Generation and application of ultra-short high-intensity laser pulses

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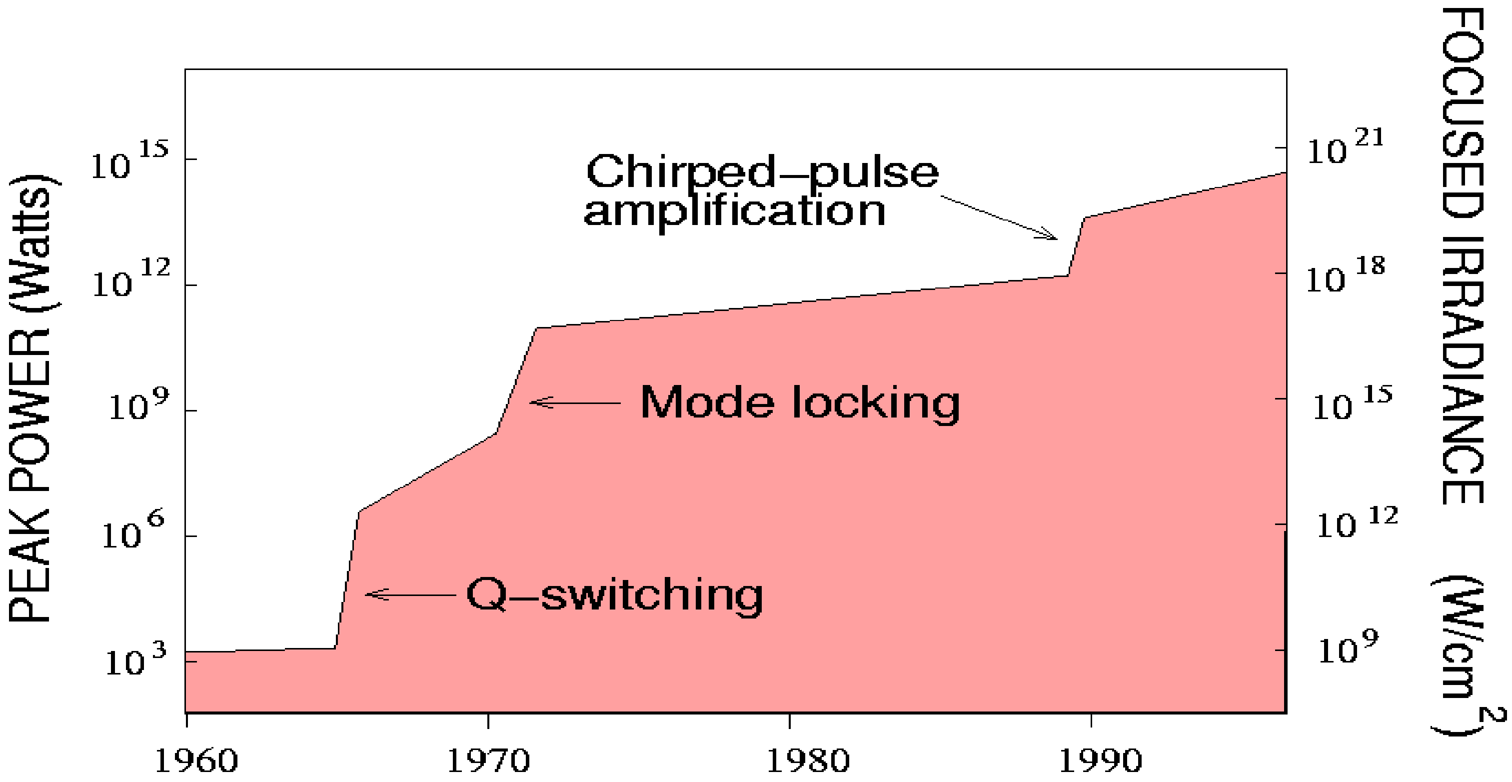
Syllabus:

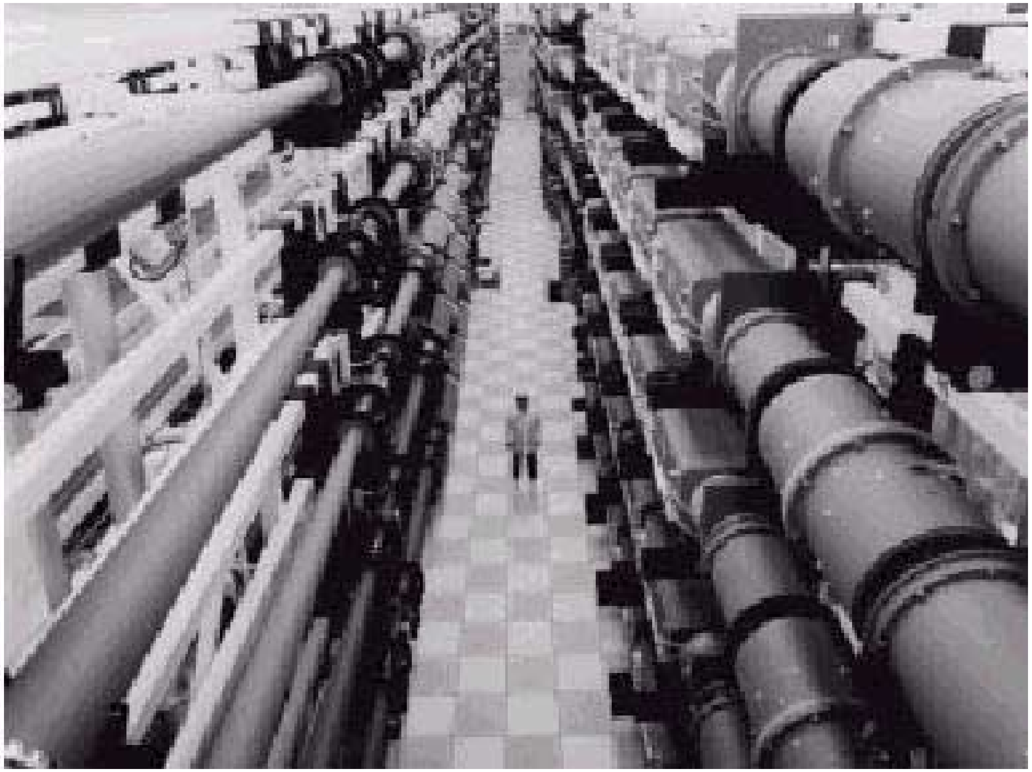
1. History of achievable highest laser power
2. Chirped Pulse Amplification (CPA) and T^3 lasers
3. PALS laser and OPCPA
4. How high are high intensities
5. Basics of plasma physics (3 minutes)
6. Laser propagation and absorption in plasmas
7. Particle-in-cell simulations
8. Ultra-short X-ray pulses and time-resolved crystallography
9. Particle acceleration. CERN on a table?
10. Nuclear reactions, positrons etc.

History of high power lasers



- Free running – typically 10 µs - 1 kW
- Q-switching – gigantic impulse – 10 ns – 100 MW
- Mode locking – short pulse – 10 ps – 100 GW
- Chirped pulse amplification – 20 fs – 1 PW

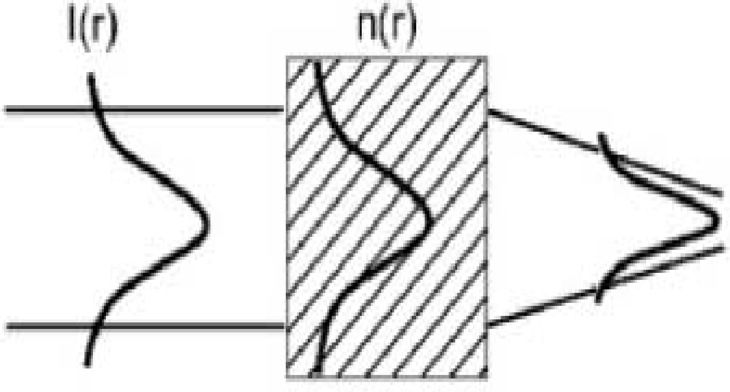
1986 – NOVA – 100 kJ, 10 TW laser, λ = 1.05 μm



- Long pulse (10 ns), high energy – large, > 50 beams, 400 M$
- Large 1 m diameter slab amplifiers, pumped by flashlamps
- Low efficiency – 0.1 %, energy 100 MJ in capacitors
- Low repetition rate – 1 pulse per one hour, 150 x 300 m hall

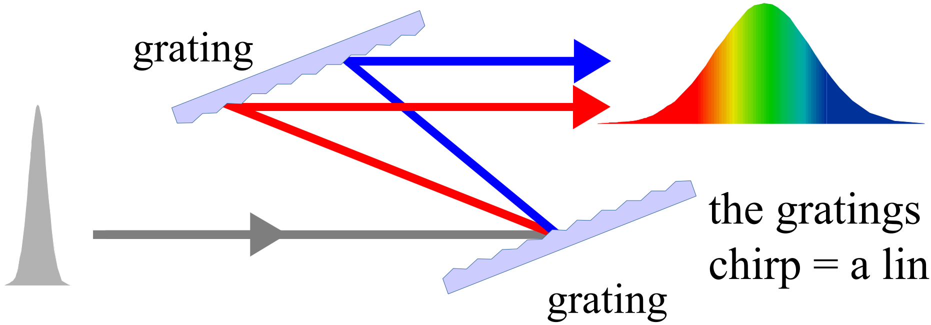
Why not ultra-short high-intensity pulse ?

- Low-energy short-pulse lasers could be small and cheap
- 500 fs laser pulses at a few nJ were available in 1985
- **<u>But, it is impossible to amplify them</u>**
- Each amplifier medium breaks at some intensity (W/cm^2) – the higher power the larger beam diameter must be
- Even much below – medium is non-linear –dielectric constant $\varepsilon = \varepsilon_l + \varepsilon_2 |E|^2 = \varepsilon_l + 8\pi/c * \varepsilon_2 I$ and $\varepsilon_2 > 0$ Higher intensity in beam centre, higher $n = \sqrt{\varepsilon}$, focusing lens – self-focusing and filamentation



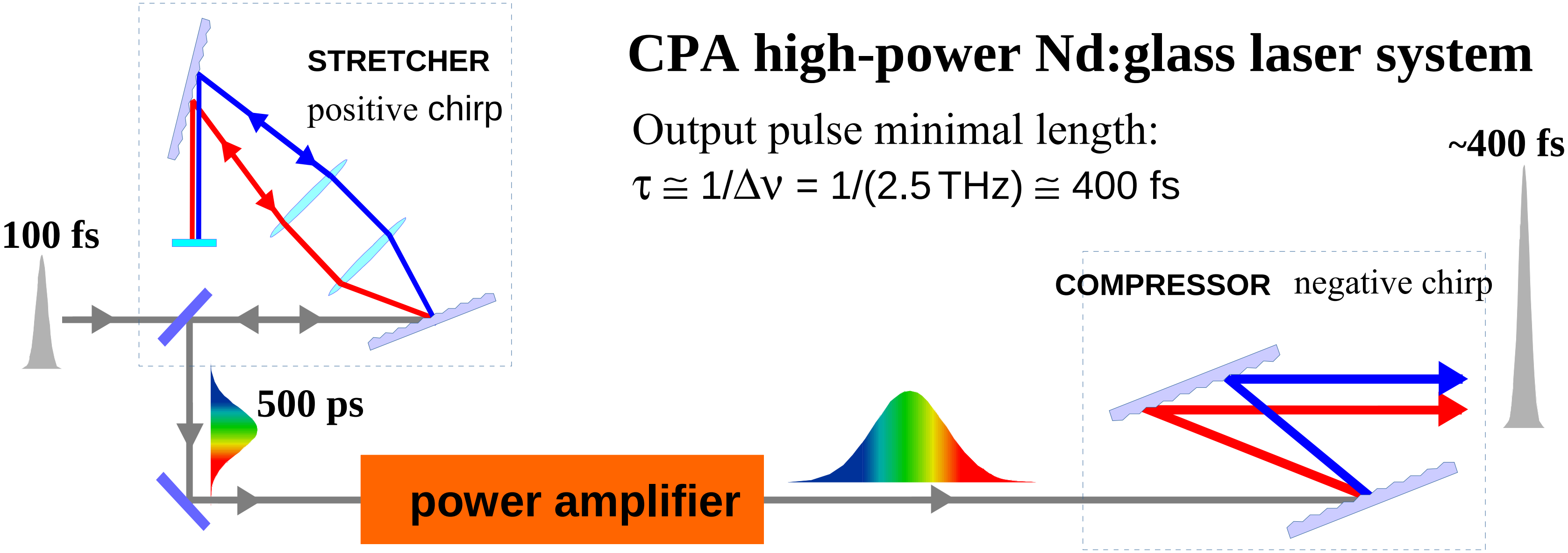
- Long pulses must be amplified and then compressed

CPA = Chirped Pulse Amplification (G. Mourou -1985)



Carrier : $\omega=\omega_0+\beta t$

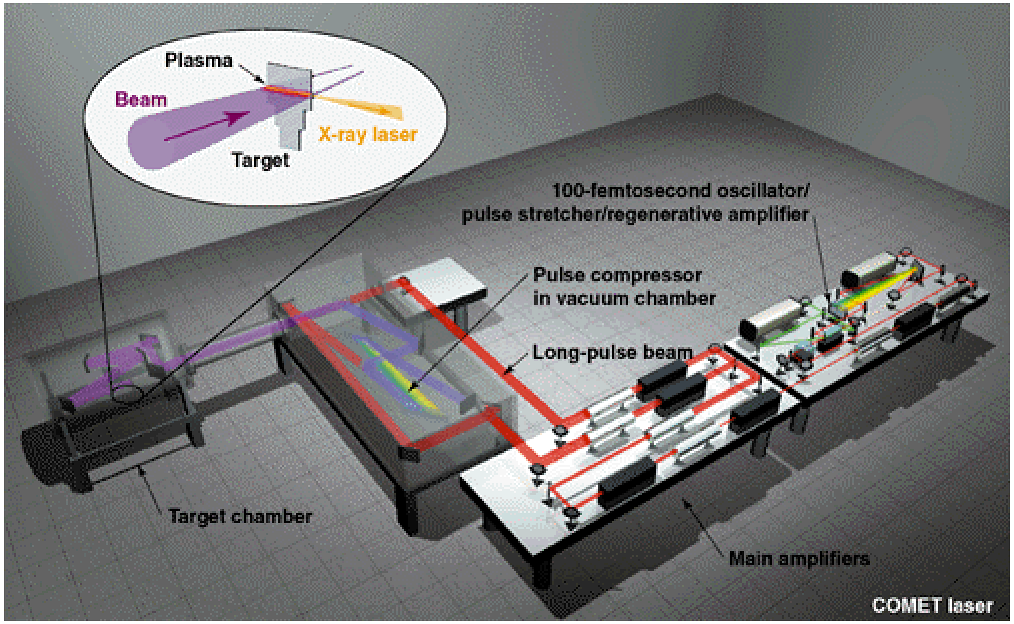
the gratings introduce a frequency dependent time delay
chirp = a linear frequency sweep, $d\omega/dt=\beta$ (here <0)



CPA high-power Nd:glass laser system

Output pulse minimal length:
$\tau \cong 1/\Delta\nu = 1/(2.5\,\mathrm{THz}) \cong 400$ fs

Table-top terawatt (T^3) CPA lasers



Ti:sapphire ($\lambda \cong 790$ nm)

$\Delta\nu$=100 THz ($\Delta\nu/\nu$= 0.1)

Pulse FWHM > 10 fs

(typically 50 – 100 fs)

Energy 100 mJ

Repetition rate 10 Hz

Power 1 TW

- Today 10 TW/10 Hz or 100 TW/1 Hz available (also 1 TW/1 kHz)
- Price ≅ 100 k$, laboratory space 10 m x 5 m
- Focal spot diameter ≅ 10 μm, focal spot ≅ 10^{-6} cm^2
- Maximum intensity I = P/S = 1 TW / 10^{-6} cm^2 = 10^{18} W/cm^2

Maximum power – petawatt laser

Compressor for 1 PW - vacuum chamber with dielectric gratings – 1 m wide

One beam line of Nova laser with new laser oscillator

600 J in 600 fs = 10^{15} W = 1 PW

Large scale 1 pulse/hour

Maximum intensity – 10^{21} W/cm^2

It is now being moved from LLNL to University of Nevada at Reno

- Femtosecond Petawatt upgrade for Gekko XII laser – ILE Osaka, Japan, completed in 2000
- Femtosecond Petawatt upgrade for Vulcan Laser – Rutherford Appleton Laboratory, UK, 2003

Prague Asterix Laser System (PALS)

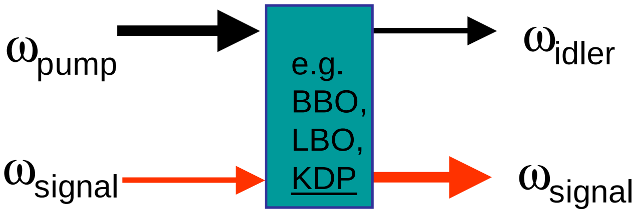
- 1 kJ, 400 ps (2.5 TW) iodine laser (λ = 1.315 μm)
- 1 pulse/ 20 minutes, focal diameter 40 μm, max. I = 5 x 10^{16} W/cm^2
- Built in Garching, Germany, sold to Prague for 1 DM, building 2.5 M$
- Is it possible to upgrade to 1 PW?
- Directly not, too narrow line width, 10 ps theoretical minimum, but ?

OPCPA = Optical Parametric Chirped Pulse Amplification

Ian Ross, John Collier, P. Matousek et al, XXV ECLIM, Formia, 4-8 May 1998

New method of fs-pulse generation: combination of parametric-amplifier (OPA) and chirped-pulse-amplification (CPA) techniques (Piskarkas et al., 1991)

OPA

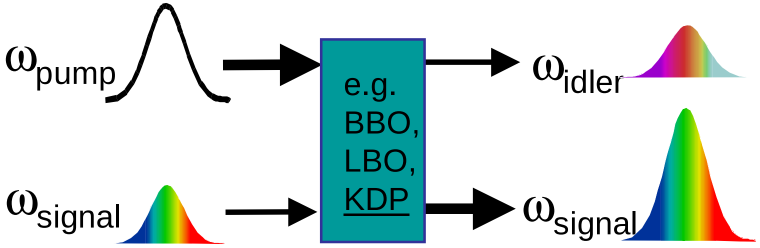


The pump + the signal mix to produce a wave $\omega_i = \omega_p - \omega_s$

$$\boxed{\omega_p = \omega_s + \omega_i}$$

BOTH **the signal** & the idler gain power

OPA + CPA



- very large bandwidth
  $(\Delta\nu \cong 100\,\text{THz} \Rightarrow \tau \cong$ **10 fs**)
- λ_{pump} and λ_{signal} independent
- no energy deposition in the OPA medium
- high quality of the output beam
- KDP: large size, no problem with damage

SOFIA & OPCPA PILOT EXPERIMENT

SOFIA **= Solid-state Oscillator Followed by Iodine Amplifiers**

OPCPA **= Optical Parametric Chirped Pulse Amplification**

Femtosecond source

Ti:Sa Femtosource Compact cM1 (Femtolasers) pumped by a diode laser Millenia Xs (Spectra Physics)

Ti:Sa fs laser

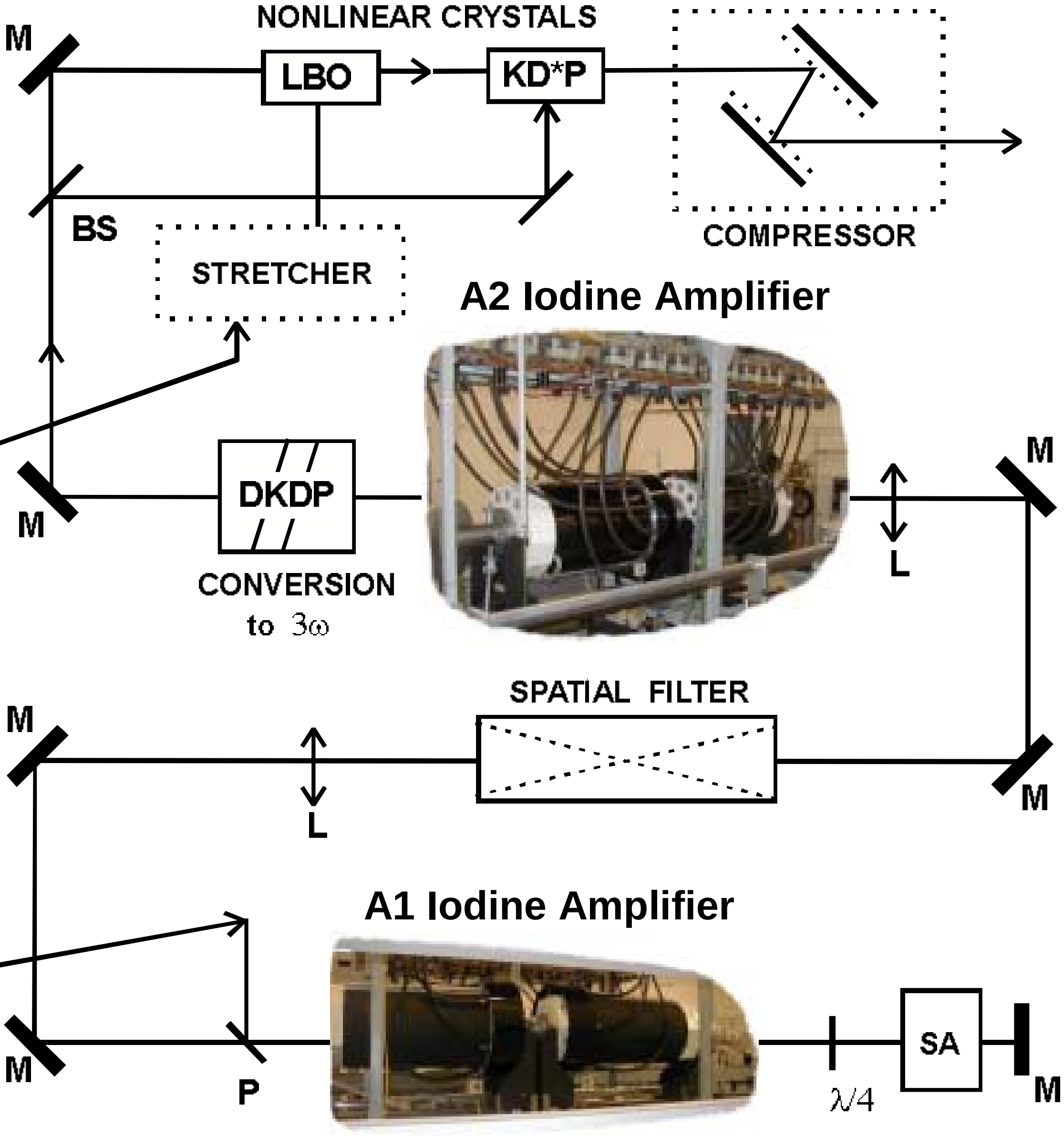
Oscillator

MOPO – HF (Spectra Physics)

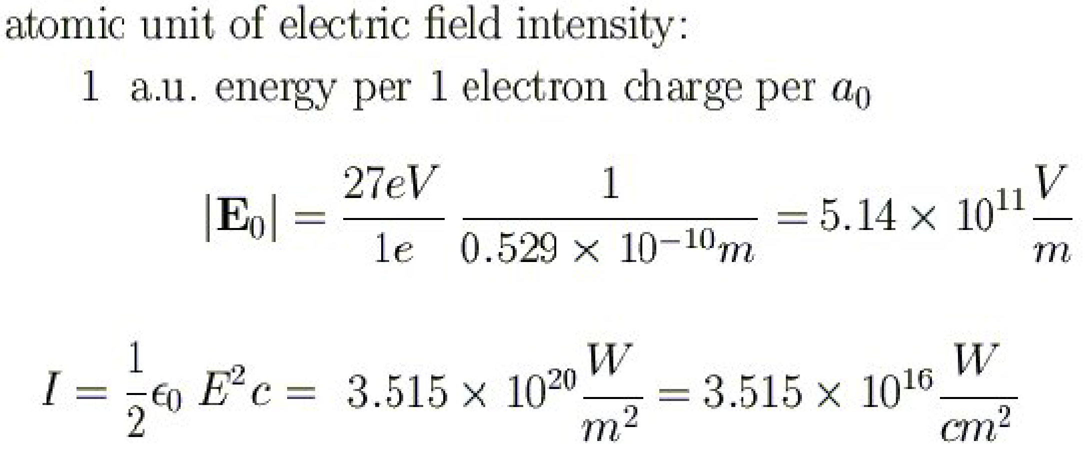
Pumping Nd:YAG

Quanta Ray PRO-290-10 YAG

MOPO Oscillator



How high is a high intensity ?



atomic unit of electric field intensity:

1 a.u. energy per 1 electron charge per a_0

$$|\mathbf{E}_0| = \frac{27eV}{1e}\,\frac{1}{0.529\times 10^{-10}m} = 5.14\times 10^{11}\frac{V}{m}$$

$$I = \frac{1}{2}\epsilon_0\,E^2 c = \ 3.515\times 10^{20}\frac{W}{m^2} = 3.515\times 10^{16}\frac{W}{cm^2}$$

Relativistic intensity – relativistic electron motion in laser field

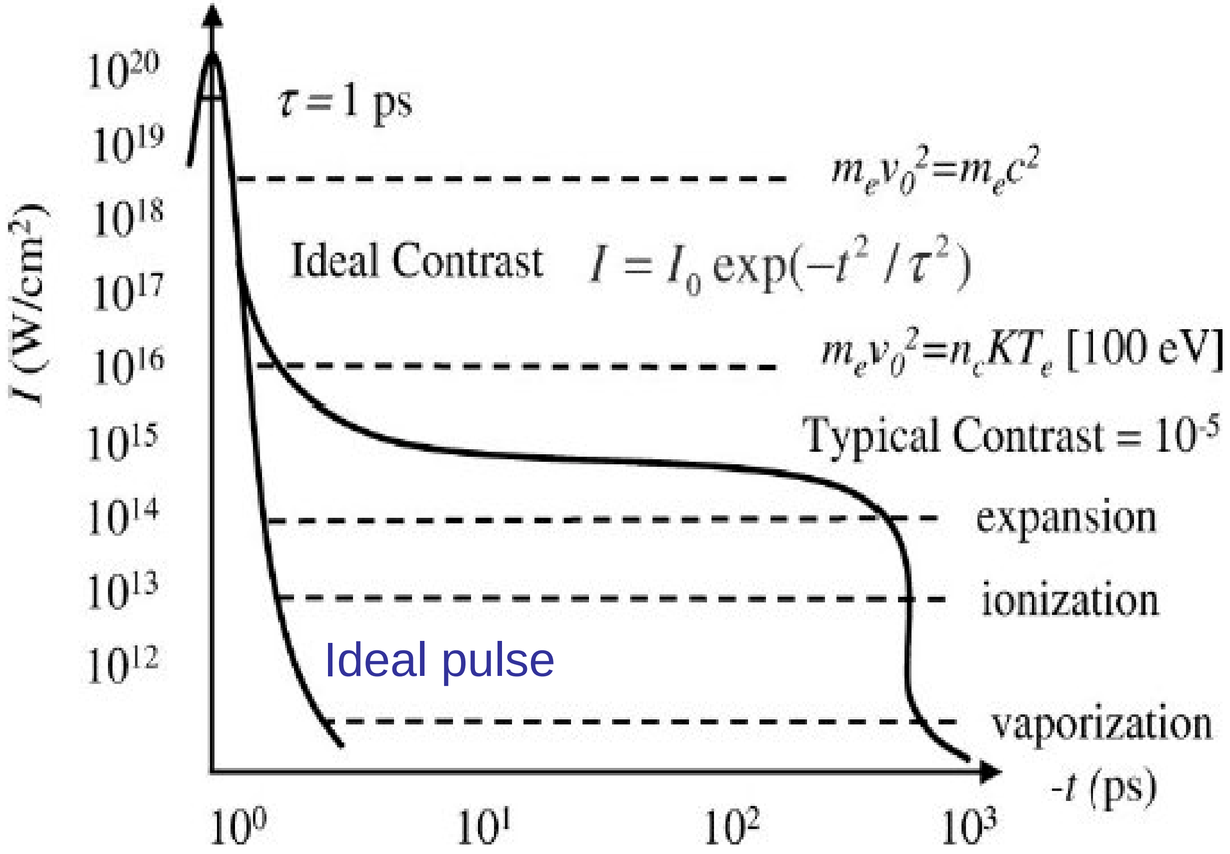
Momentum of oscillation in laser field $p_L = e\,E_L / \omega_0 = m_{e0}\,c$

$I_r = ½\,\varepsilon_0\,E_L^2\,c = ½\,\varepsilon_0\,m_{e0}^2\,c^3 \;/\; e^2\,\omega_0^2$, $\lambda = \ c\,\omega_0 / 2\pi$

$I_r\,\lambda^2 = 1.35 \times 10^{18}$ W/cm^2 x μm^2

Often $Q_r = a_0^2 = I/I_r$ $\quad$ a_0 = normalized amplitude

Laser interaction with solids



Contrast may be increased by using second harmonics ($2\omega_0$) typically 10^{-7}-10^{-8}

Contrast may be high enough for $I = 10^{17}$ W/cm^2 but not for relativistic intensities

Water monolayer on the target surface may be important – protons max. q/m

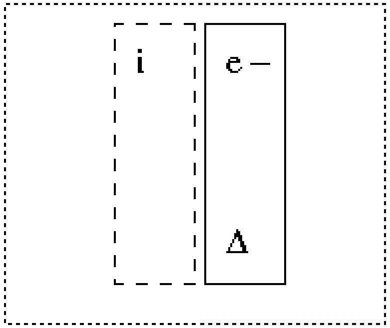
Introduction into plasma physics

- **Plasma oscillations**

  let electron density n_e and ion density
  $n_i = n_e/Z$ (Z-mean ion charge),
  let slab of electrons of thickness is Δ
  moved to distance Δ with respect to ions,
  let ions do not move

$$E = 4\pi\sigma = 4\pi e n_e \Delta$$

$$\frac{\mathrm{d}^2\Delta}{\mathrm{d}t^2} = a = \frac{eE}{m_e} = \left(\frac{4\pi e^2 n_e}{m_e}\right)\Delta$$



Equation of electron motion harmonic oscillations with plasma frequency ω_{pe}

$$\boldsymbol{\omega_{pe} = (4\pi e^2 n_e/m_e)^{1/2}}$$

- **Plasma waves** – without thermal motion particle outside of capacitor do not know about field – propagation due to $T_e \neq 0$ – longitudinal wave
- Dispersion relation $\boldsymbol{\omega^2 = \omega_{pe}^2 + 3 k^2 v_{Te}^2}$ where $v_{Te}^2 = k_B T_e / m_e$
- Interaction with electrons of velocity $v = \omega/k$, Landau damping – eln.acceleration

Introduction into plasma physics - continued

- **Debye length** – distance to which electrons and ion can separate potential energy equal to thermal energy

  $k_B T_e = e E \lambda_{De}$ and $E = 4\pi e n_e \lambda_{De}$

  so

  $\boldsymbol{\lambda_{De} = (k_B T_e / 4\pi e^2 n_e)^{1/2} = v_{Te} / \omega_{pe}}$

  also any static charged is screened at Debye length

- High frequency plasma **dielectric constant** (for laser field)
  Laser field $E_L = E \exp(-i \omega_0 t)$

$$\frac{d\vec{v}}{dt} = -\frac{e\vec{E}_L}{m_e} \qquad \vec{v} = -i\frac{e\vec{E}}{m_e\omega_0} \qquad \vec{j} = i\frac{e^2 n_e \vec{E}}{m_e\omega_0}$$

$$\nabla \times \vec{H} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} - \frac{4\pi}{c}\vec{j} = -\frac{i\omega_0}{c}\left(1 - \frac{4\pi e^2 n_e}{m_e\omega_0^2}\right)\vec{E}$$

Plasma dielectric constant ε

grows when $m_e \uparrow$ and/or $n_e \downarrow$

$$\varepsilon = 1 - \frac{4\pi e^2 n_e}{m_e\omega_0^2} = 1 - \frac{\omega_p^2}{\omega_0^2}$$

Laser reflection and propagation

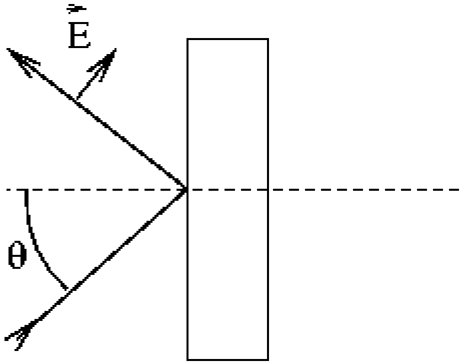
- Laser wave number $k^2 = (\omega_0/c)^2\ \varepsilon$, exponential decrease for $\varepsilon < 0$
- Laser only skins behind **critical density** $\mathbf{n_c = (m_e\ \omega_0^2)/(4\ \pi\ e^2)}$, laser radiation is reflected at the critical density
- For Nd-laser (1.05 μm) critical density $n_c = 10^{21}$ cm^{-3}, for comparison fully ionized solid density Al – $n_e = 7.8 \times 10^{23}$ cm^{-3}
- **Relativistic self-focusing** – $m_e = m_{e0}/(1 - v_{osc}{}^2/c)^{1/2} = \mathbf{m_{e0}/(1- a^2)^{1/2}}$
- **Ponderomotive force** – energy of electron oscillating is given by his position, so it is potential energy is $U = (e^2\ |E|^2)/(4\ me\ \omega_0{}^2)$ so force acting on electron is

$$\mathbf{F = - \nabla U = - (e^2)/(4\ me\ \omega_0{}^2)\ \nabla\ |E|^2}$$

Ponderomotive force pushes electrons (for long pulses together with ions) out of laser beam – **ponderomotive self-focusing**

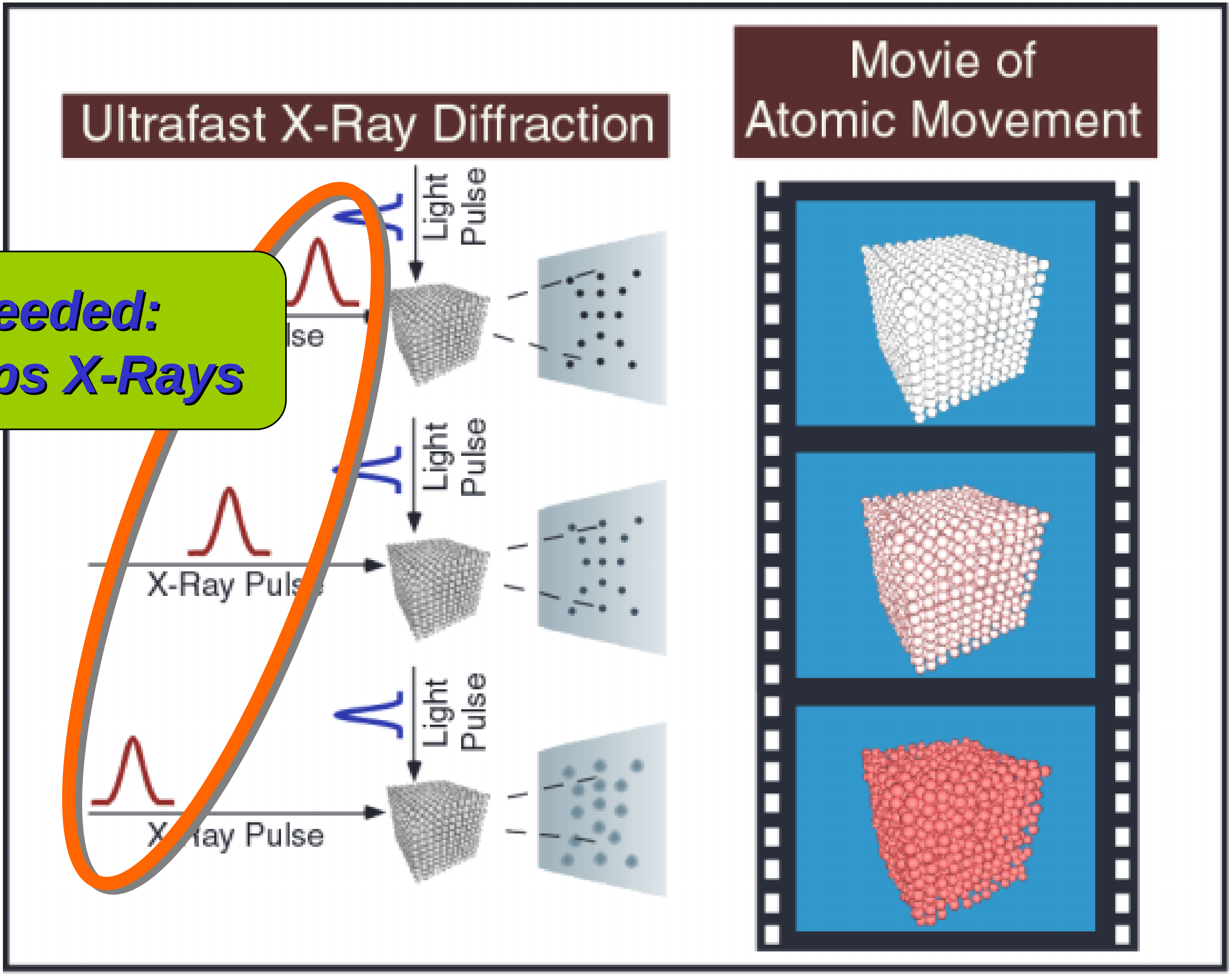
Laser absorption

- **Multiphoton ionization** – 1 laser period in dense targets
- **Collisional absorption** – low temperatures $\nu_{ei} \sim T_e^{-3/2}$
- **Resonance absorption** – laser radiation obliquely incident on planar target, p-polarization = electric field in the plane of incidence = electric field normal to target exist, laser reflected in underdense plasma ($\varepsilon = \sin^2 \theta$), but skins to critical density, where it resonantly drives plasma waves, essentially linear absorption mechanism, optimum angle given by $(k_0 L)^{2/3} \sin^2 \theta = 1$, then $\eta_A = 0.5$ at high laser intensities – small group of hot electrons heated – non-Maxwellian electron distribution, electrons preferentially accelerated out of plasma, but the are reflected by plasma-vacuum boundary



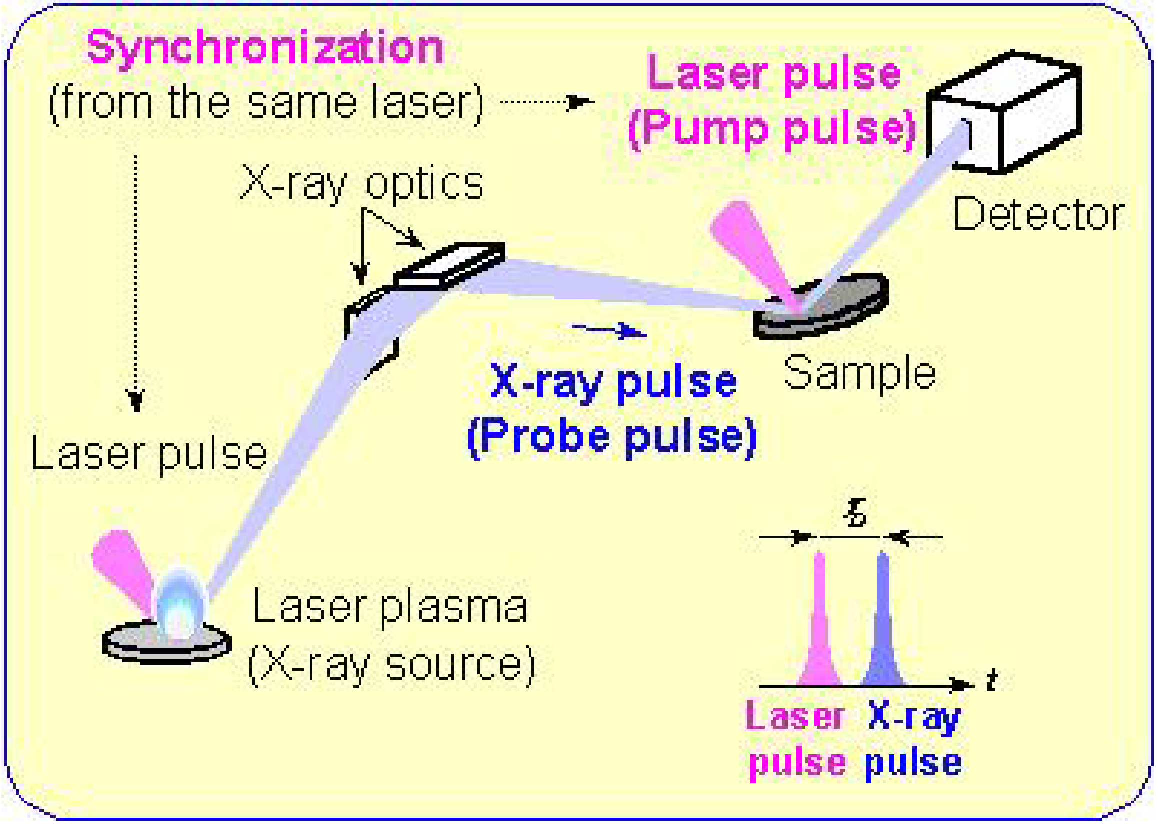
- **Vacuum heating** – very short pulse – step-like plasma vacuum boundary, very small skin, electron accelerated during ½ period into vacuum and when he returns to plasma, laser field cannot stop him, so energy is absorbed
- **Relativistic vacuum heating** – works for normal incidence, $\mathbf{F_M = -e\,(v/c \times B)}$ normal to the target comparable with $F_E = e\,E$, and $F_M \rightarrow$ vacuum heating

Time-resolved Crystallography



Needed:
Sub-ps X-Rays

Scheme of x-ray pulse-probe measurement



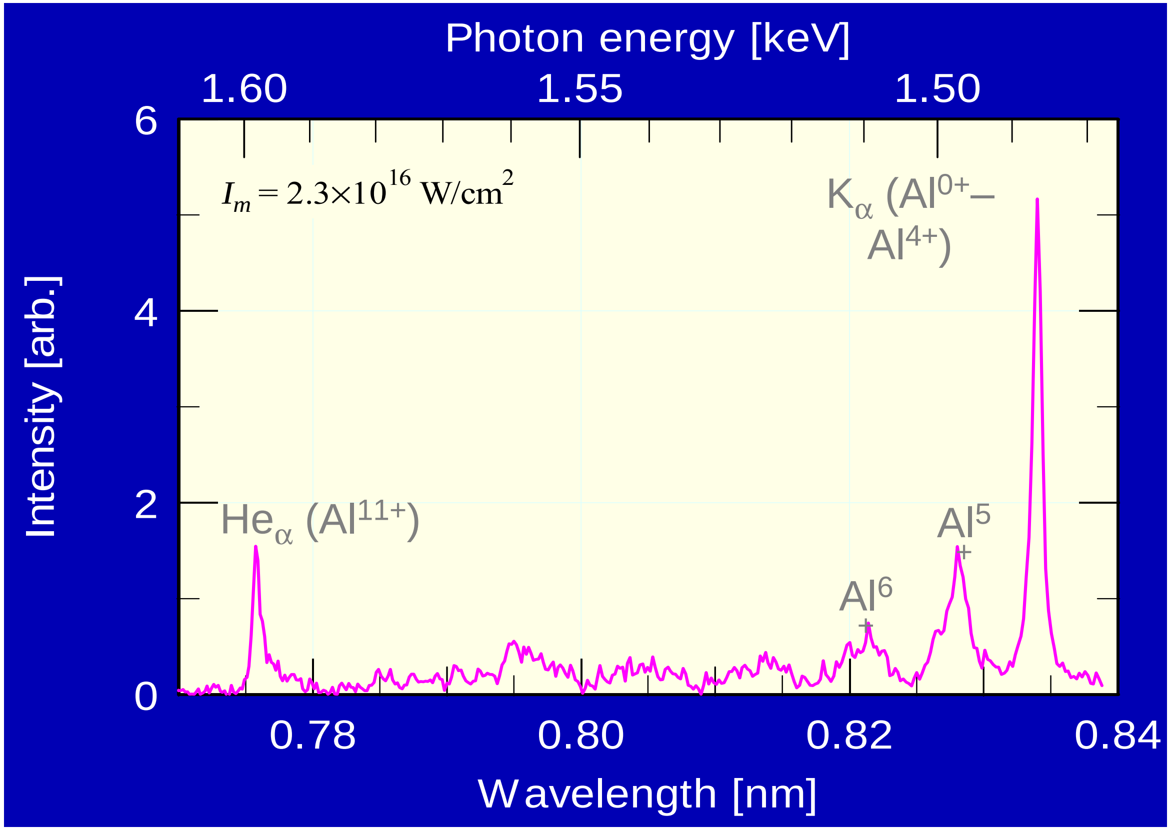
Weak laser pulse – sample excitation

Main laser pulse – generates X-ray pulse incident with variable delay on sample

K-α emission best – shortest pulse, high intensity, narrow spectrum

Moderate laser intensities – 10^{16} – 10^{17} W/cm^2 – preferable
higher intensities - fast electron fly longer distance, x-ray pulse longer

Time integrated spectra from solid target

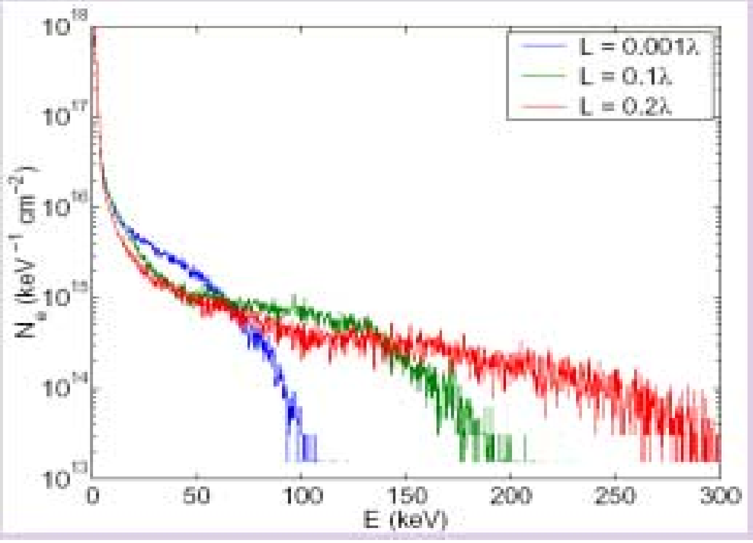


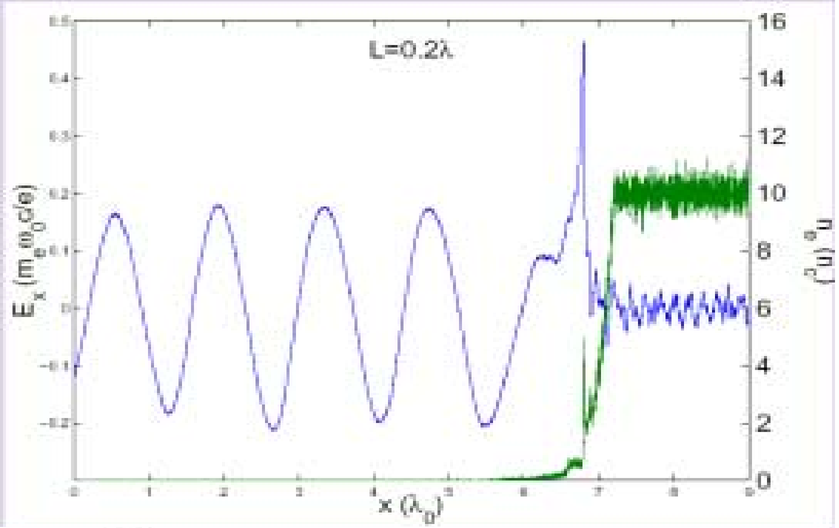
Nakano, NTT Japan
Solid Al target
Irradiated 100 fs
30 mJ Ti:Sapphire
laser λ = 790 nm
$I_m = 2.3 \times 10^{16}$ W/cm^2
p-polarization
Incidence angle 30^o

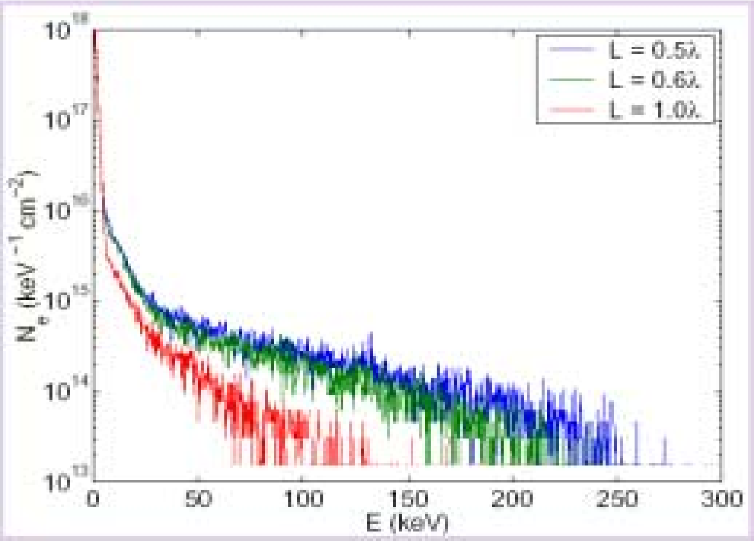
Resonance He-like line – 1598 eV – pulse lengths 30 ps (our simulation)

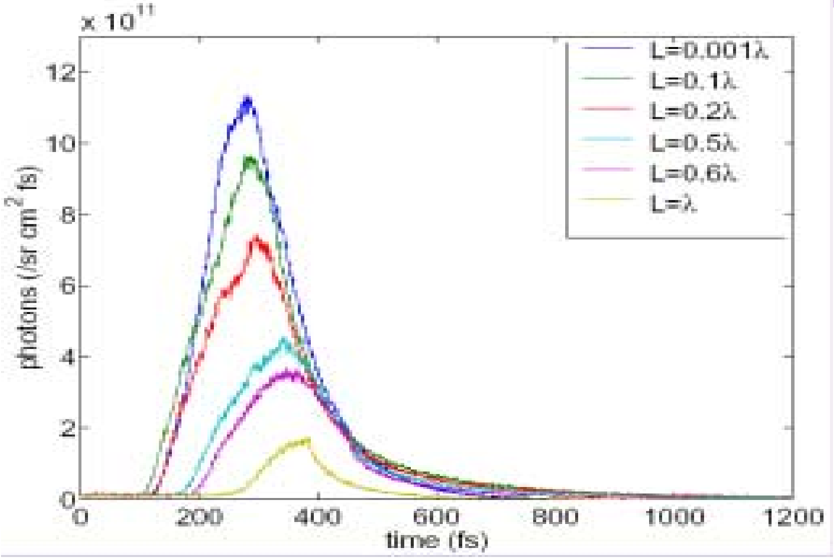
K-α emission – when energetic electron penetrates into cold target it can knock out electron from K-shell, vacancy is filled quickly (<10 fs) either Auger electron or photon is emitted (1488 eV)

Our simulations of Nakano experiment

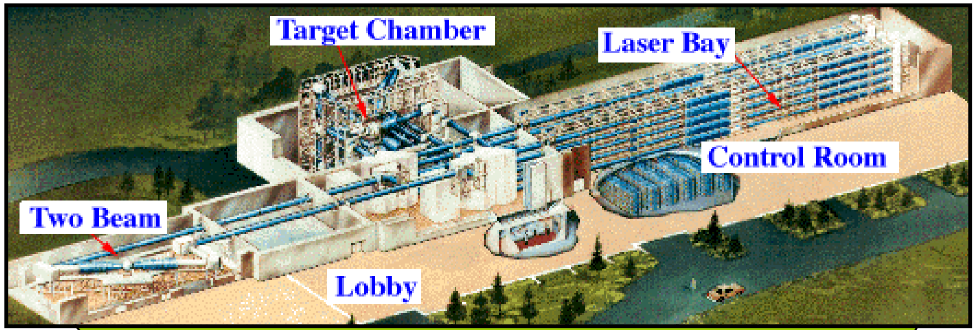




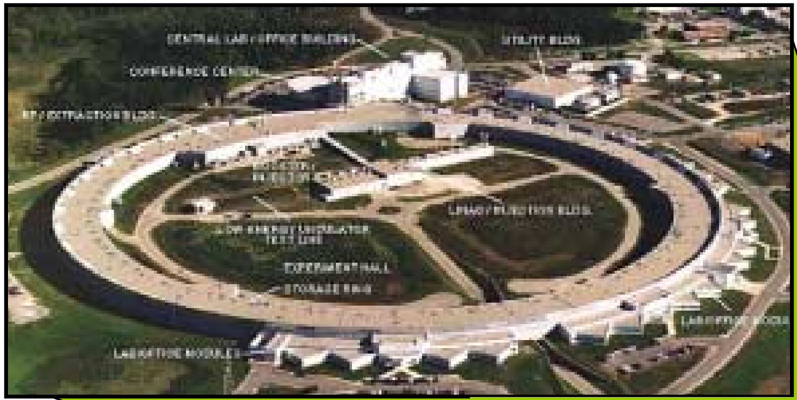




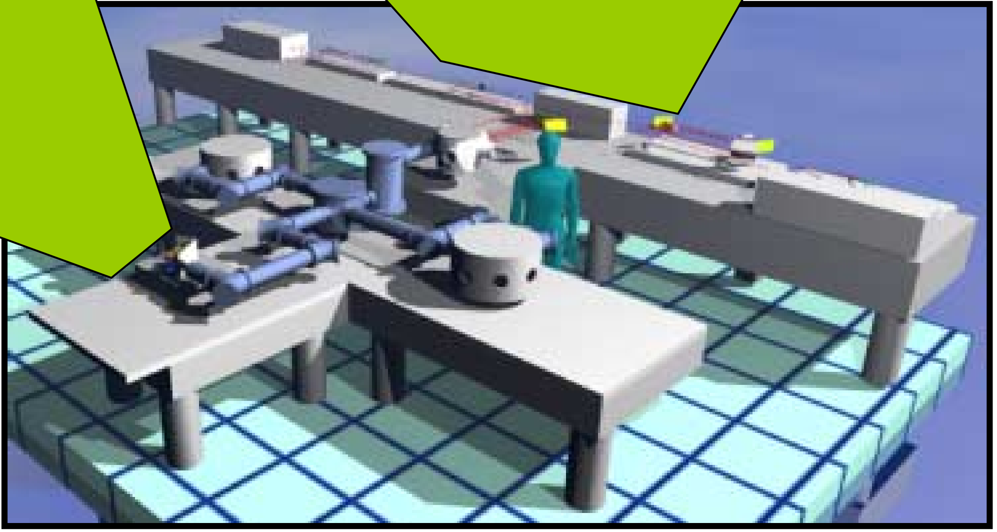
Big Science in the Small Laboratory



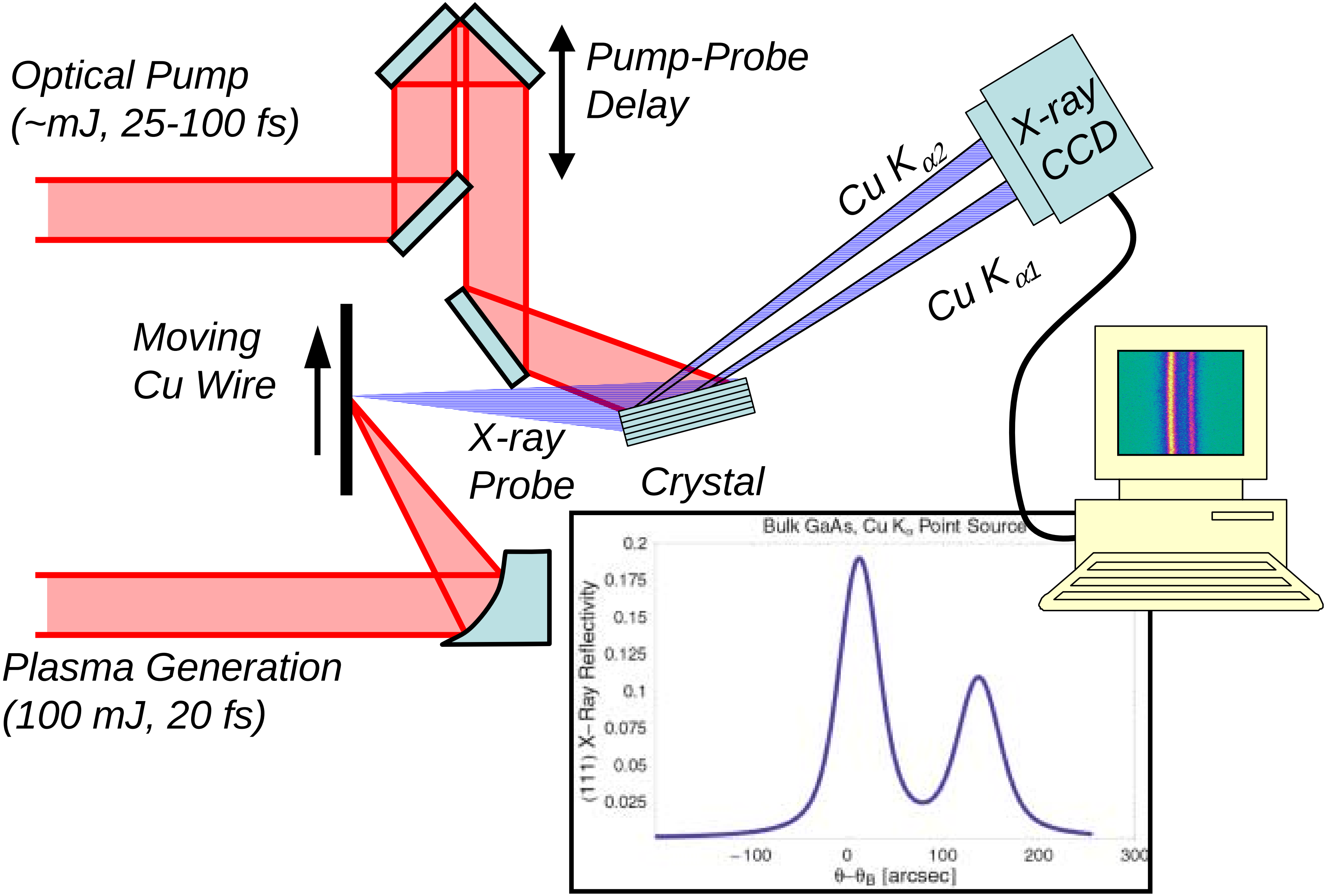
Terawatt lasers



High-flux keV x-rays



Ultrafast X-ray Diffractometer



Optical Pump
(~mJ, 25-100 fs)

Pump-Probe
Delay

X-ray
CCD

Cu K $\alpha 2$

Cu K $\alpha 1$

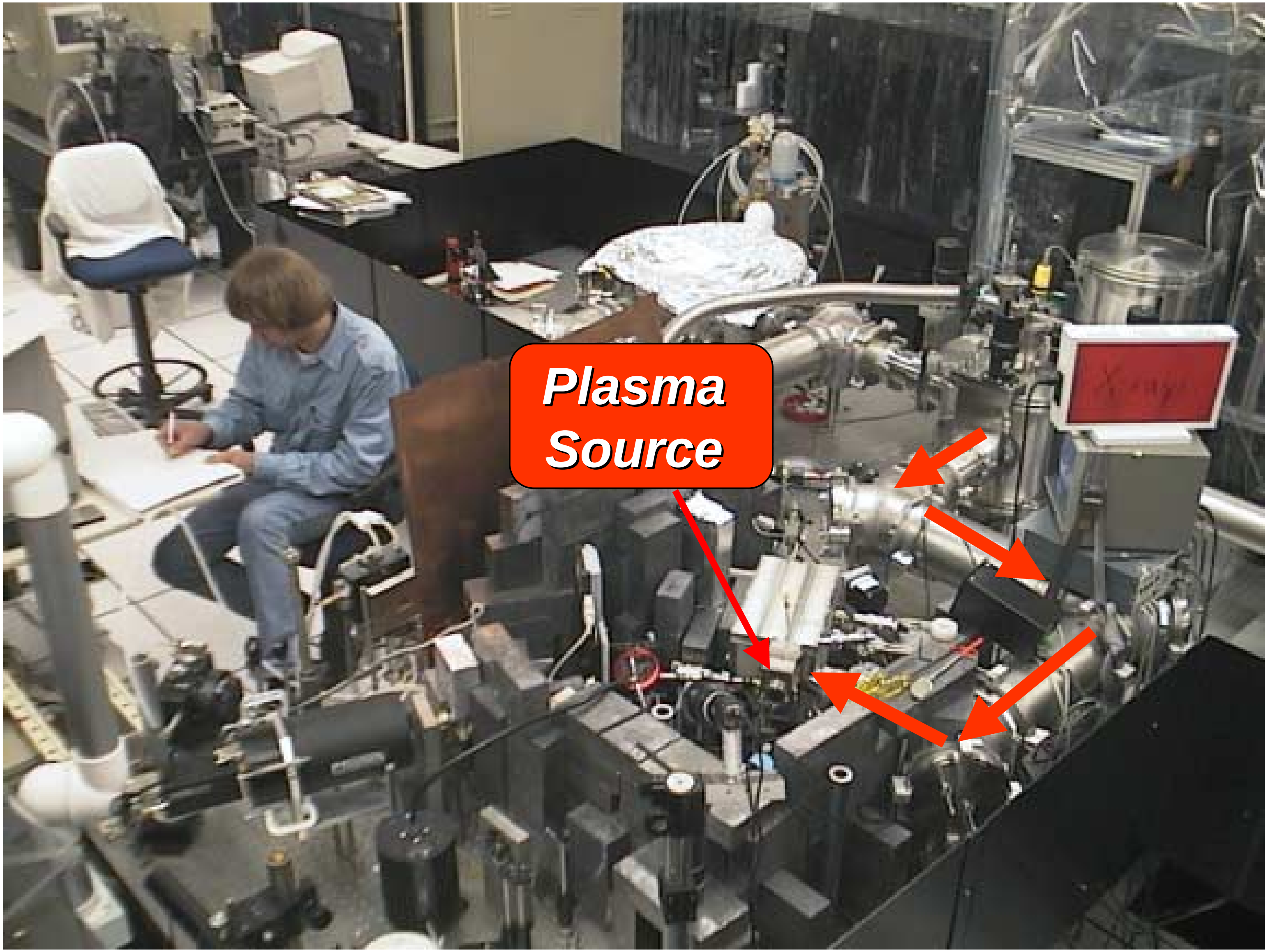
Moving
Cu Wire

X-ray
Probe

Crystal

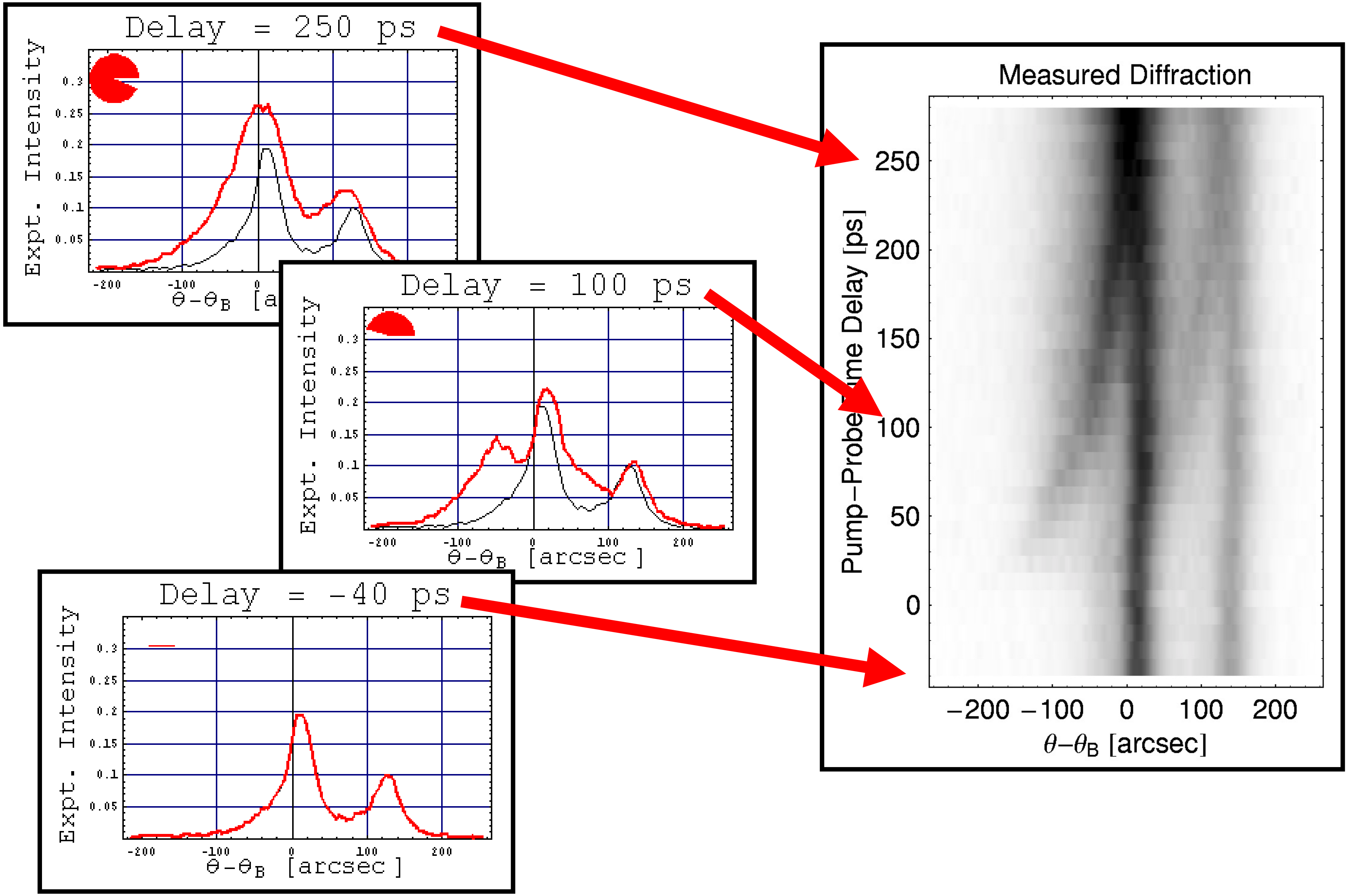
Plasma Generation
(100 mJ, 20 fs)

Laboratory Setup – UCSD (Wilson-Squier group)



Plasma Source

Ultrafast X-ray Diffraction: The Movie

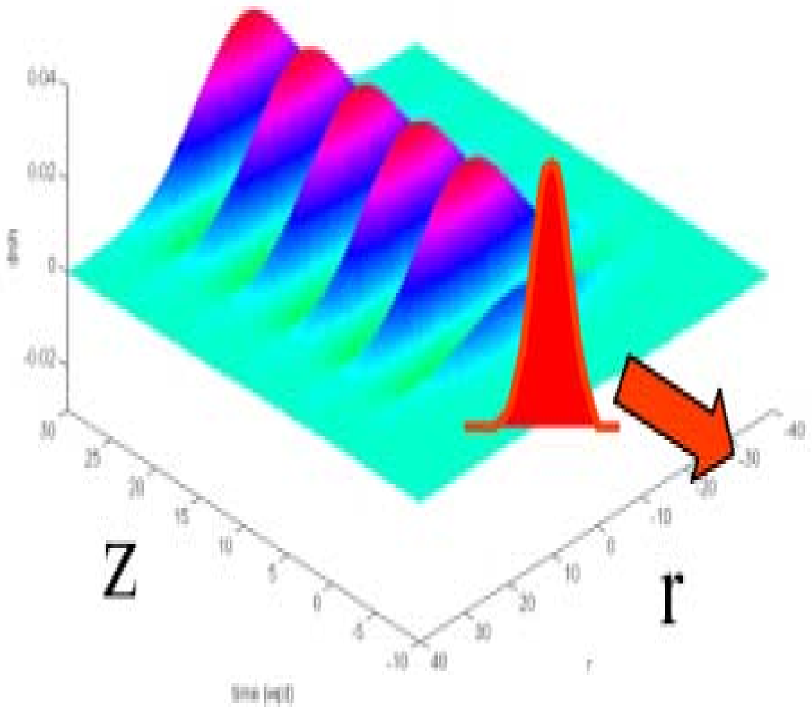


Electron acceleration

- Acceleration by plasma waves in short pulse interaction
- Accelerating electric fields – **200 GV/m**

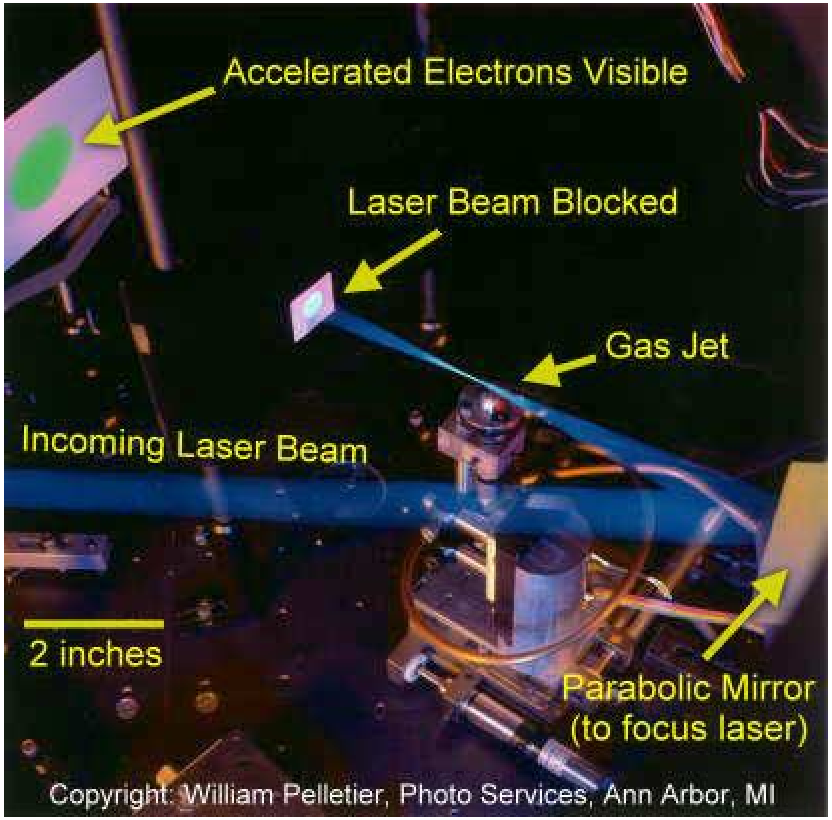
  compared with 20 MV/m in conventional RF linacs

  so 1 m instead 10 km - **CERN on a table**



Wakefield accelerator
when short pulse propagates in underdense plasma electrons are displaced by ponderomotive force and when laser pulse is away they oscillate with respect to ions – plasma wave (called wakefield) is formed

Experiment – CUOS, Univ. of Michigan, Ann Arbor



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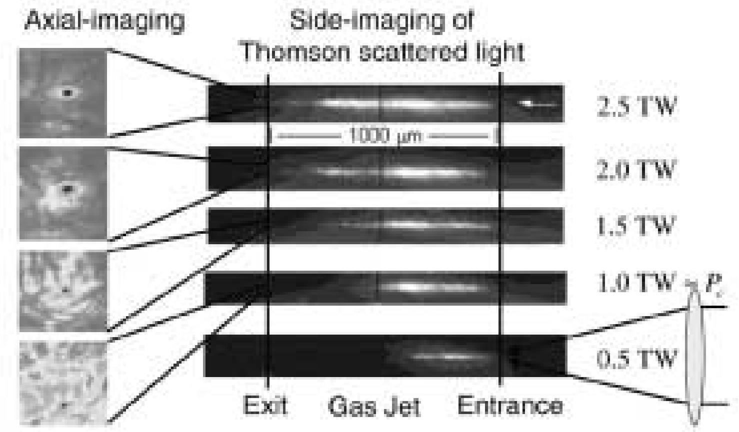
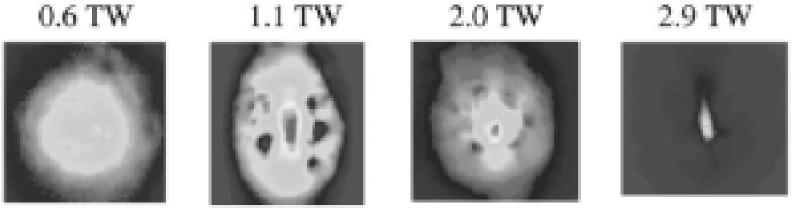


Electron spots on the screen



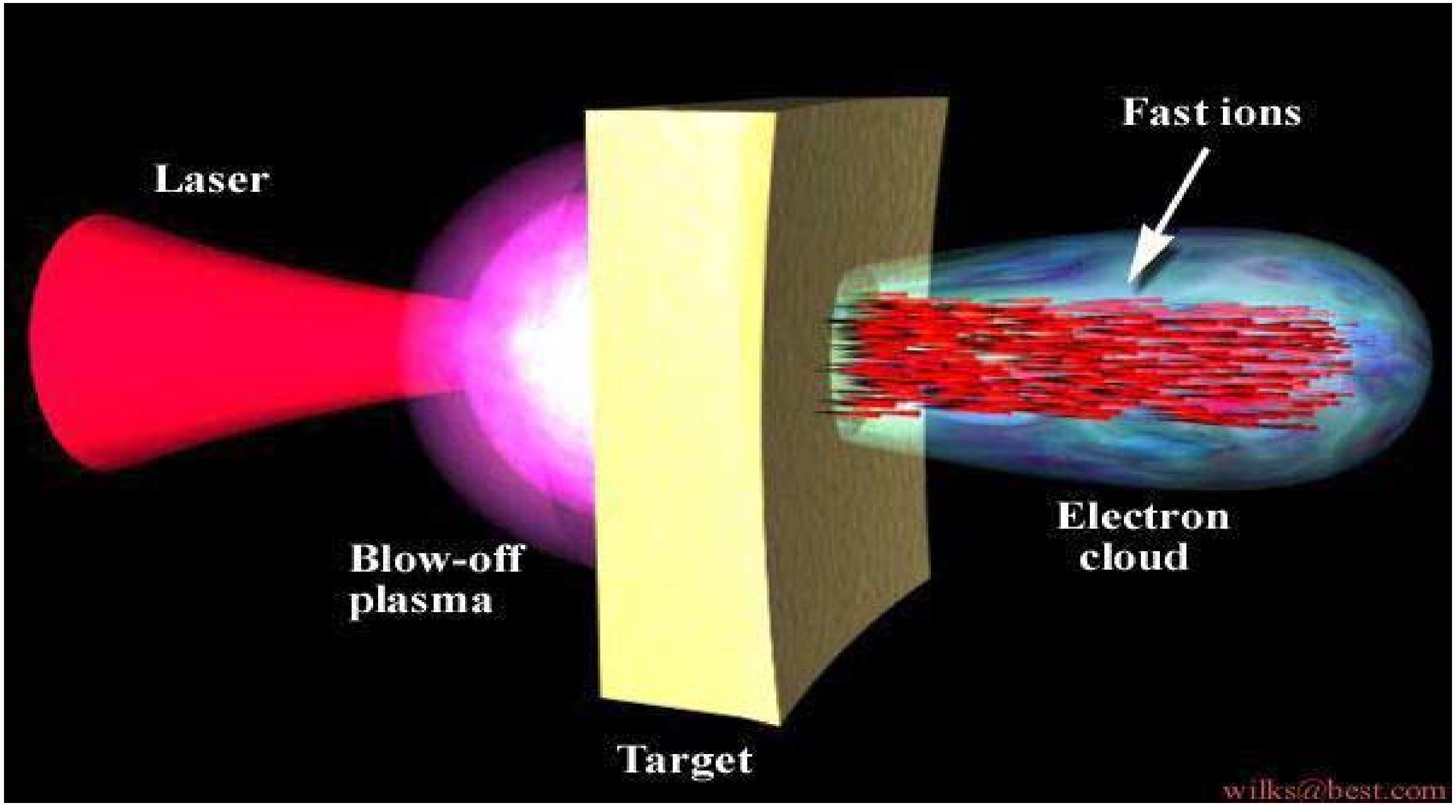
Laser pulse – relativistic self-guiding at high intensities

Electron beam – transverse emittance $\varepsilon_\perp \leq 0.06\,\pi$ mm mrad

(1 order better than in best electron guns !)

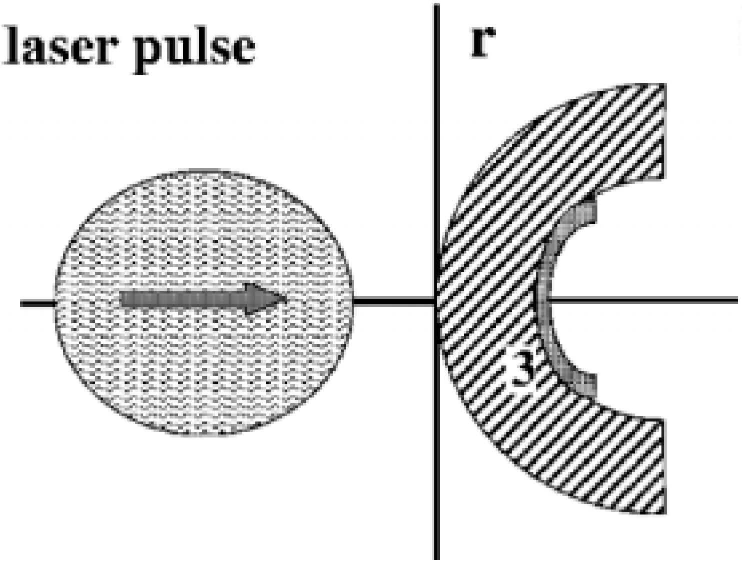
High number 10^{10} electrons/per bunch, but energy spread 1 – 50 MeV

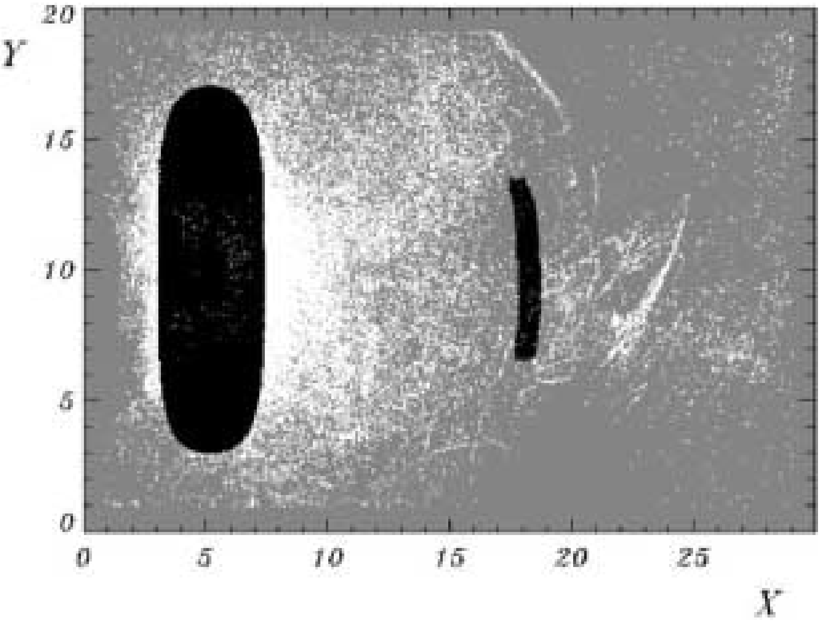
Fast ions – nearly always protons



Foil targets are used – for any material – very energetic protons
Proton has best q/m, difficult to get rid of water layer on surface
Proton of energy up to 60 MeV observed on back side
Up to 10^{13} protons/per pulse (10^{8} A/cm^{2}) $\varepsilon_{\perp} \leq 1\ \pi$ mm mrad

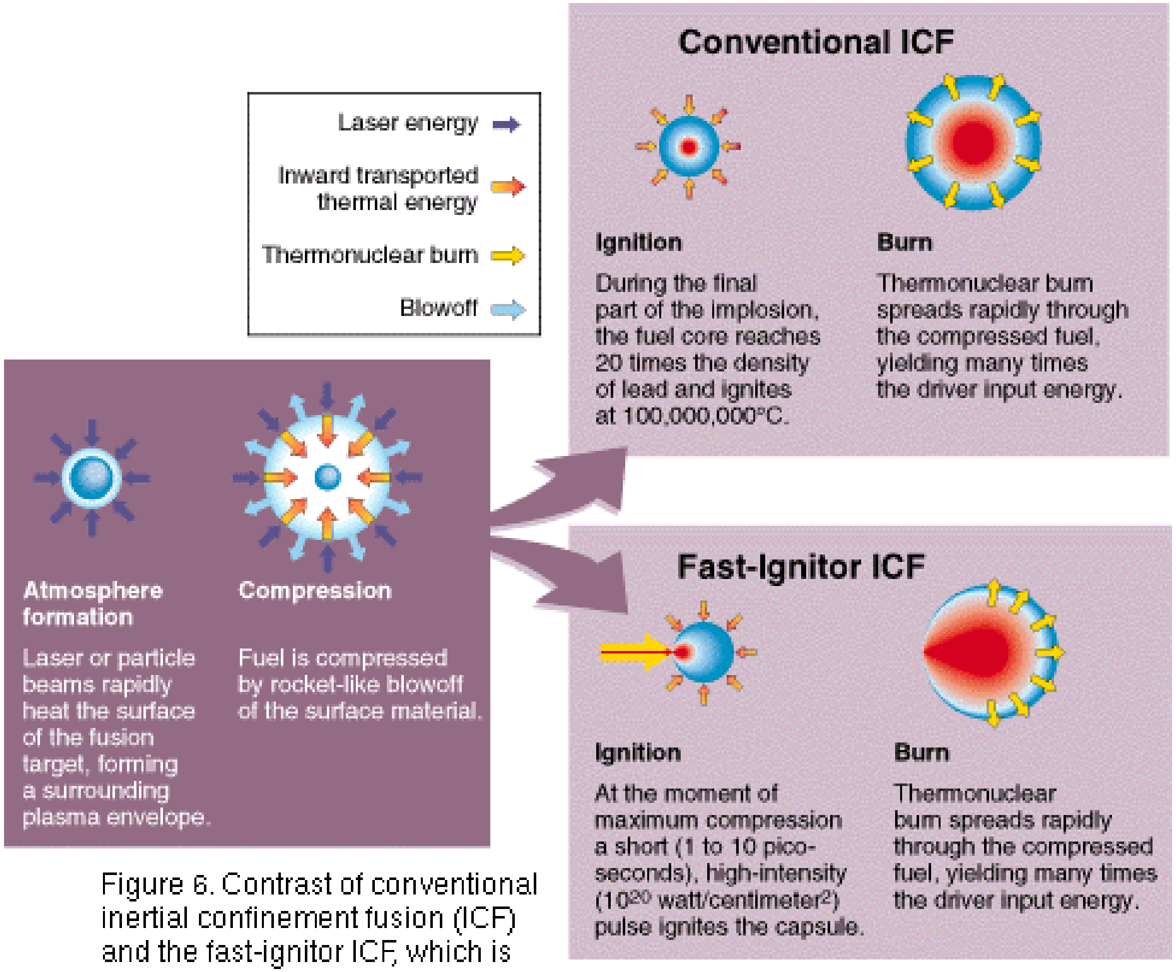
Ion acceleration for oncology ($\Delta E/E \leq 0.03$)





Proton layer (3) of diameter comparable to laser focal spot used
Thin black layer on the fig. are the accelerated protons
PIC simulation by Bulanov et al., Physics Letters A, 2002
This is only simulation but
at JAERI at their 100 TW/1 Hz laser
they already started to build **6 m radius storage ring** for laser accelerated **C ions** (they say, they know how to get rid of water layer)

Fast ignition of inertial nuclear fusion



Atmosphere formation

Laser or particle beams rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.

Compression

Fuel is compressed by rocket-like blowoff of the surface material.

Conventional ICF

Ignition

During the final part of the implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.

Burn

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the driver input energy.

Fast-Ignitor ICF

Ignition

At the moment of maximum compression a short (1 to 10 picoseconds), high-intensity (10^{20} watt/centimeter^2) pulse ignites the capsule.

Burn

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the driver input energy.

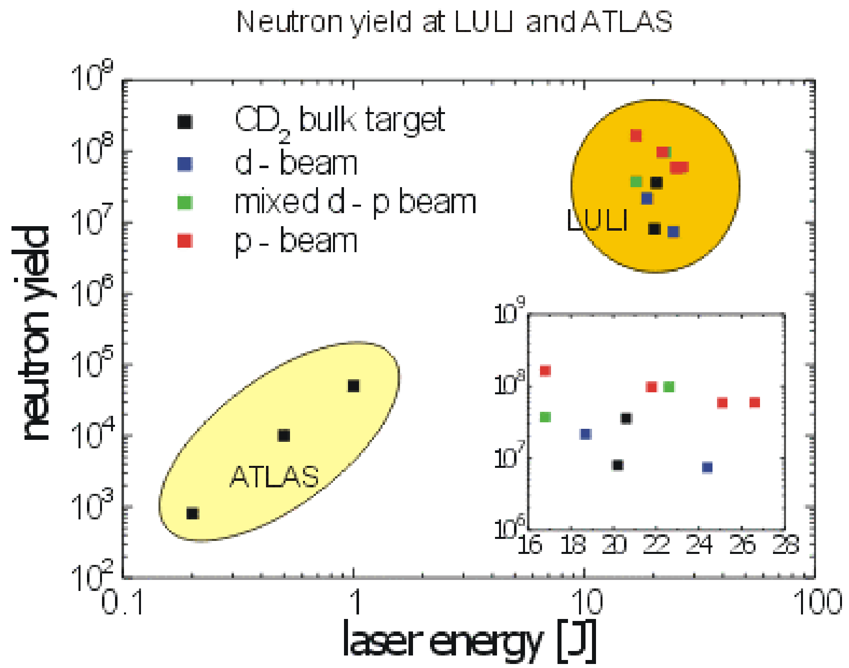
Figure 6. Contrast of conventional inertial confinement fusion (ICF) and the fast-ignitor ICF, which is used on the Petawatt laser.

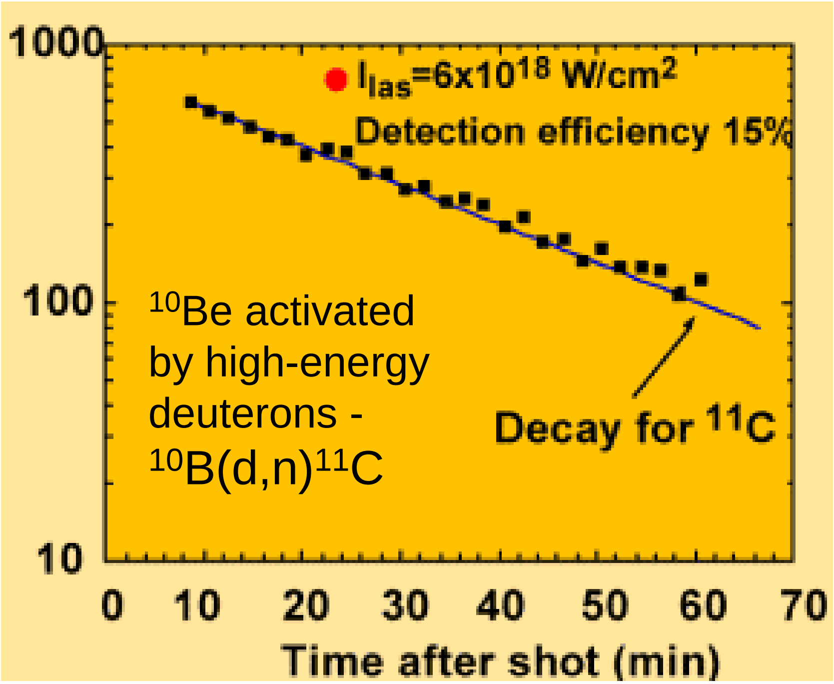
By long pulse lasers, it is not difficult to produce DT of 200 g/cm^3 needed for inertial fusion

But it is difficult to produce high temperature 5 keV needed to ignite fuel (in 1D simulations it works fine)

Why not use fast electrons or ions generated by short pulse for fast heating the fuel?

Laser induced nuclear reactions





- Ultra-short intense neutron source > 10^8 neutrons/shot,
  neutron source intensity 10^{20} neutrons/(cm^2 s)
  with 10 Hz repetitions frequency 10^9 neutrons/s continuously
- Positron-active isotope ^{11}C (> 10^5 atoms/shot) is used as source for PET
- Source of positrons, γ-rays, isomers, etc.