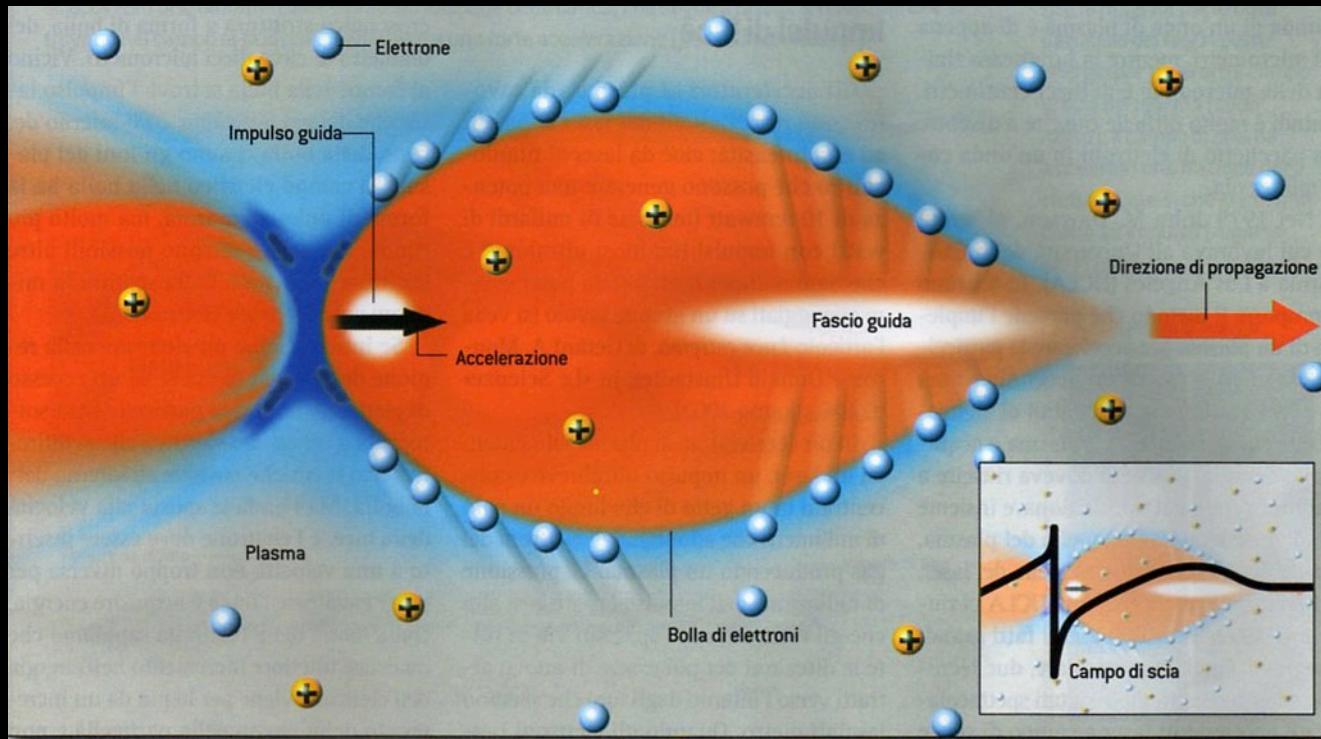
FLAME target area



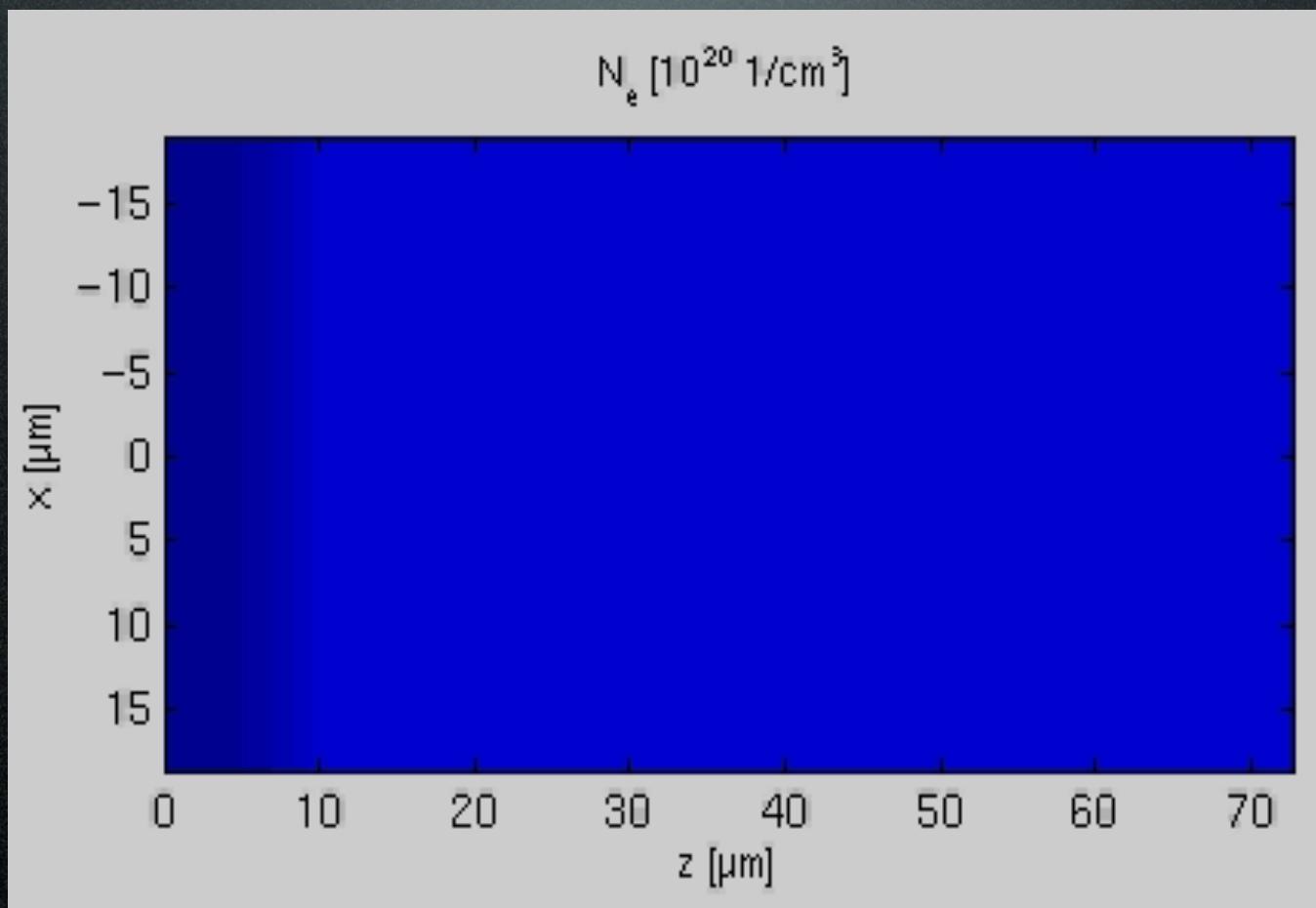
Direct production of e-beam



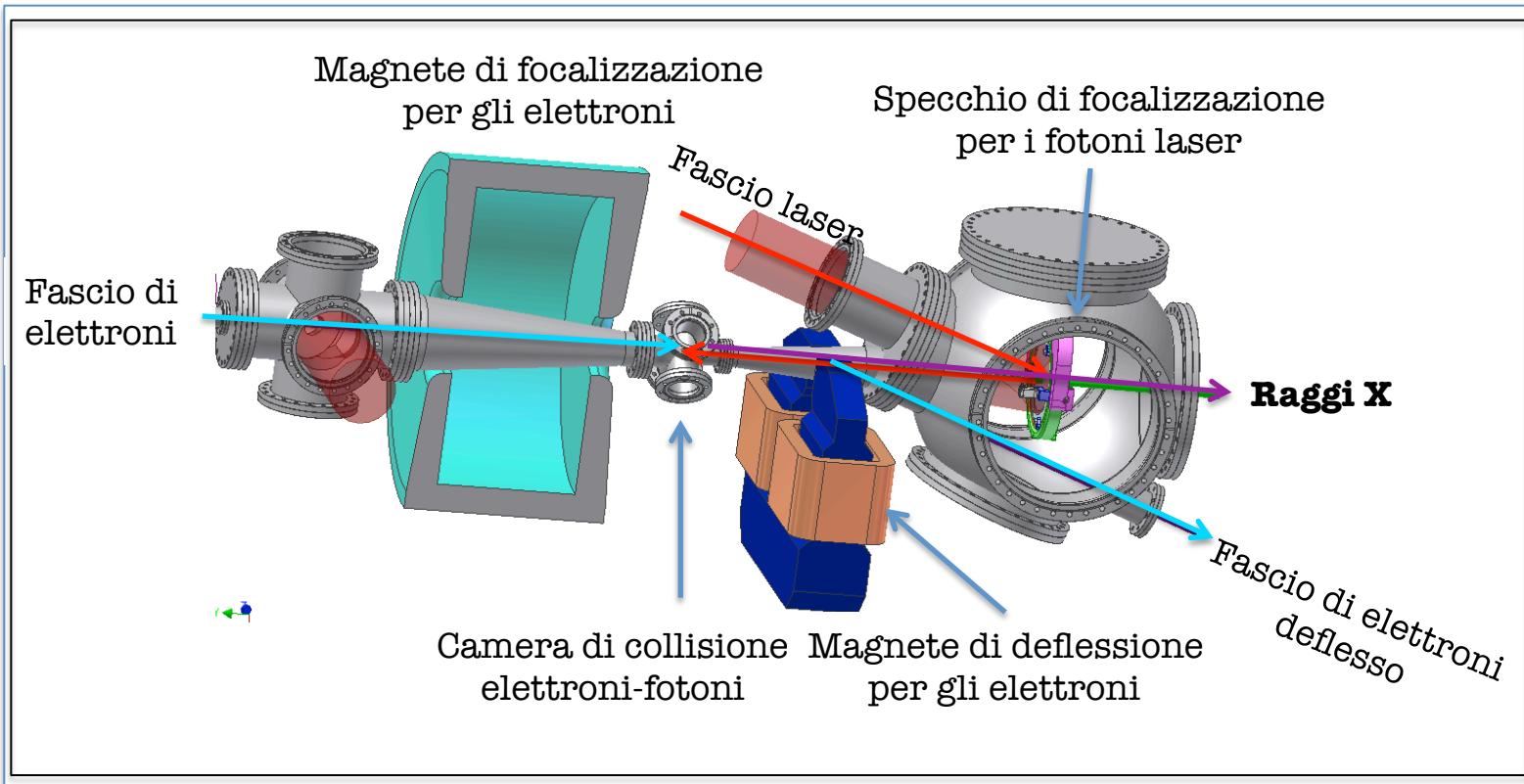
High quality beam Plasma Accelerattion

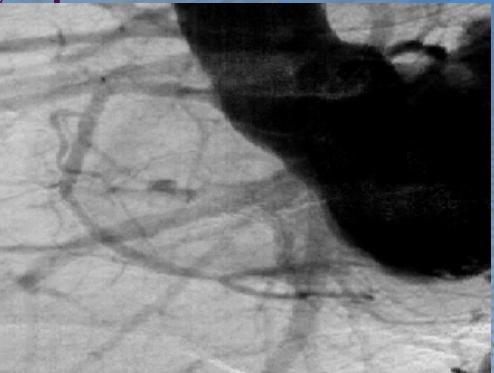
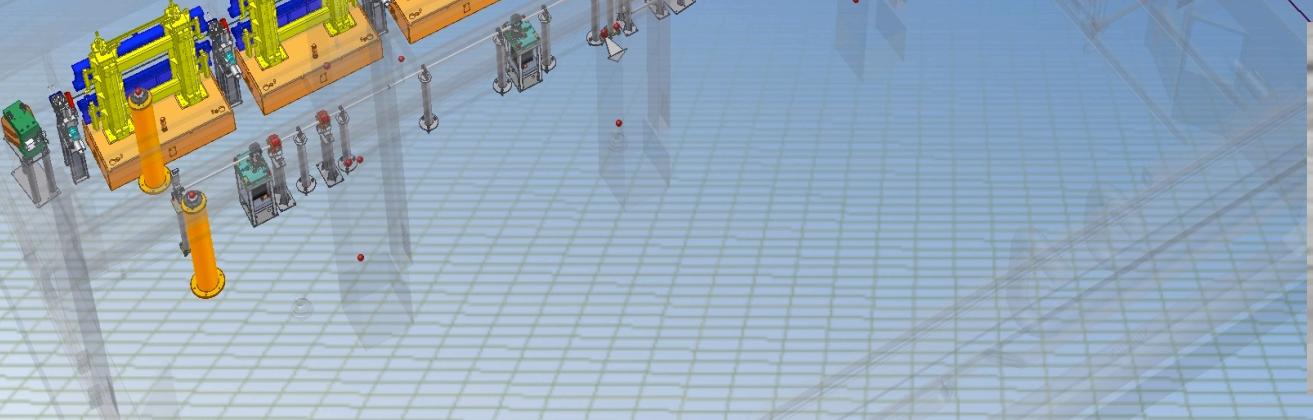
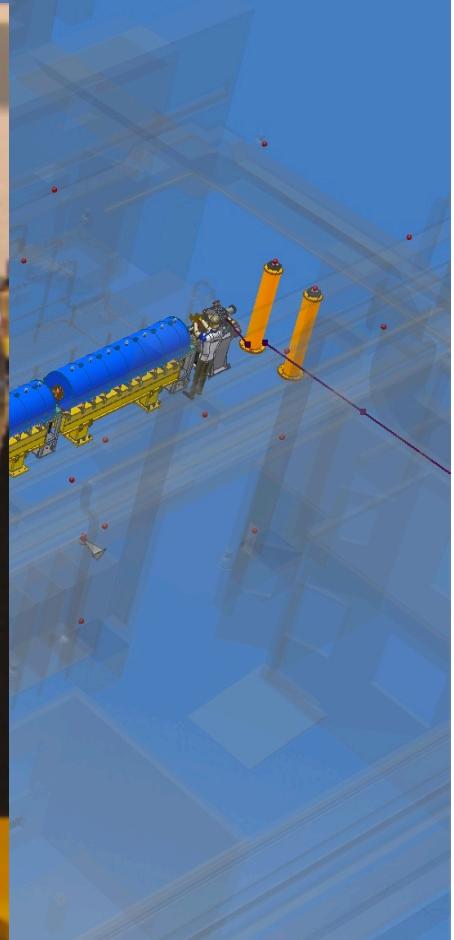
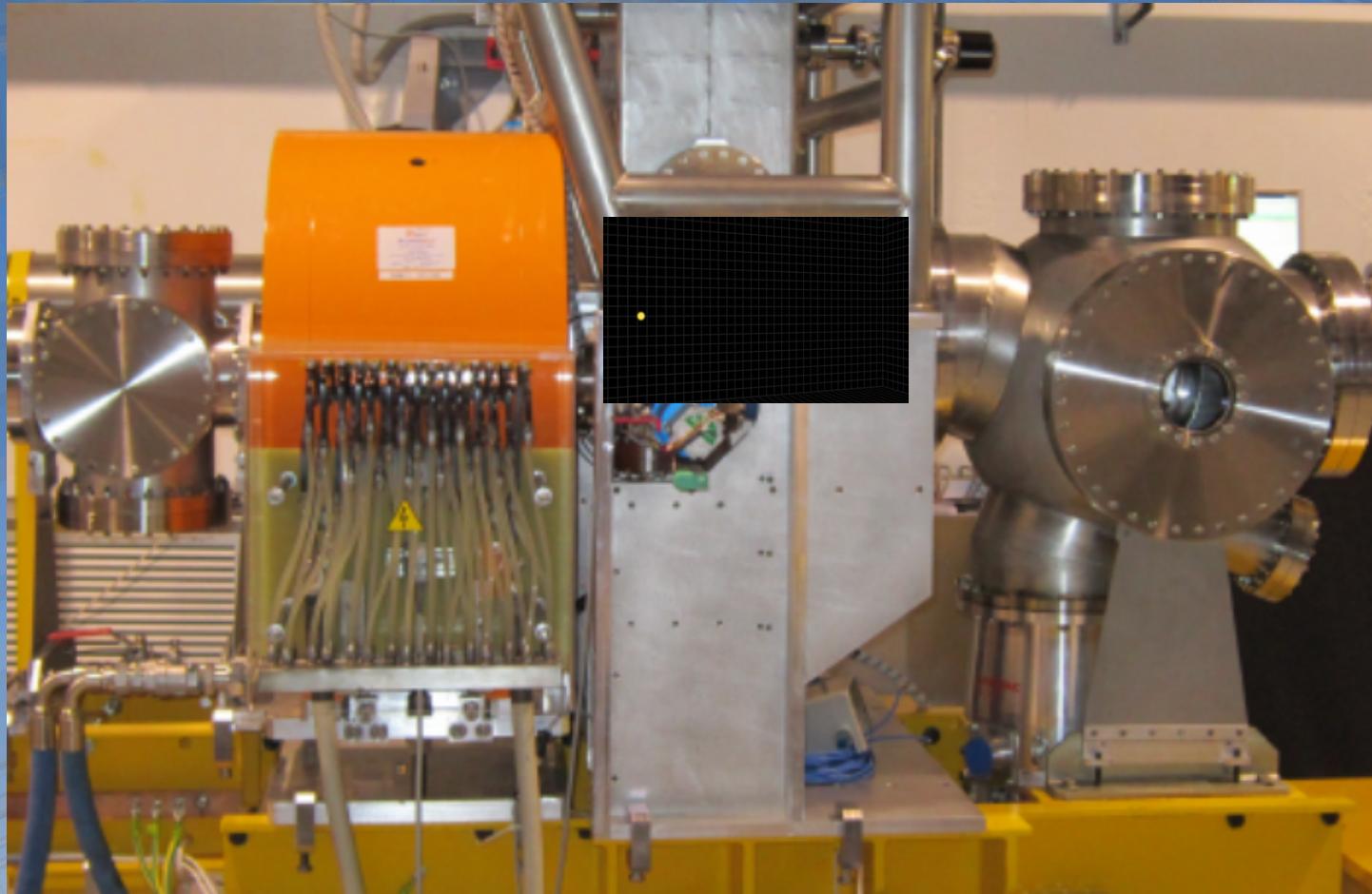


Accelerazioen di particelle mediante laser in plasma

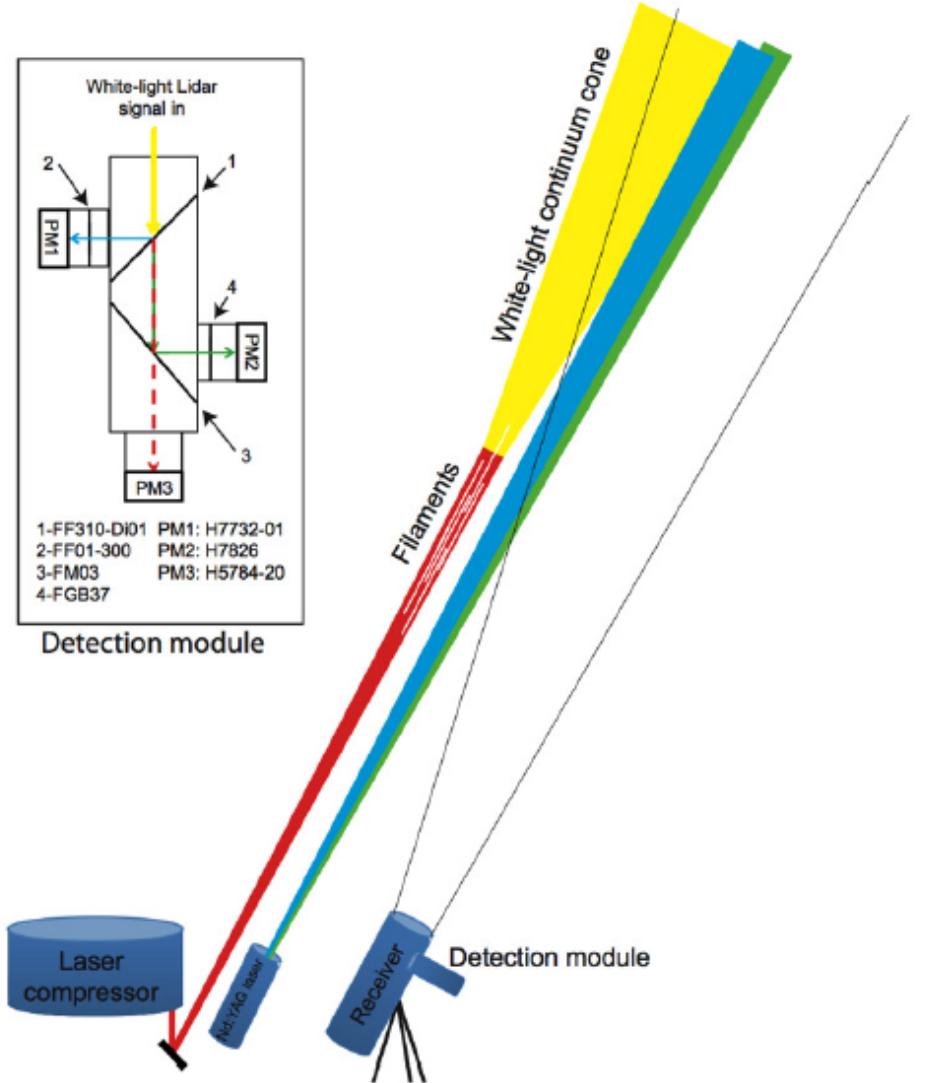


Thomson/Compton Interaction region

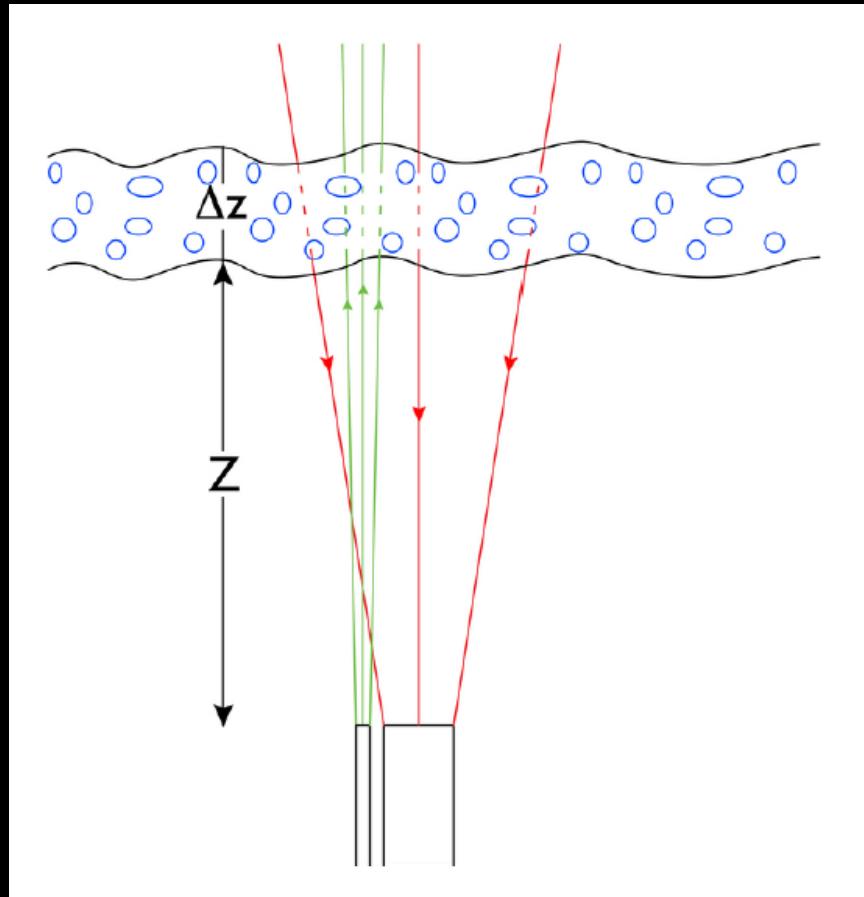




Propagazione del laser in aria

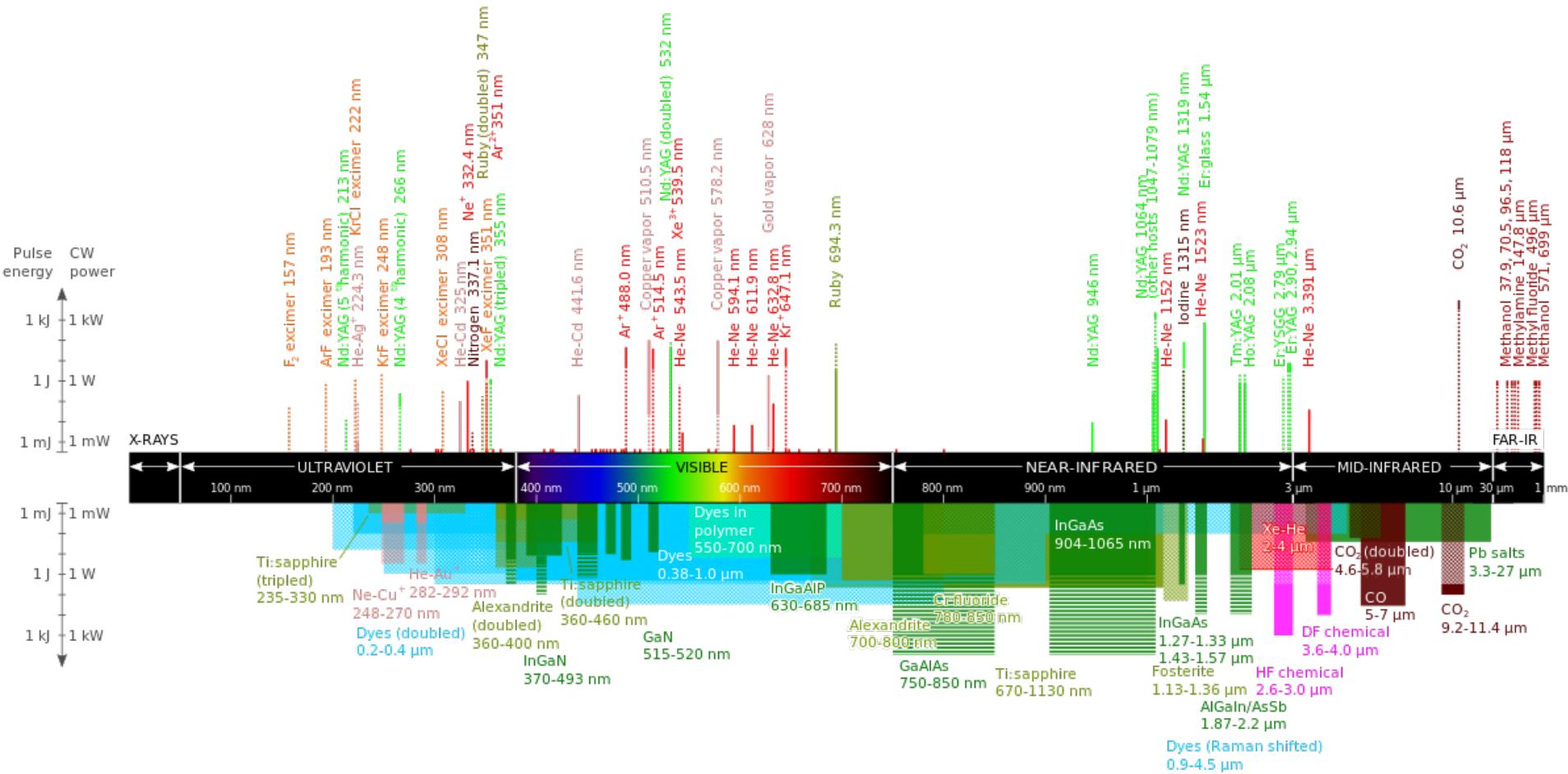


LIDAR - Laser Imaging Detection and Ranging



$$P(z) = P_0 \frac{A}{z^2} \eta_{\text{ott}} \frac{c\tau}{2} \beta(z) T^2(z).$$

Wavelengths of commercially available atomic lasers



1. Well known and proven technology
2. One Laser One Color.
3. Limited by Mirrors ==> No X rays.

Ultra-Small

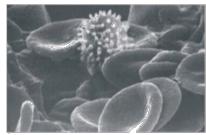
Nature



Flea



Human hair
~30 μm wide



Red blood cells
& white cell ~ 5 μm

10^{-3} m



Head of a pin ~1mm

The Microworld

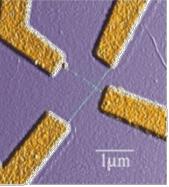
100 μm

DVD track



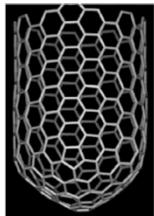
10 μm

1 μm Electrodes connected with nanotubes



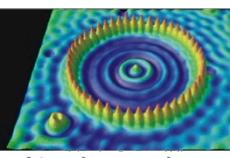
100 nm

Carbon nanotube ~ 2nm diameter

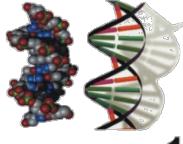


1 nm

Atomic corral ~ 14 nm diameter



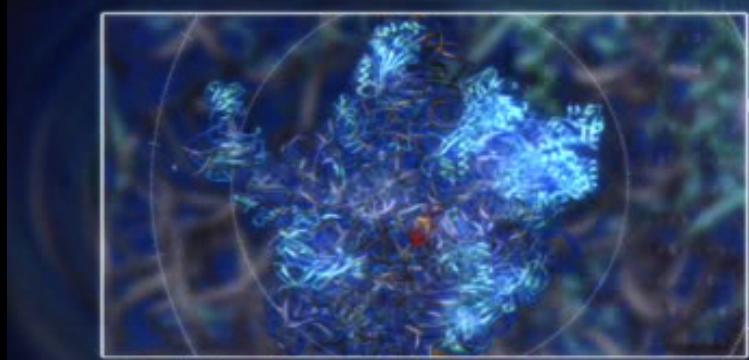
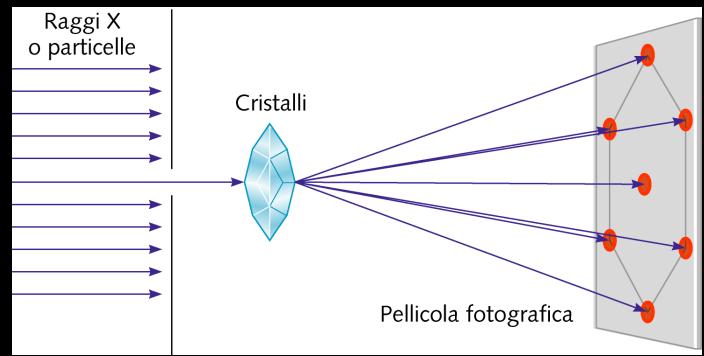
DNA helix
~3 nm width



Water molecule



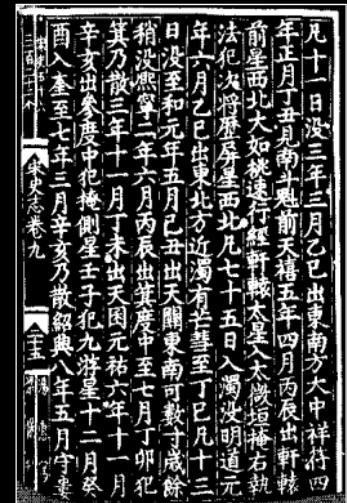
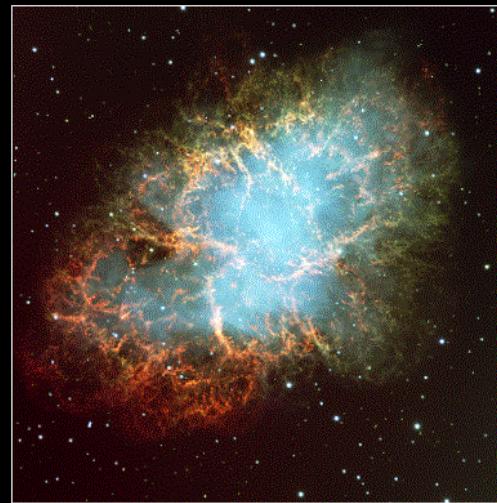
Technology

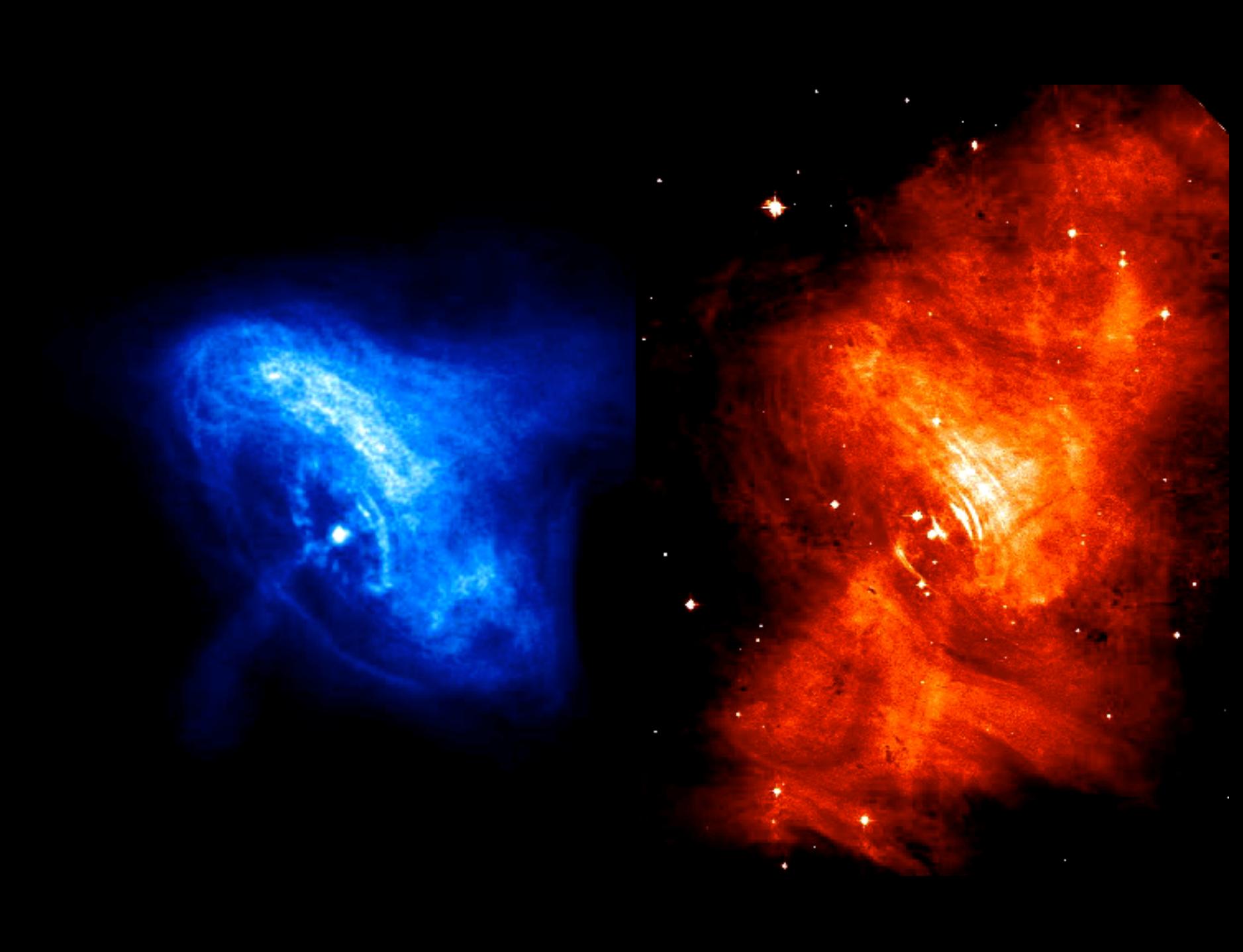


Radiazione di Sincrotrone

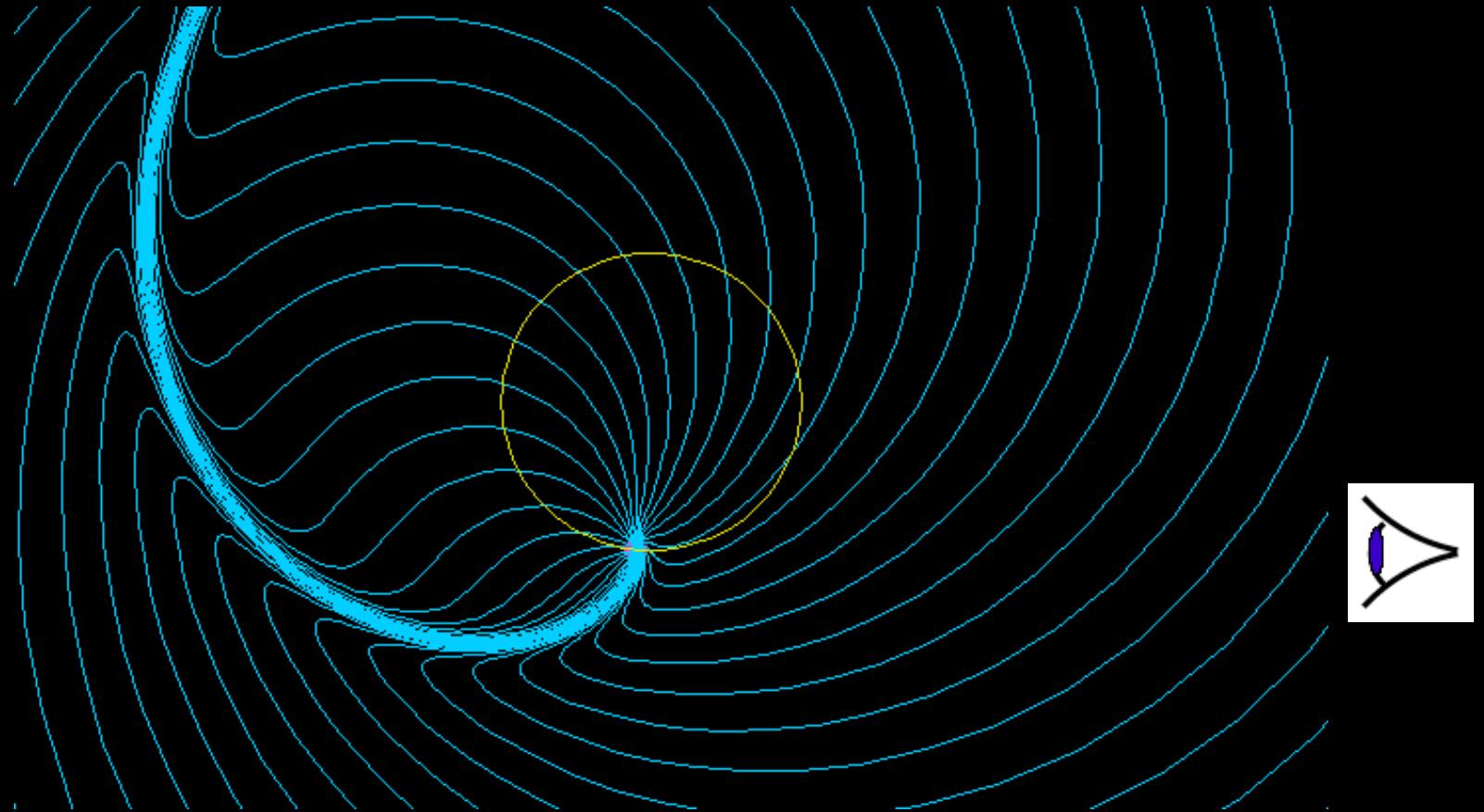
Crab Nebula

Remnant of Supernova in 1054 AD



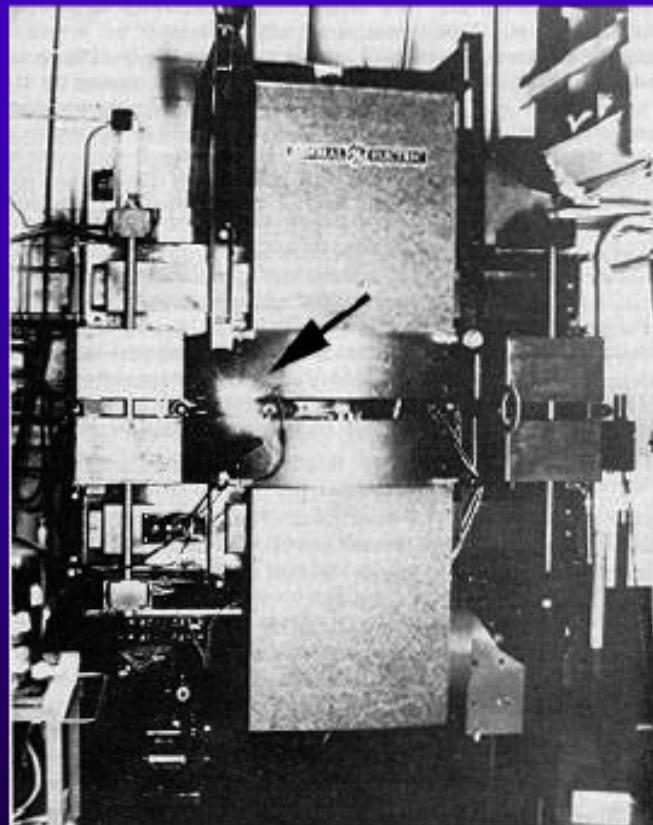


Particella carica in moto circolare



GE Synchrotron

New York State



**First light observed
1947**

Elettra (Trieste)



ESRF (Francia)



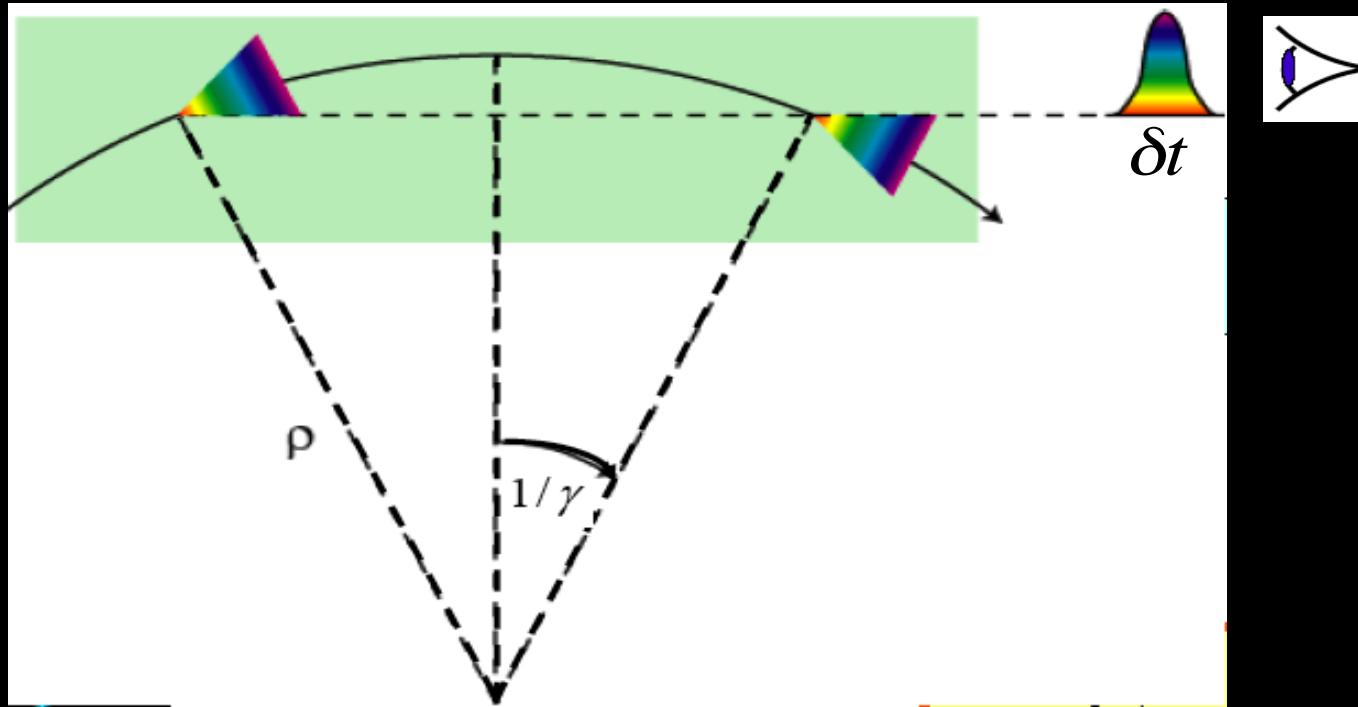
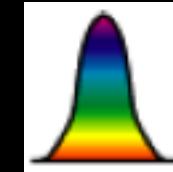
SLS (Svizzera)





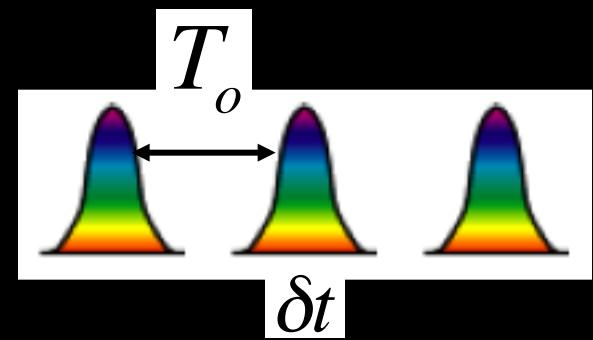
Durata dell' impulso

$$\delta t \approx \frac{\rho}{E^3} \approx 100 \text{ ps}$$

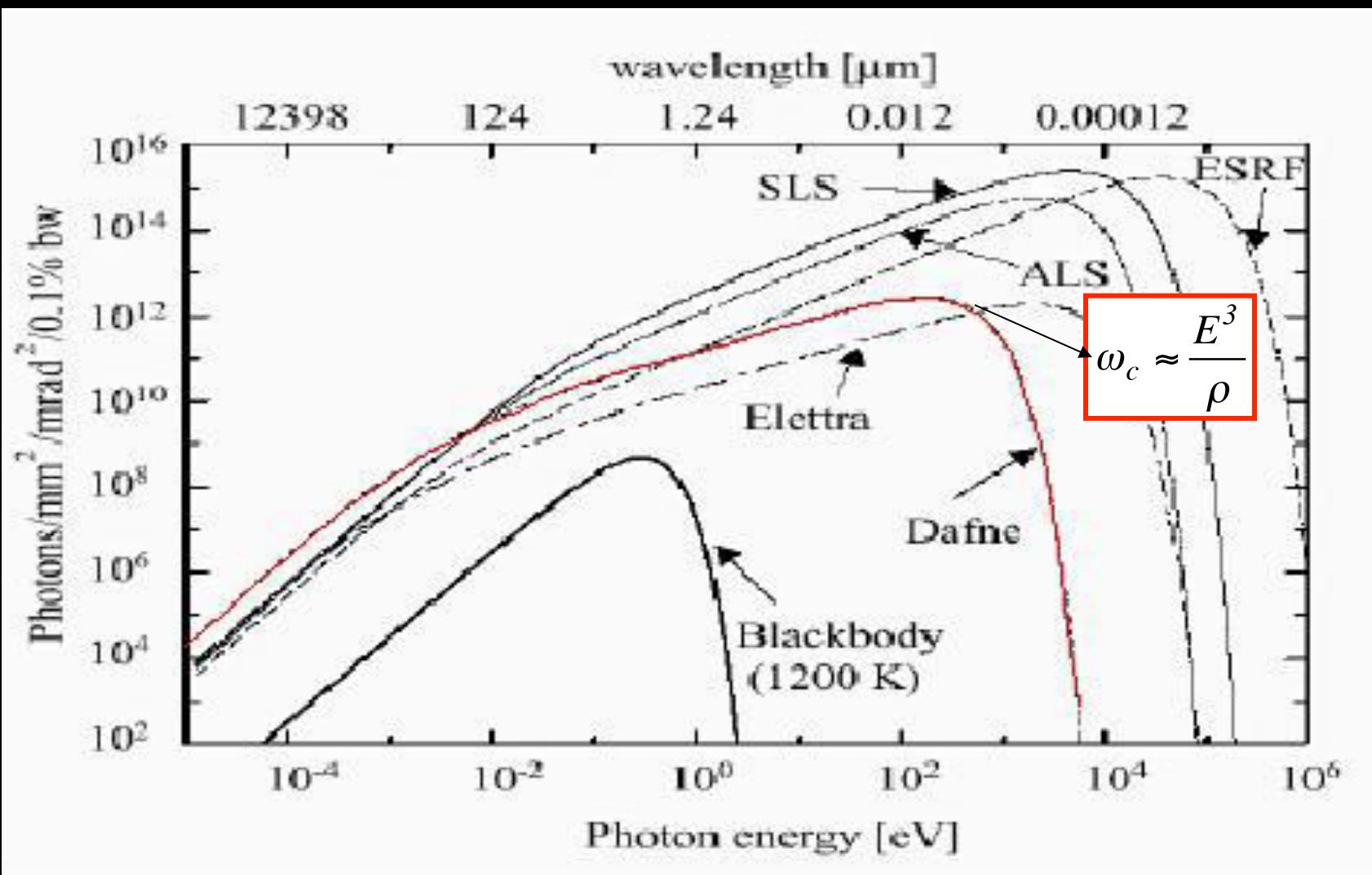


Ripetizione dell' impulso

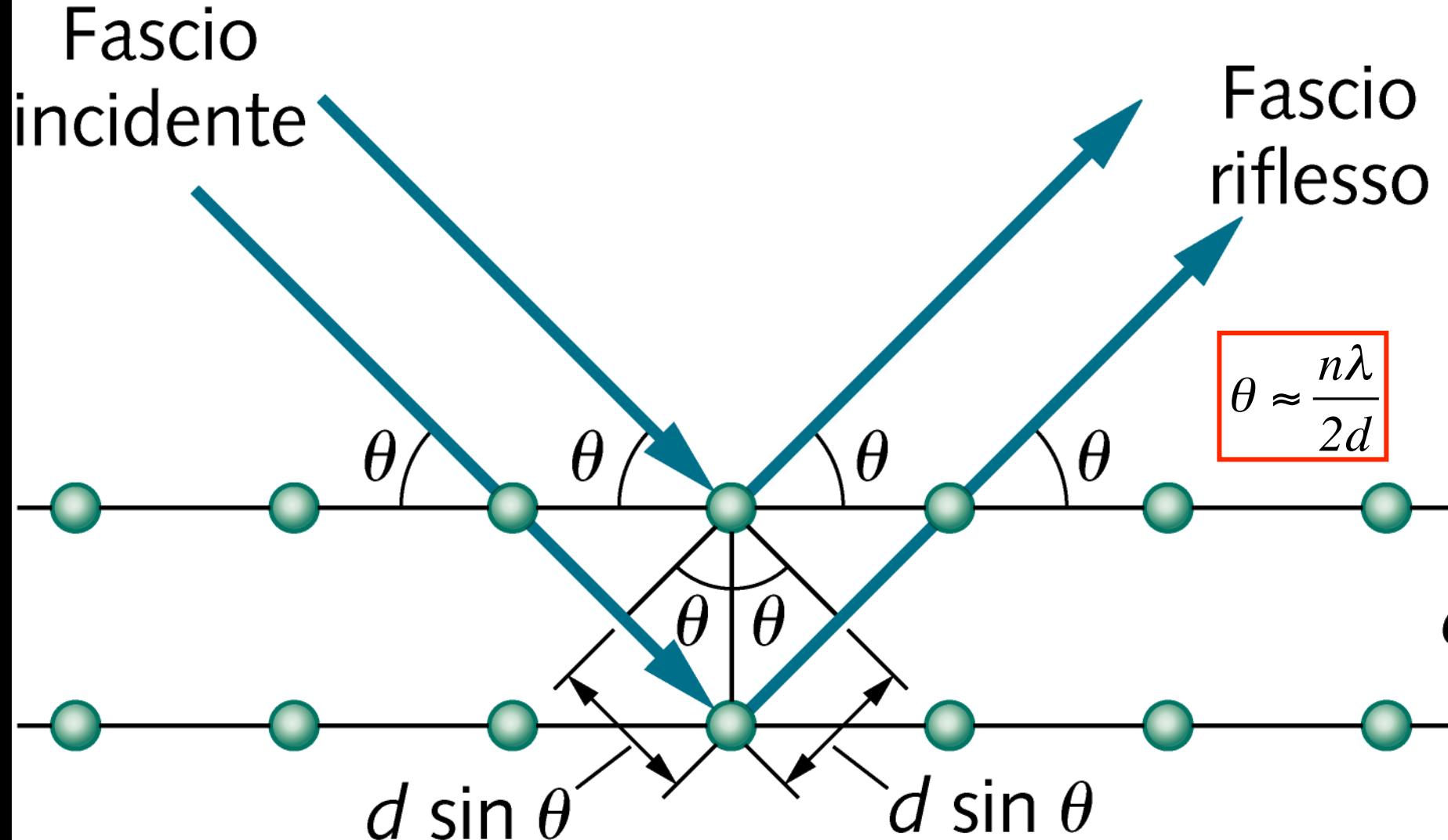
$$\omega_o = \frac{2\pi}{T_o}$$

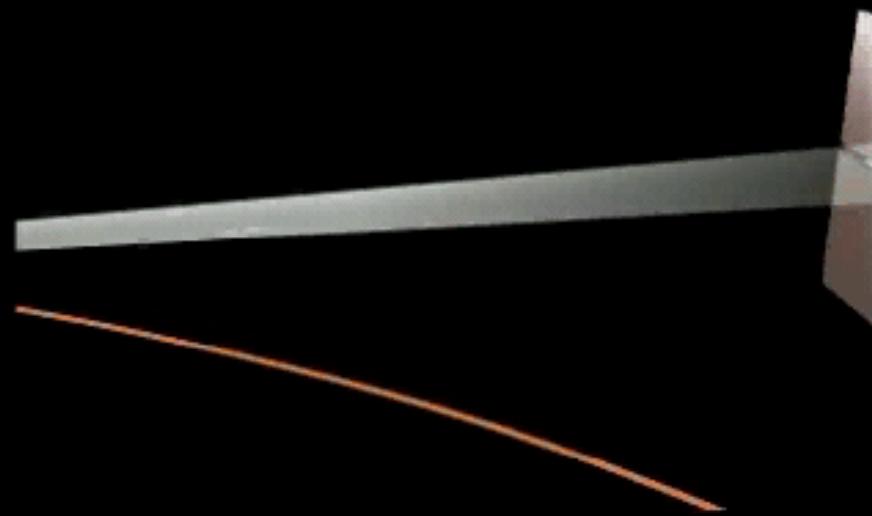


$$\langle P_s \text{ (MW)} \rangle_{\text{iso}} = 0.088463 \frac{E^4 \text{ (GeV)}}{\rho \text{ (m)}} I \text{ (A)} .$$



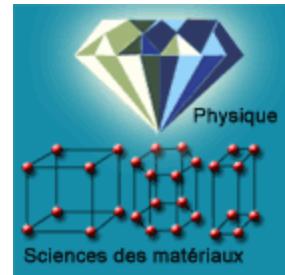
Monocromatore - Legge di Bragg



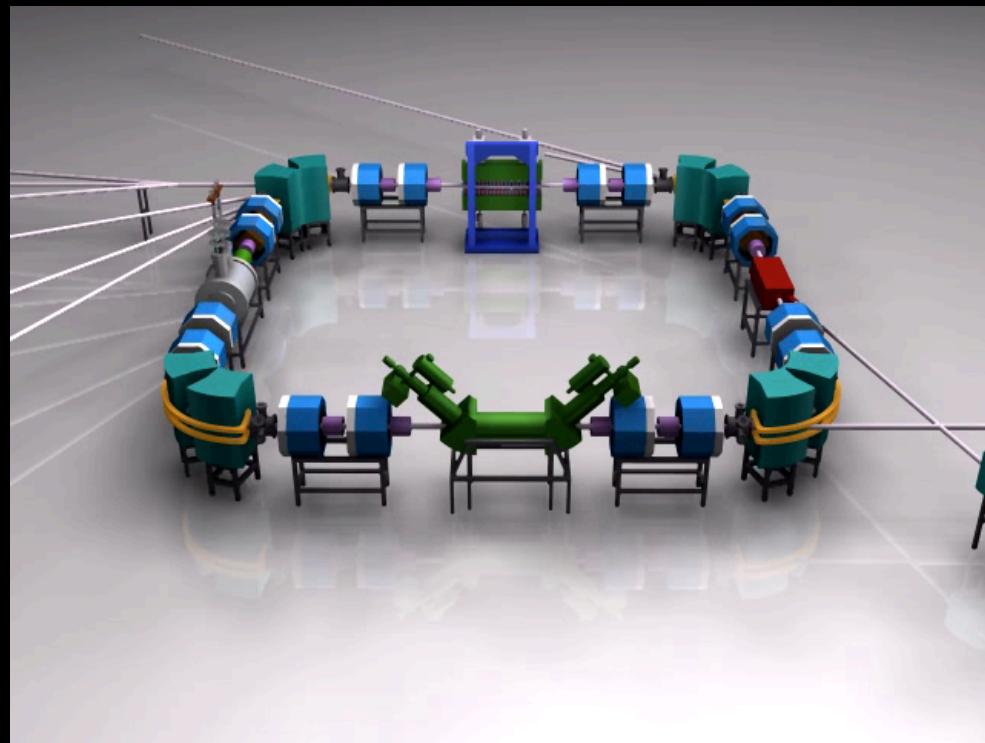
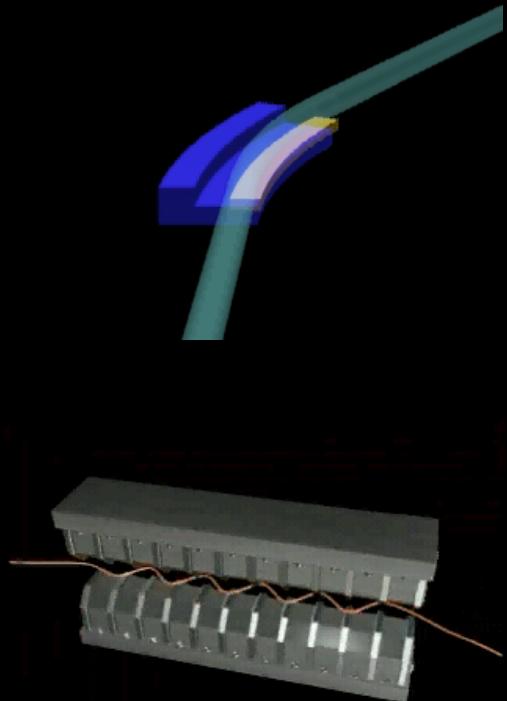


Raggi X
o particelle

Cristalli

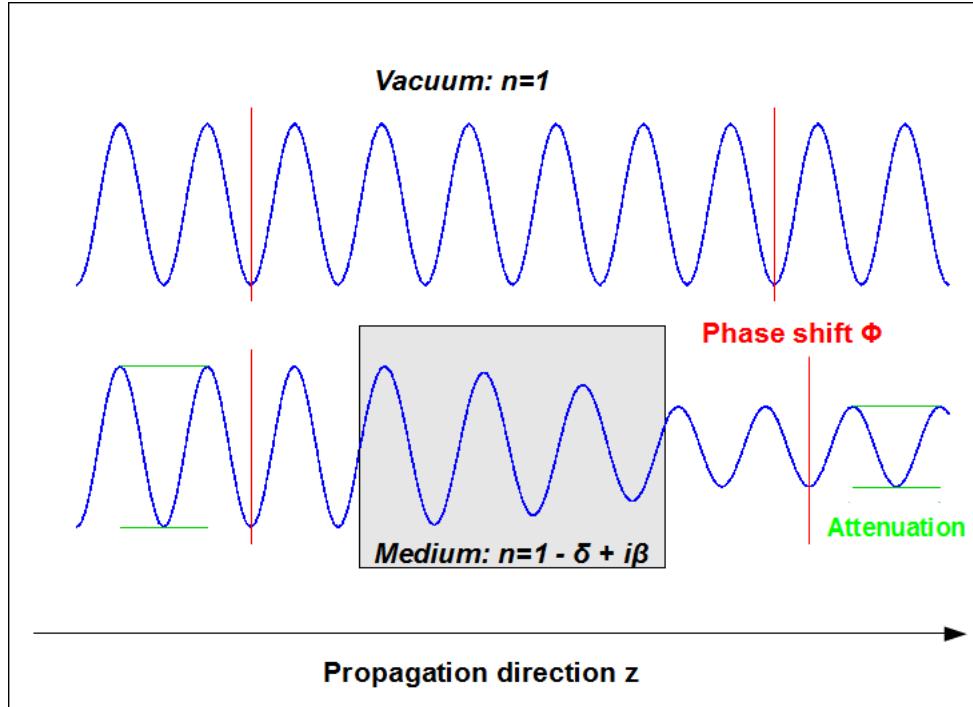


Pellicola fotografica





Phase Contrast Imaging

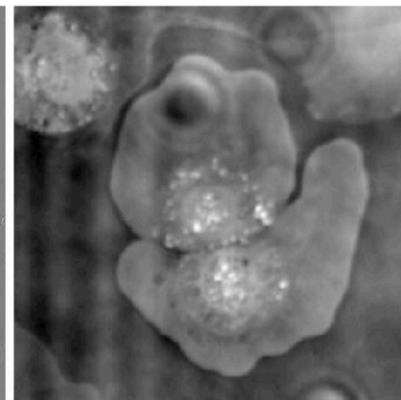
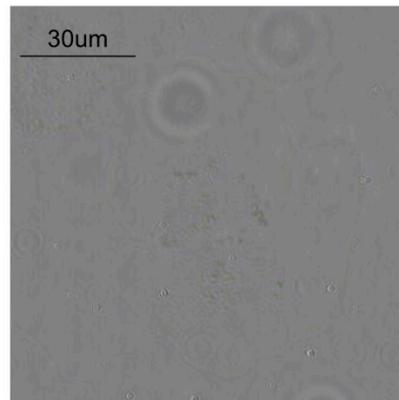


Standard X-ray imaging techniques like [radiography](#) or [computed tomography \(CT\)](#) rely on a decrease of the X-ray beam's intensity ([attenuation](#)) when traversing the [sample](#), which can be measured directly with the assistance of an [X-ray detector](#).

In [Phase Contrast Imaging](#) however, the beam's [phase shift](#) caused by the sample is not measured directly, but is transformed into variations in intensity, which then can be recorded by the detector.

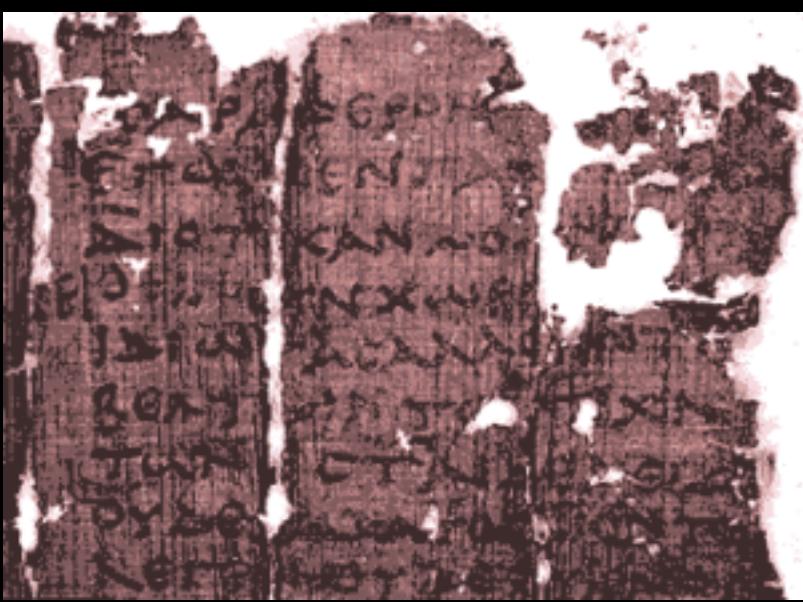


Photos Courtesy of Laura Waller



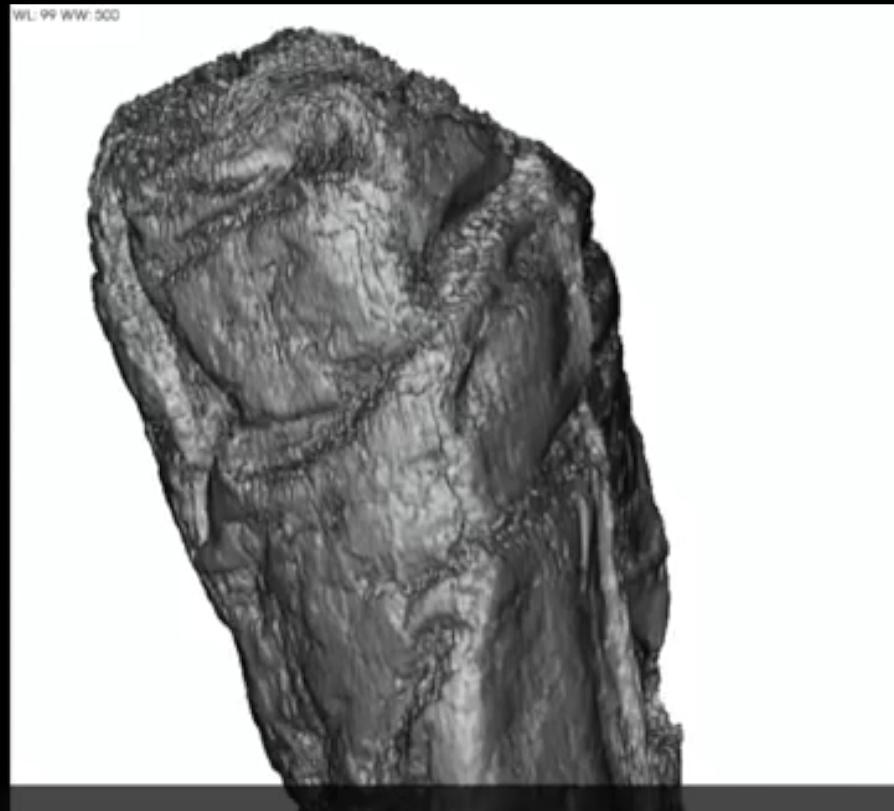
Villa dei papiri – Ercolano – 79 d. C.





Tomografia a raggi X in contrasto di fase

Vito Mocella del CNR-IMM di Napoli in collaborazione con E.Brun e C. Ferrero dell'ESRF

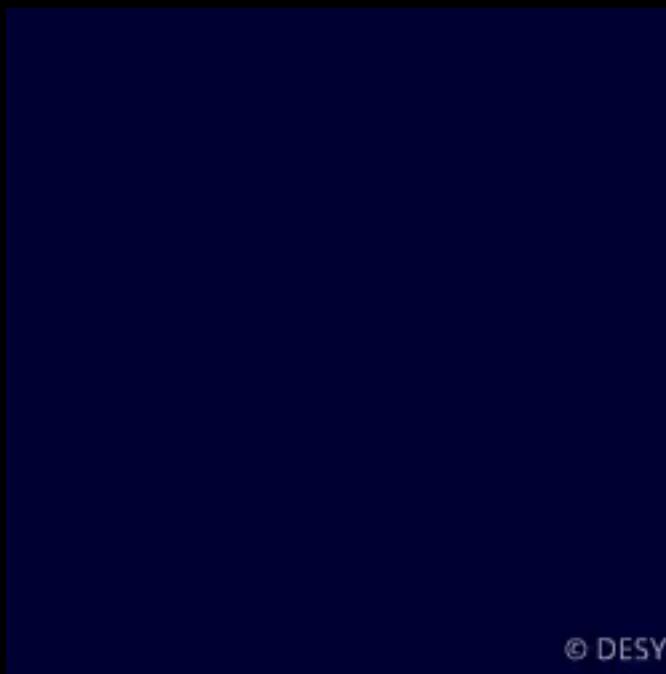


Volume Rendering of an Herculaneum

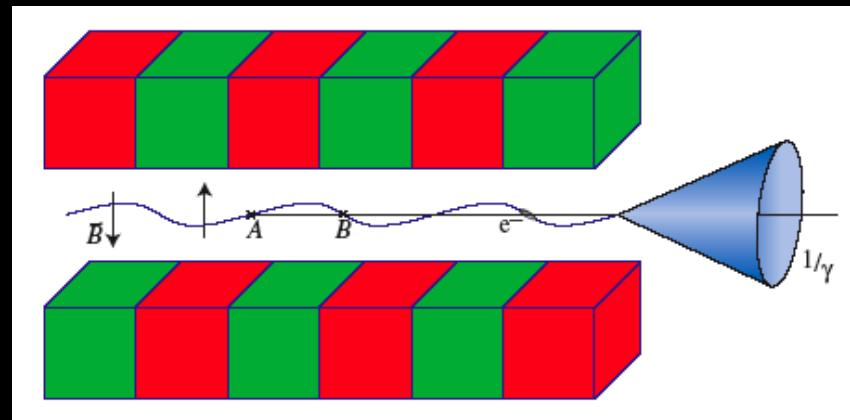
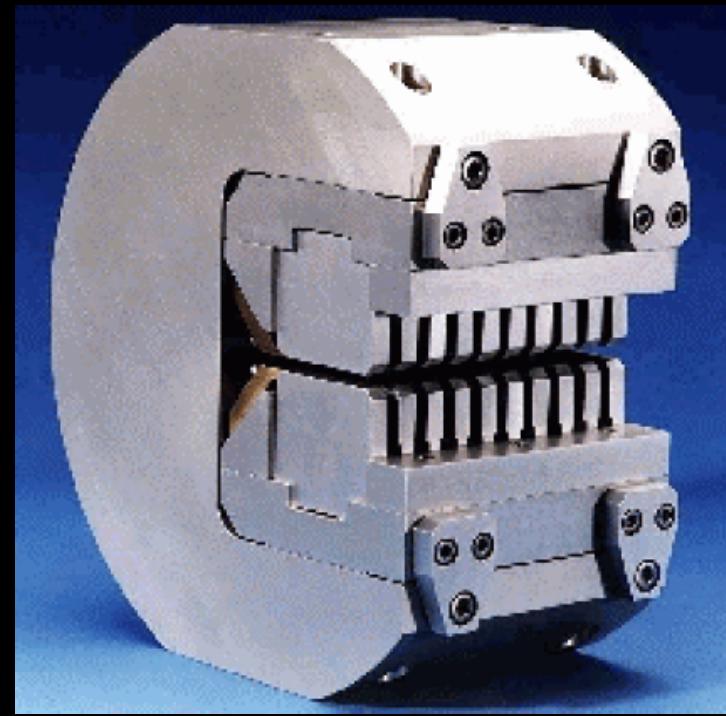
卷之三

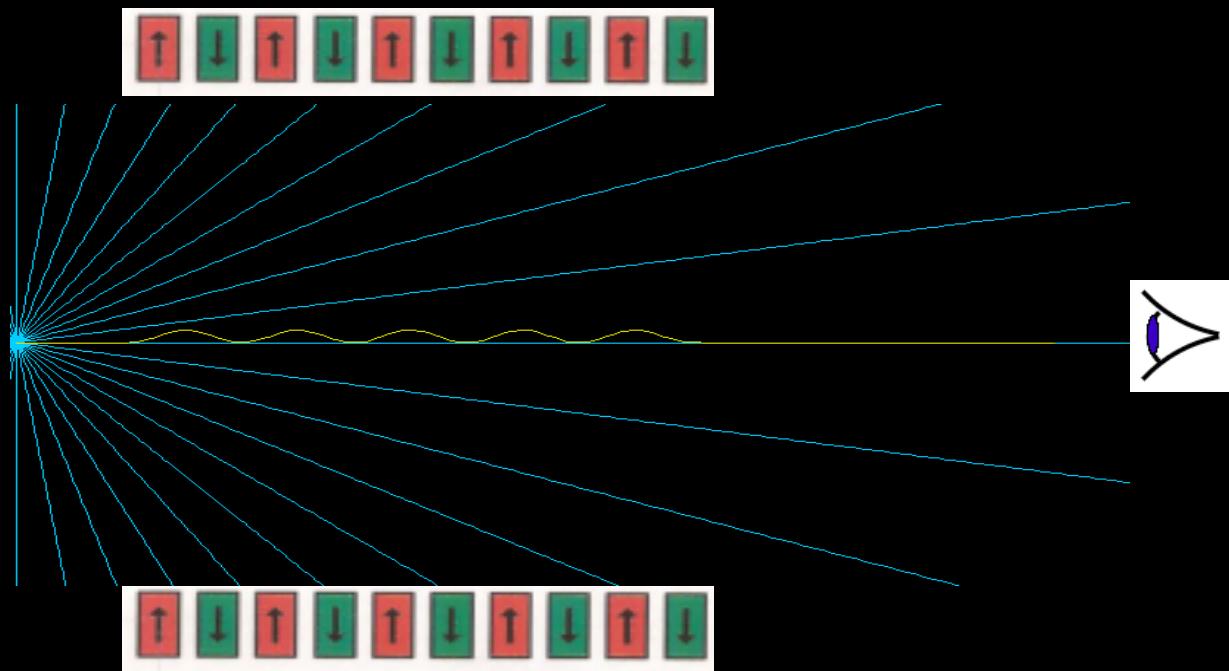
卷之二
人本圖說
卷之三
人本圖說

Laser ad Elettroni Liberi - FEL

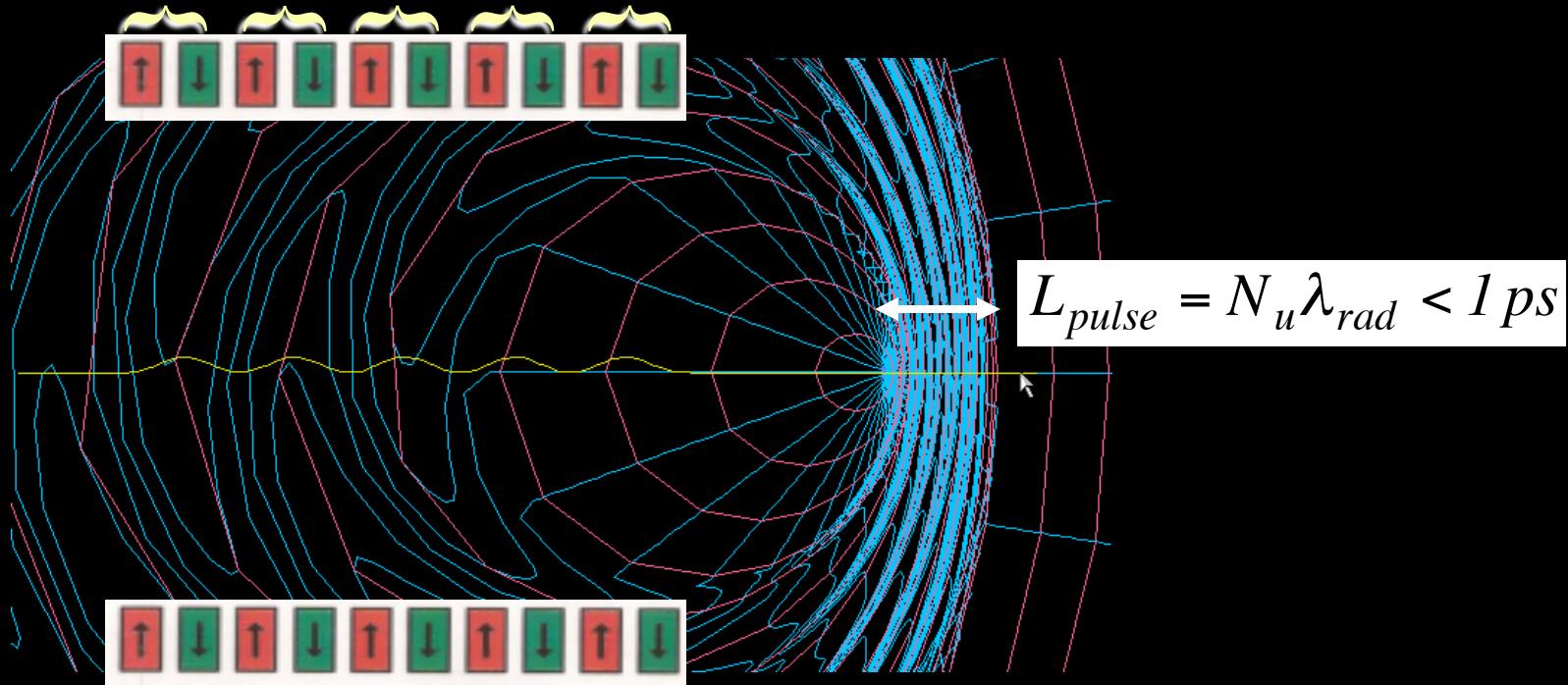


© DESY

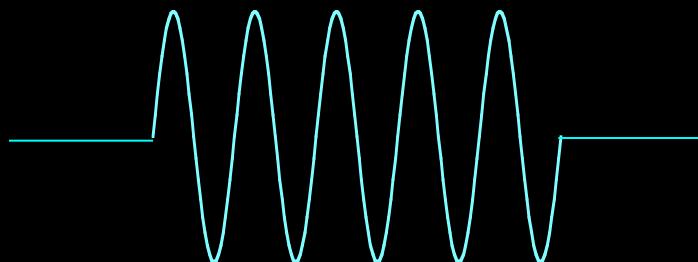




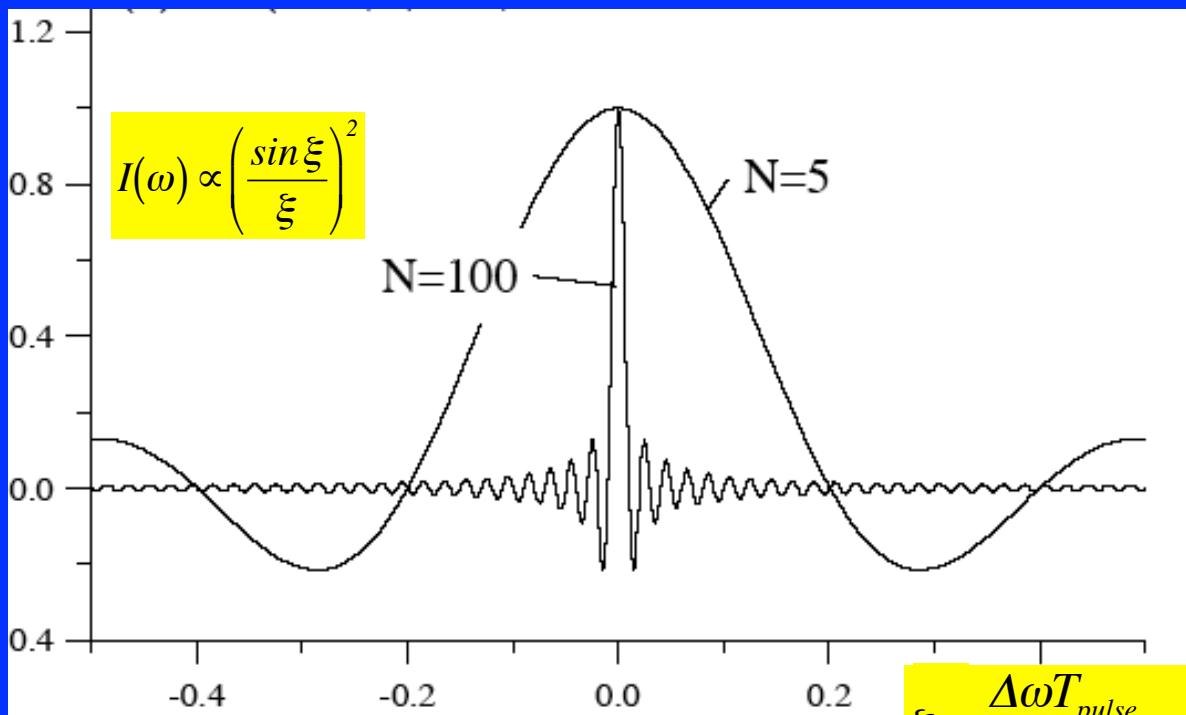
$$N_u = 5$$



$$\lambda_{rad} \propto \frac{\lambda_u}{2\gamma^2}$$



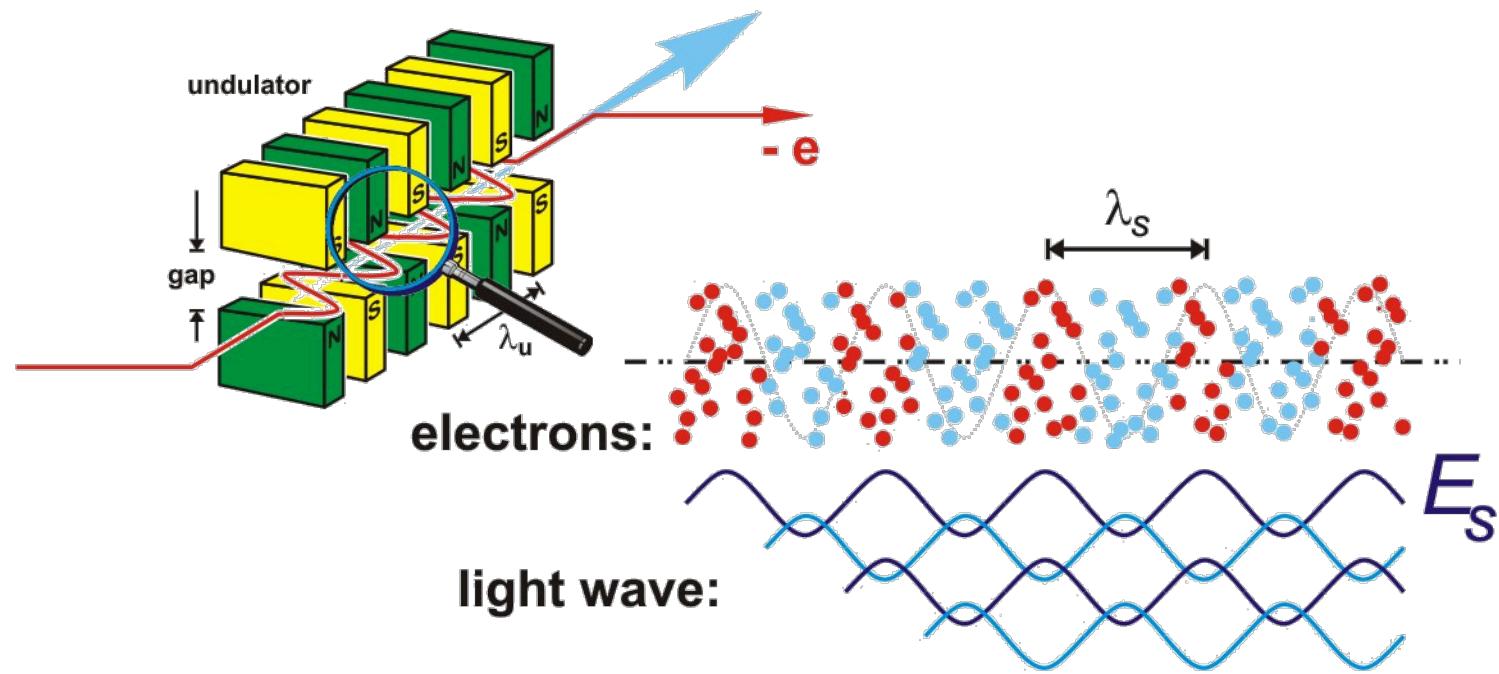
Spectral Intensity



$$\xi = \frac{\Delta\omega T_{pulse}}{2} = \pi N_w \frac{\omega - \omega_{res}}{\omega_{res}}$$

$$\frac{\Delta\omega}{\omega} \approx \frac{1}{N_w}$$

Line width



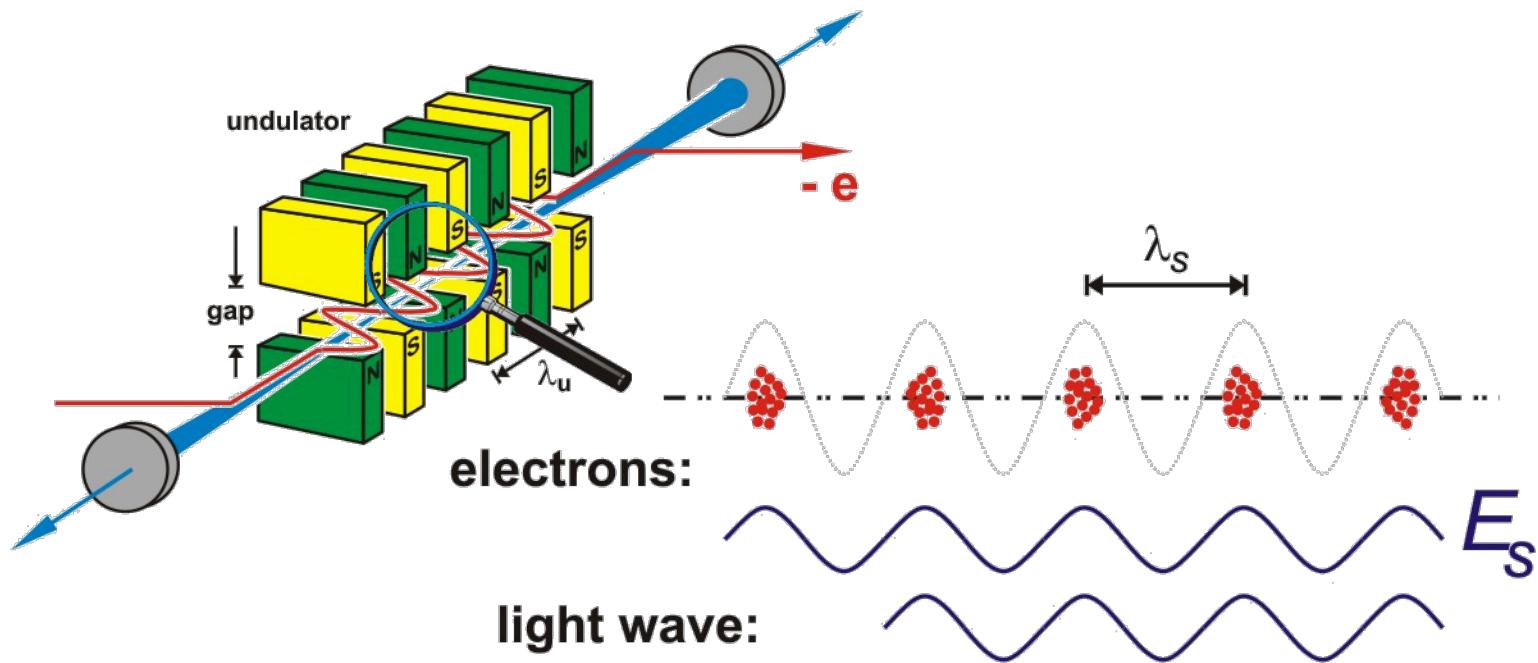
Radiated Power :

$$P \propto n_e \text{ (number of electrons)}$$

destructive interference
→ shotnoise radiation





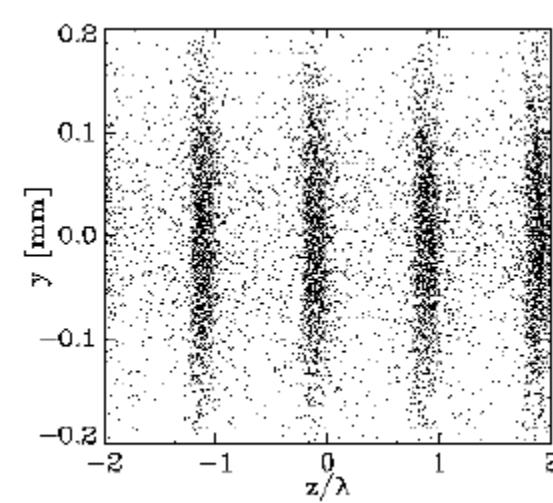
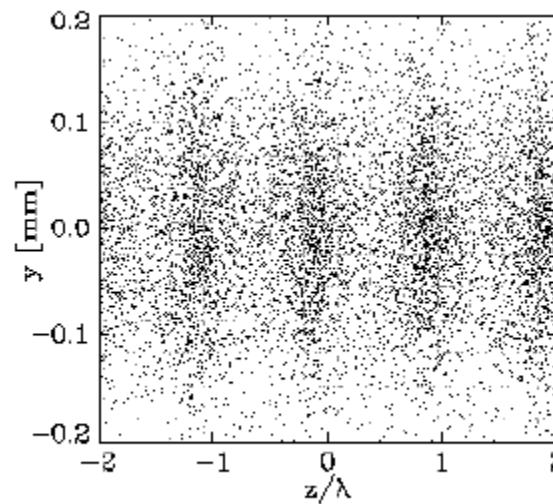
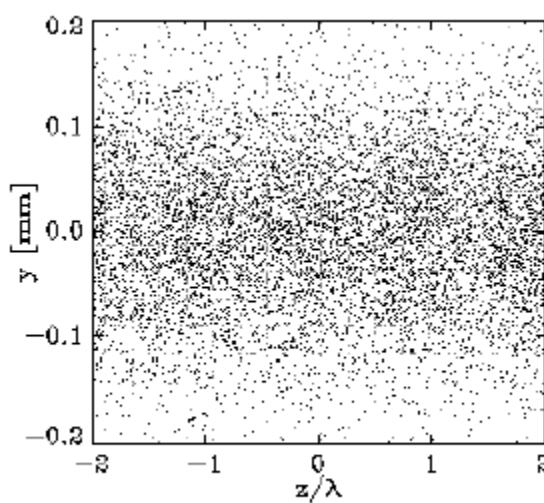


Radiated Power :

$$P \propto n_e^2 \left(\text{number of electrons} \right)$$

$$n_e \sim 10^6 - 10^9$$

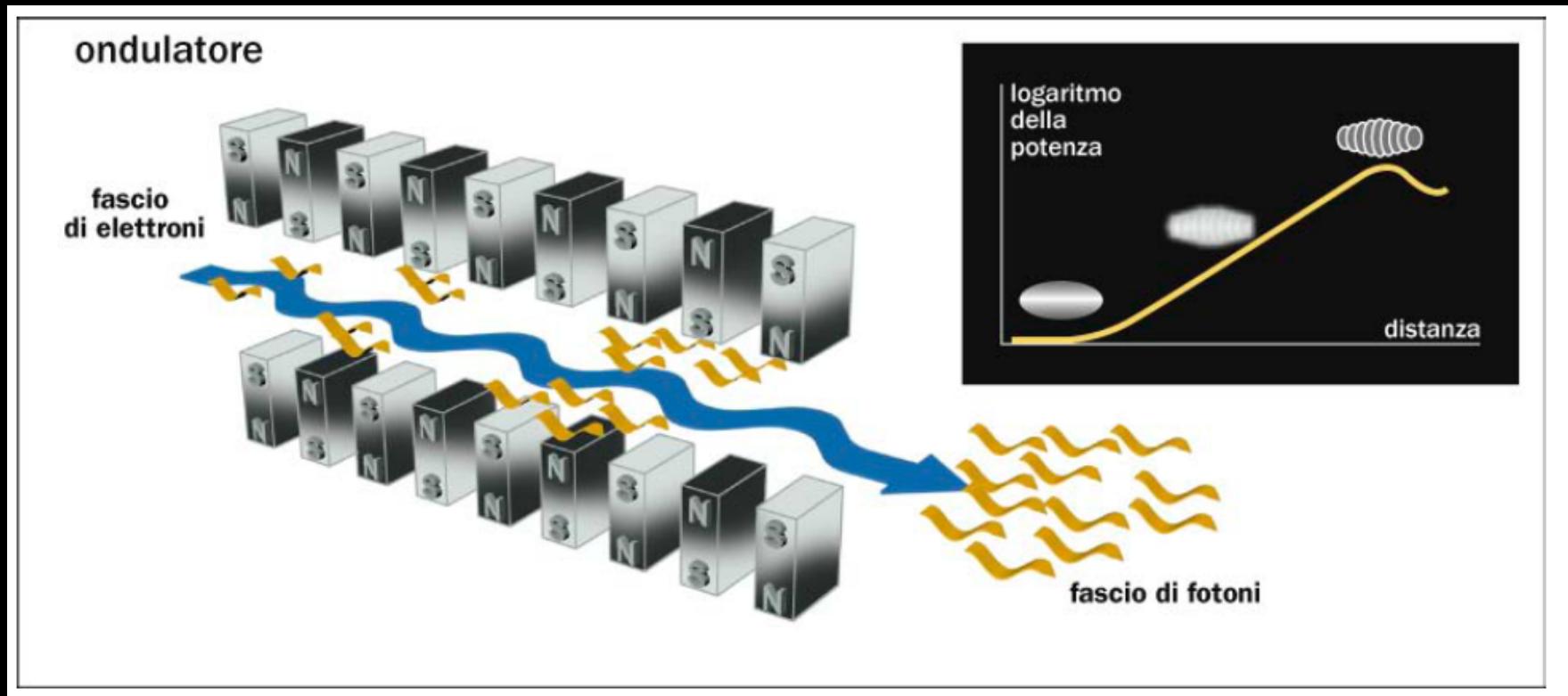
constructive interference
 \longrightarrow **enhanced emission**



Free Electron Laser

Self-Amplified-Spontaneous-Emission

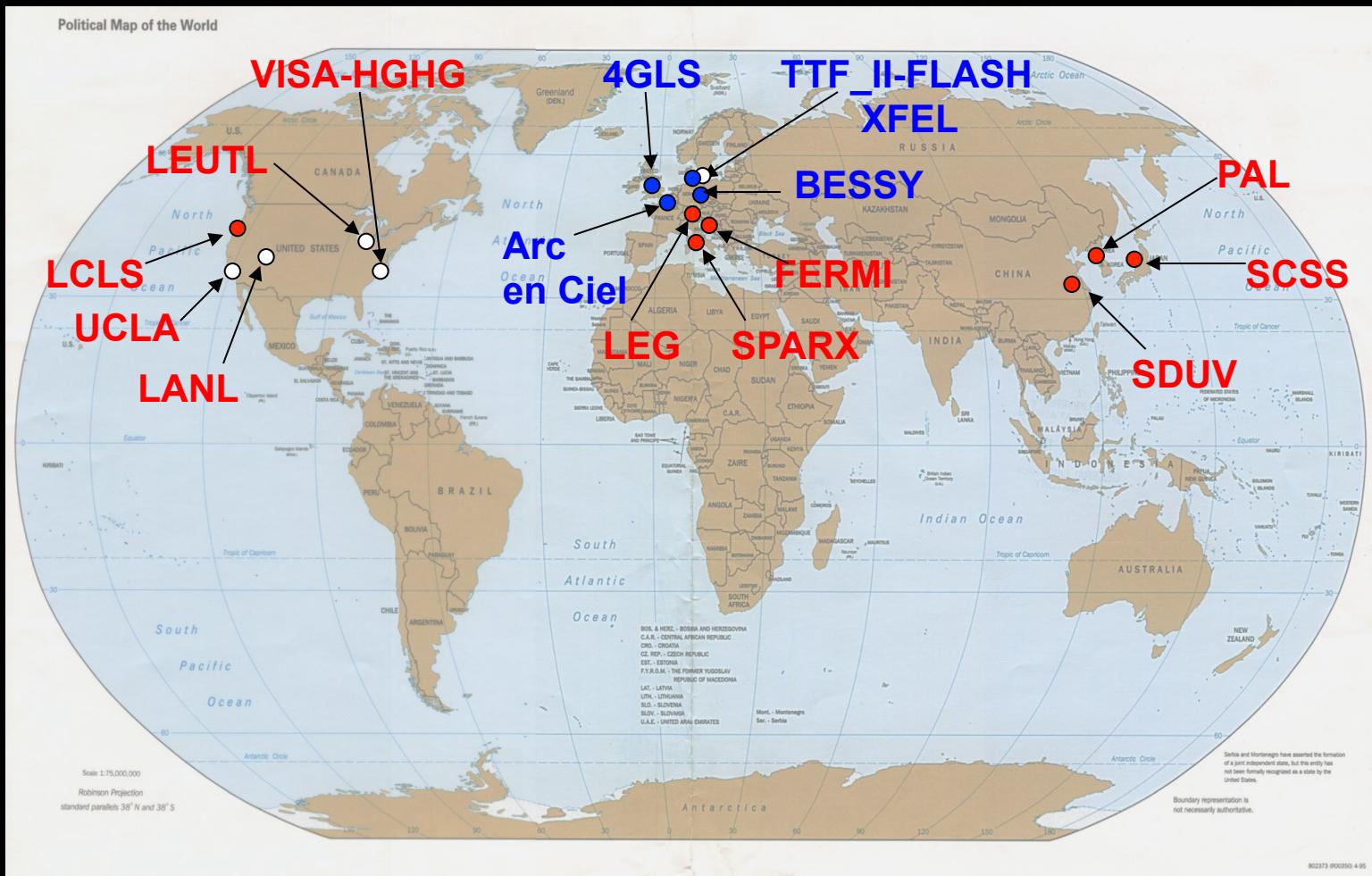
(Senza Specchi - Accordabile - Raggi X)



$$\lambda_r = \frac{\lambda_u}{2\gamma^2} (1 + a_u^2 + \gamma^2 \theta^2)$$



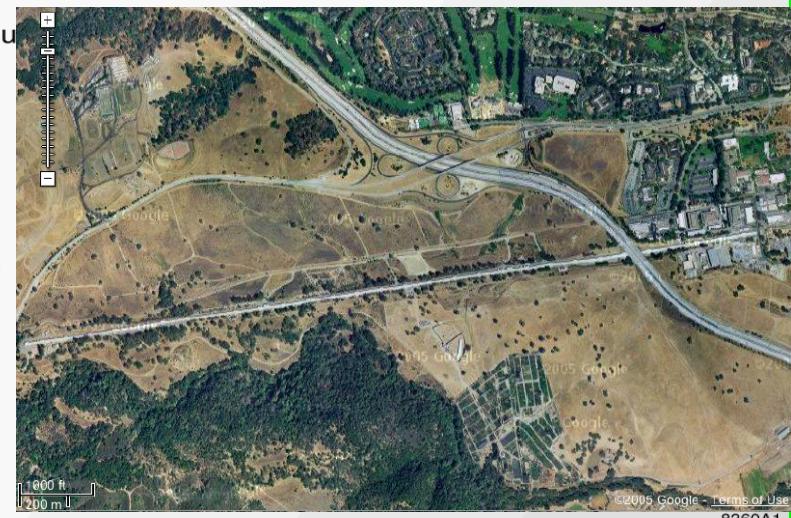
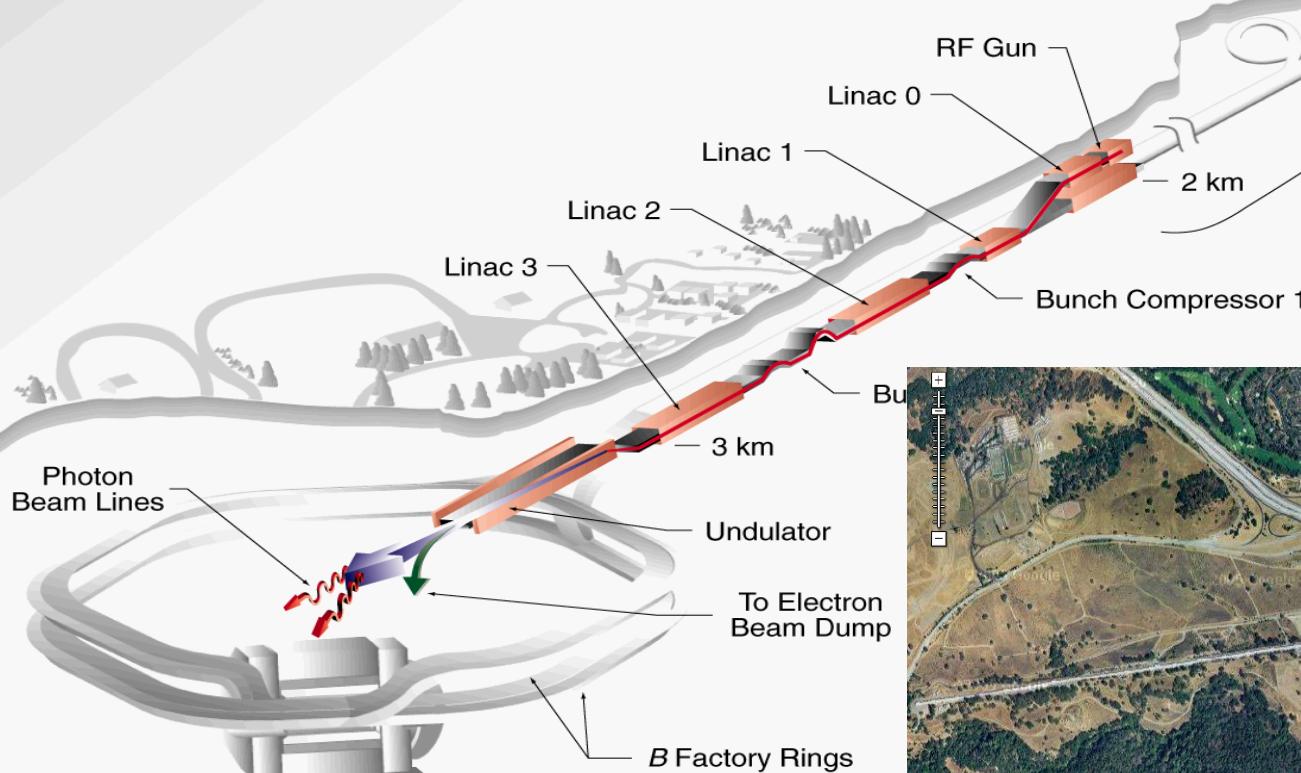
Short Wavelength SASE FEL



LCLS at SLAC

The LCLS
(Linac Coherent Light Source)

1.5-15 Å



X-FEL based on last 1-km of existing SLAC linac

The FEL Applications

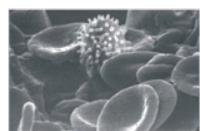
X-Rays have opened the Ultra-Small World X-FELs open the Ultra-Small and Ultra-Fast Worlds

Ultra-Small

Nature



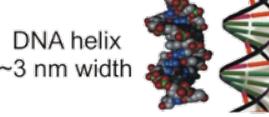
Human hair
~30 μm wide



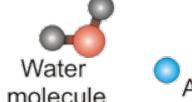
Red blood cells & white cell ~ 5 μm



Virus ~ 200 nm

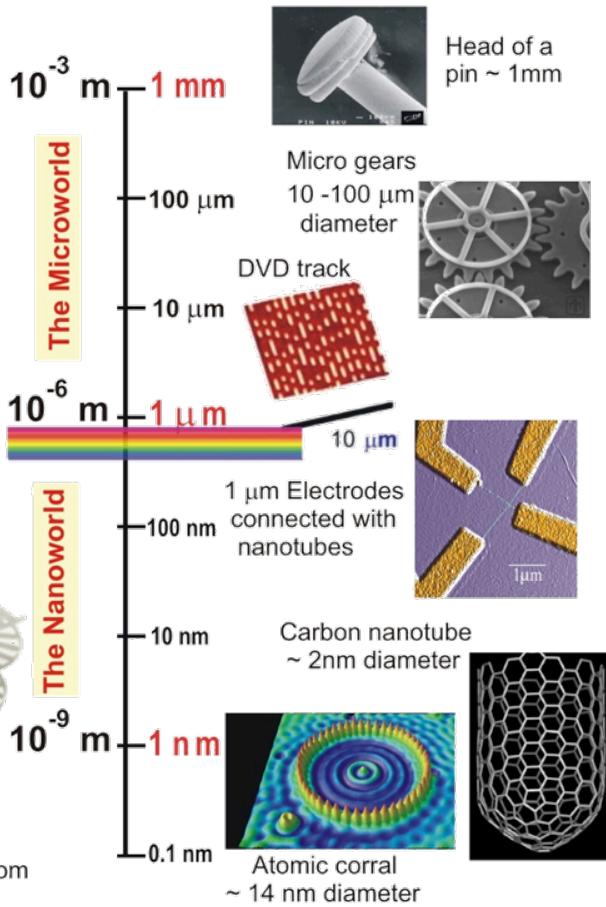


DNA helix ~3 nm width



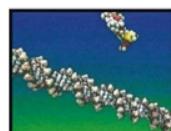
Water molecule

Technology



Ultra-Fast

Nature



Hydrogen transfer time in molecules is ~ 1ns

Spin precesses in 1 Tesla field is 10 ps

Shock wave propagates by 1 atom in ~ 100 fs

Water dissociates in ~10 fs

Light travels 1 μm in 3 fs

Bohr period of valence electron is ~ 1 fs

10^{-9} s

10^{-12} s

10^{-15} s

s

H

s

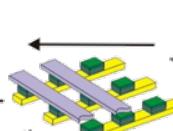
fs

fs

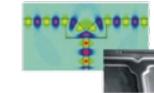
fs

fs

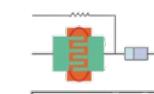
Technology



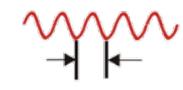
Computing time per bit is ~ 1 ns



Optical network switching time per bit is ~ 100 ps

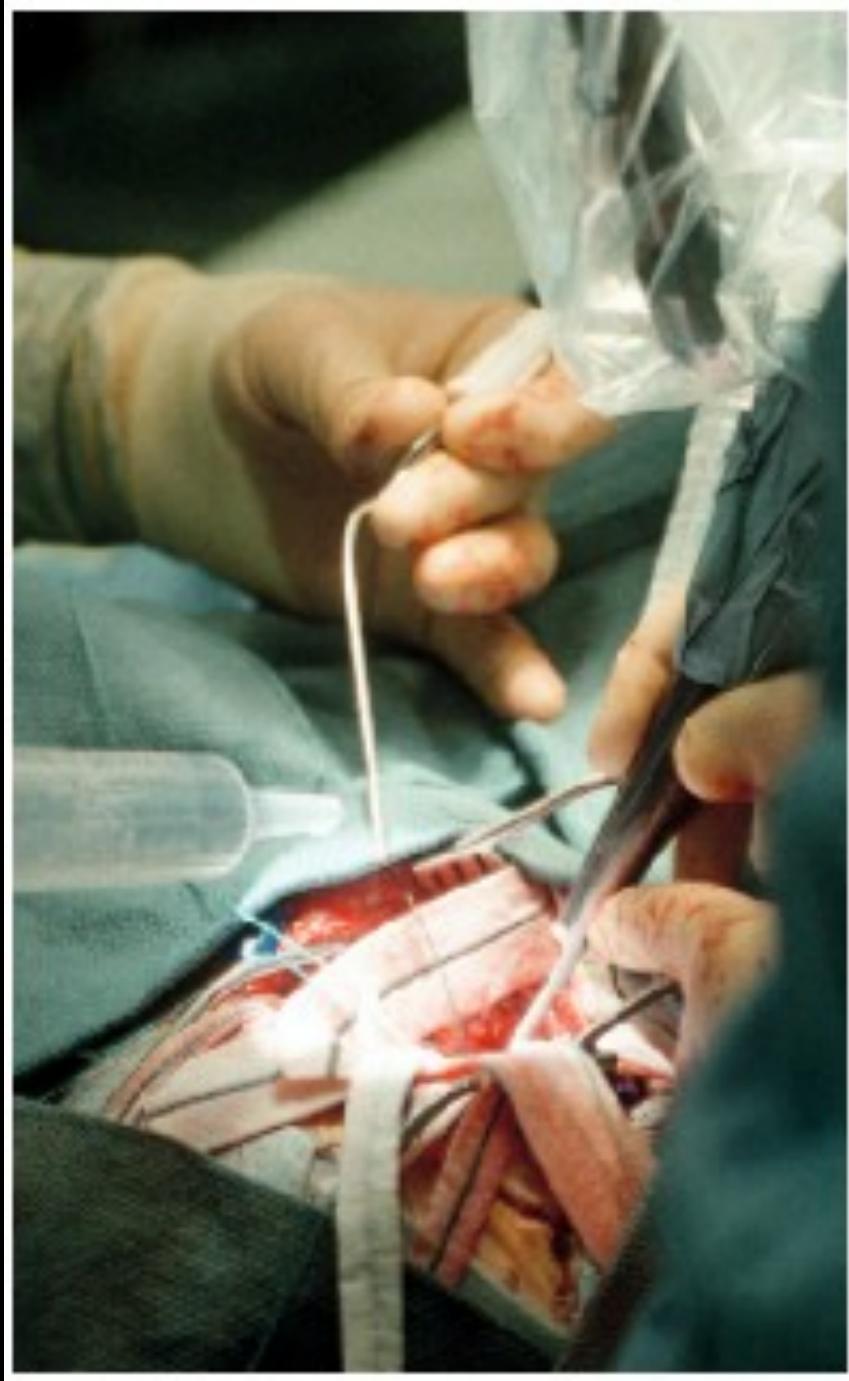


Laser pulsed current switch ~ 1ps



Shortest laser pulse is ~ 1 fs

Oscillation period of visible light is ~ 1 fs

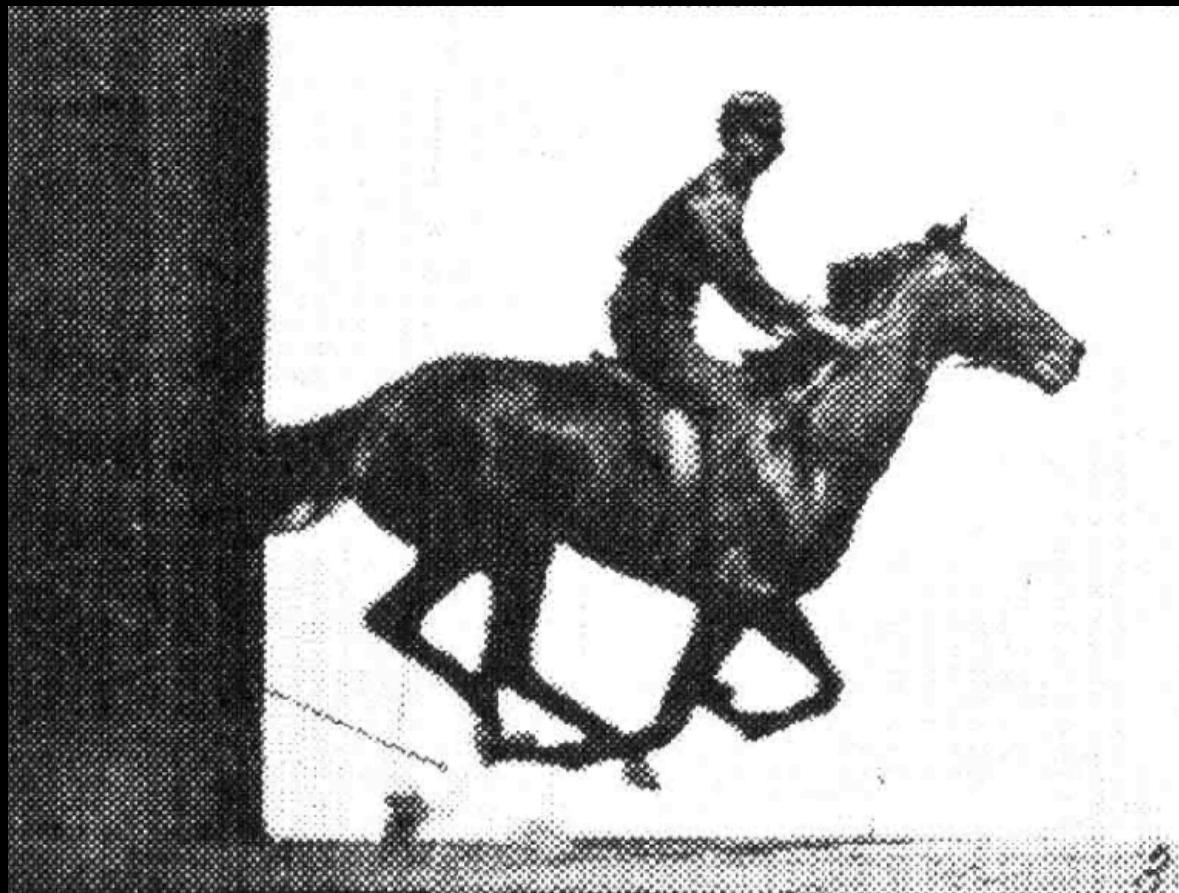




E. Muybridge

E. Muybridge at L. Stanford in 1878

disagree whether all feet leave the ground during gallop...



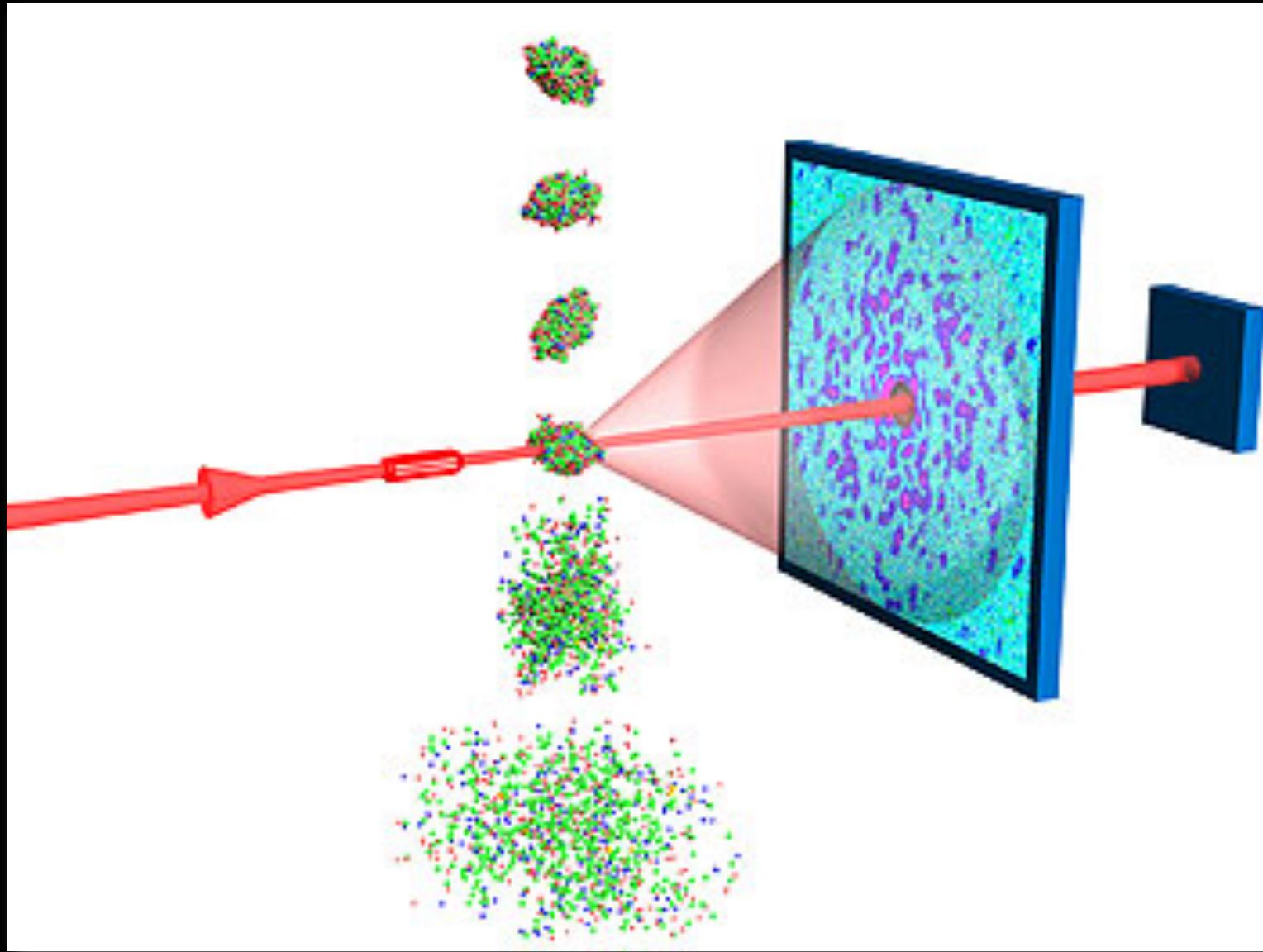
used spark photography to freeze this ‘ultra-fast’ process

E. Muybridge, *Animals in Motion*, ed. L. S. Brown (Dover Pub. Co., New York 1957)
Courtesy Paul Emma (SLAC).

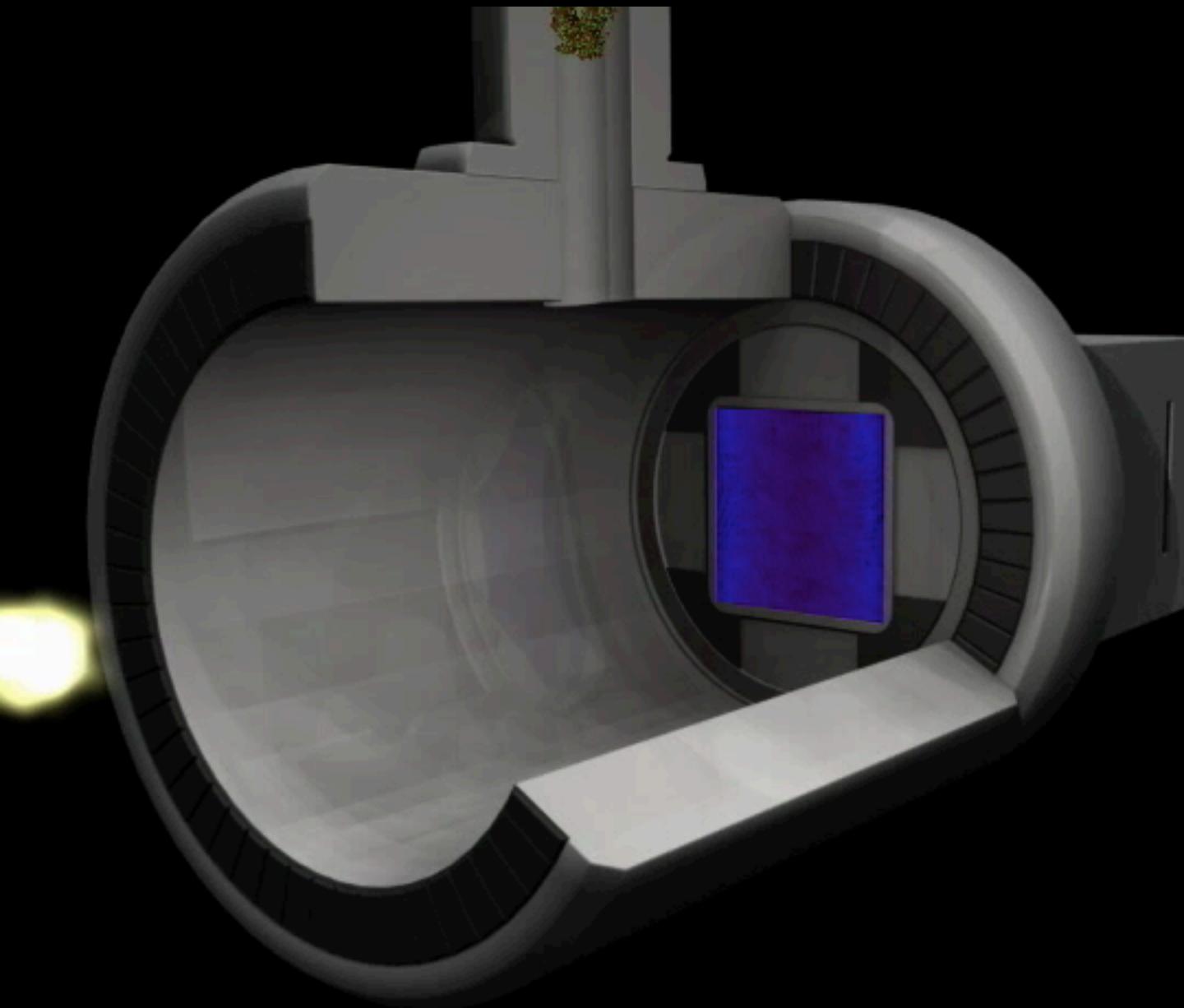
Coulomb Explosion of Lysozyme (50 fs)
Single Molecule Imaging with Intense X-rays

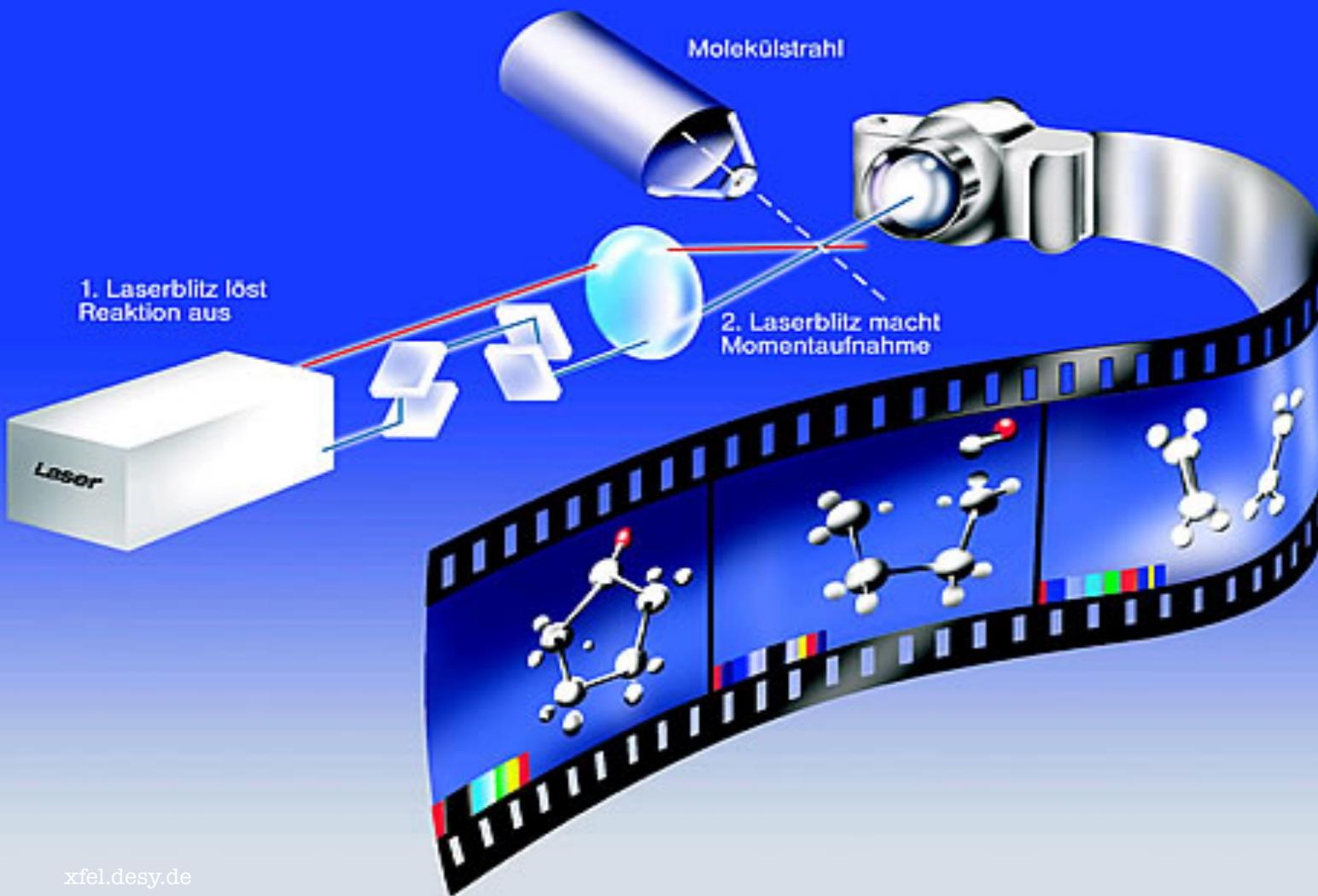
Atomic and
molecular
dynamics occur
at the *fsec*-scale

J. Hajdu, Uppsala U.



Experimental hall (Single Protein Imaging)





Open Labs 2015
Sabato 23 maggio
dalle ore 9,30 alle 20,00

Arrivederci & Grazie

