Generation of energetic X-rays and accelerated particles in intense short-pulse laser target interactions

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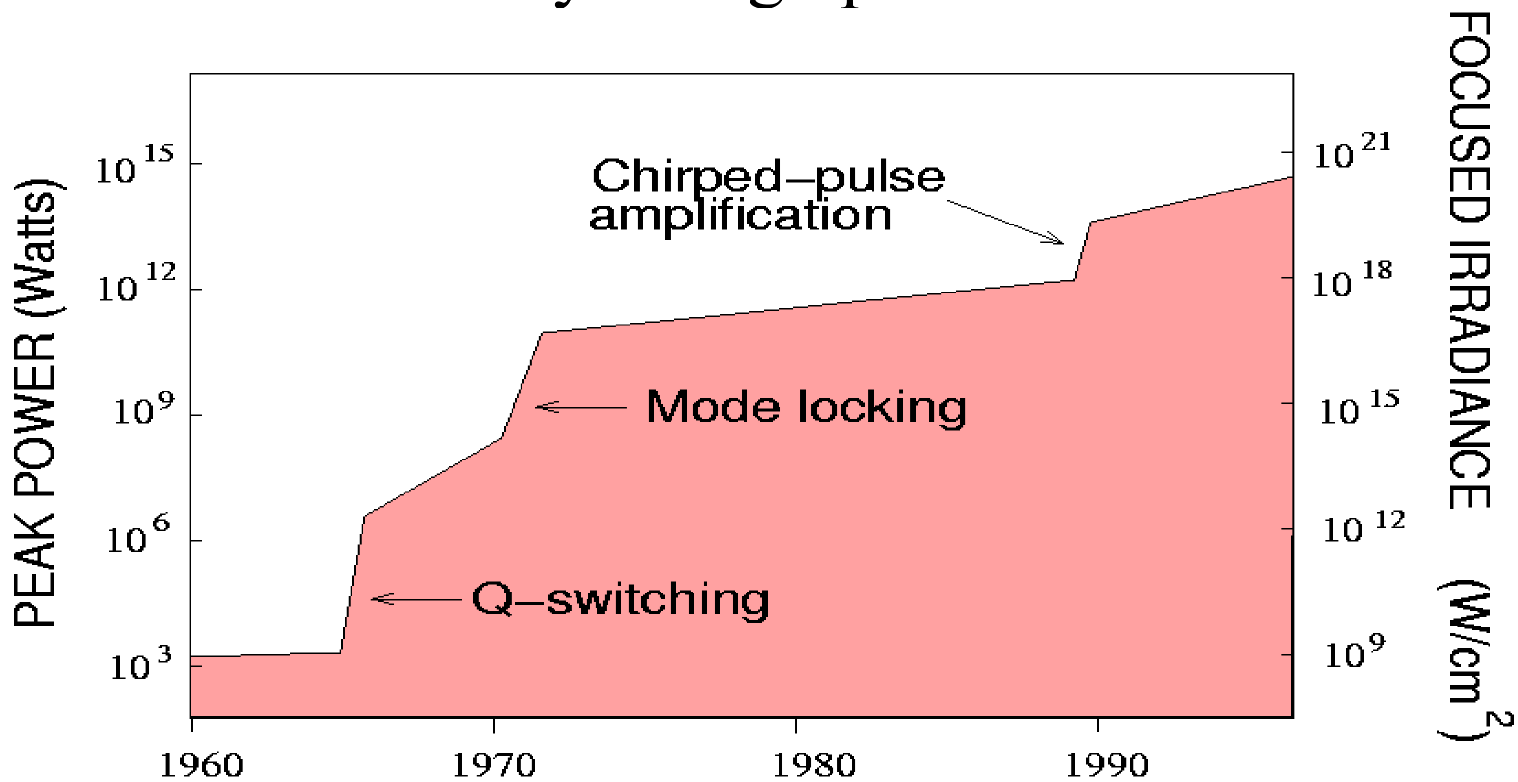
Syllabus:

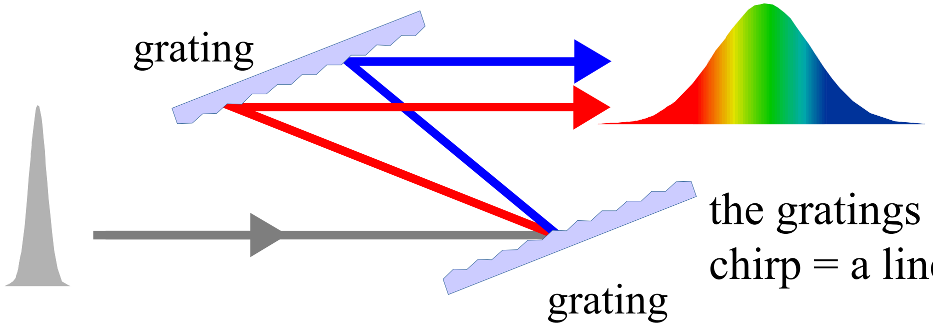
1. History of achievable highest laser power
2. Chirped Pulse Amplification (CPA) and T^3 lasers, PW lasers
3. Ultrafast X-ray diffraction with lasers
4. PIC + MC simulations
5. PIC simulation with ionization
6. Ion acceleration – TNSA mechanism
7. Generation of monoenergetic ion beams
8. Wakefield electron acceleration
9. Other electron acceleration mechanisms
10. Nuclear reactions, PET isotopes etc.
11. Fast Ignition of ICF fusion

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
- Laser electric field = 1st Bohr orbit in H for $I = 3.5\times10^{16}$ W/cm^2
- Relativistic electron oscillations for $I\lambda^2 > 1.35\times10^{18}$ W/cm$^2\times\mu$m^2

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

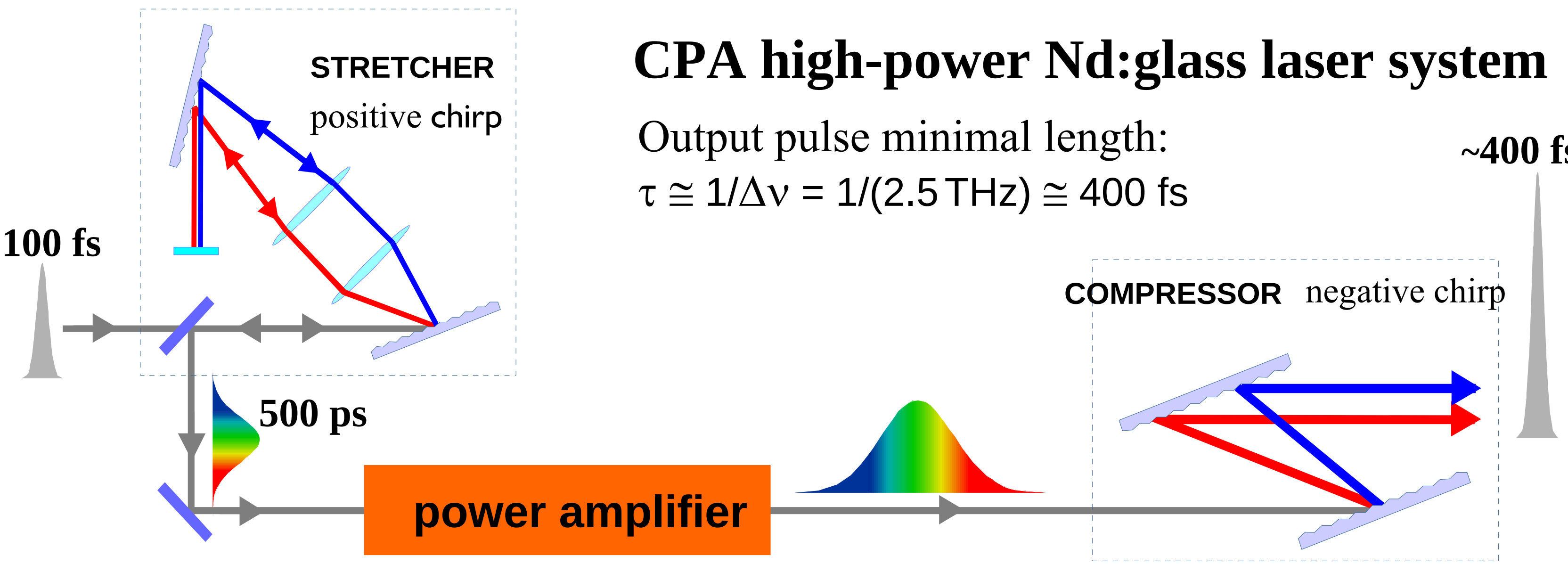
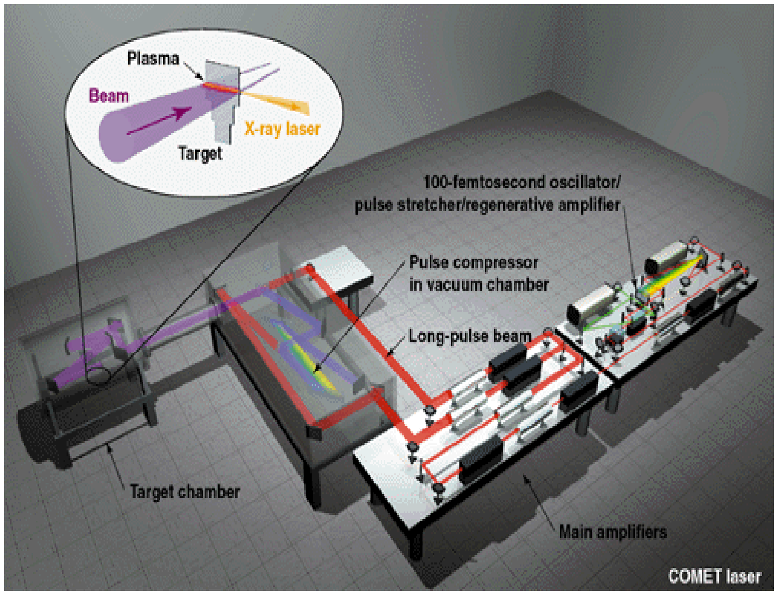
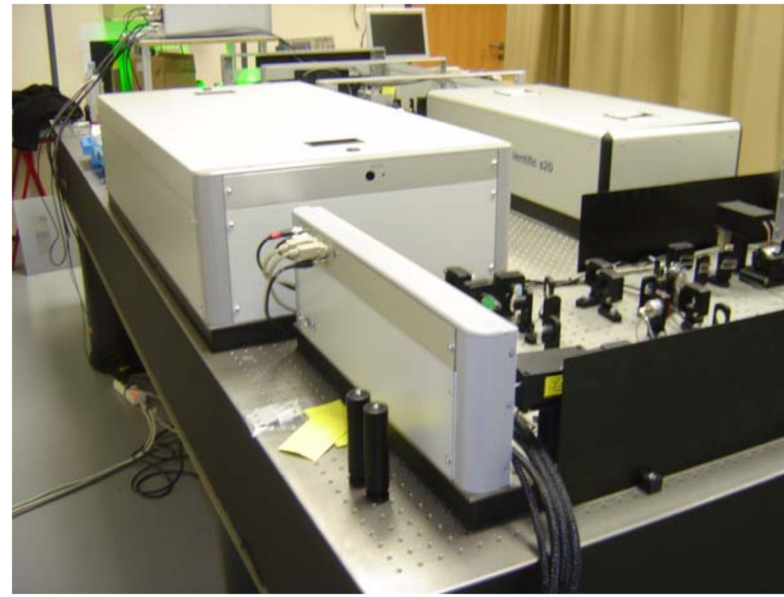


Table-top terawatt (T^3) CPA lasers





Ti:sapphire ($\lambda \cong 790$ nm), $\Delta\nu$=100 THz ($\Delta\nu/\nu$= 0.1), Pulse FWHM > 5 fs (typically 30 – 50 fs), Energy 50 mJ , Power 1 TW, Repetition rate 10 Hz

Left – Comet Laser – LLNL, USA; Right – 0.1 TW laser for CTU-FNSPE

- Today 10 TW/10 Hz or 100 TW/1 Hz available (also 1 TW/1 kHz)
- Price $\cong$ 300 k$, laboratory space 10 m x 5 m
- Focal spot diameter $\cong$ 10 μm, focal spot $\cong 10^{-6}$ cm^2
- Maximum intensity I = P/S = 1 TW / 10^{-6} cm^2 = 10^{18} W/cm^2

Ultimate power – PW lasers -1st path – Nd-lasers long pulse (~600 fs) ⇒ big energy (600 J)

One beam of big laser (1st – Nova, LLNL, 1999, CPA oscillator and stretcher, closed 01)

Femtosecond Petawatt upgrade for Gekko XII laser – ILE Osaka, Japan, 2000
Femtosecond Petawatt upgrade for Vulcan Laser – RAL, UK, 2003

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

10^{15} W = 1 PW, < 1 pulse/hour
Maximum intensity – 10^{21} W/cm^2

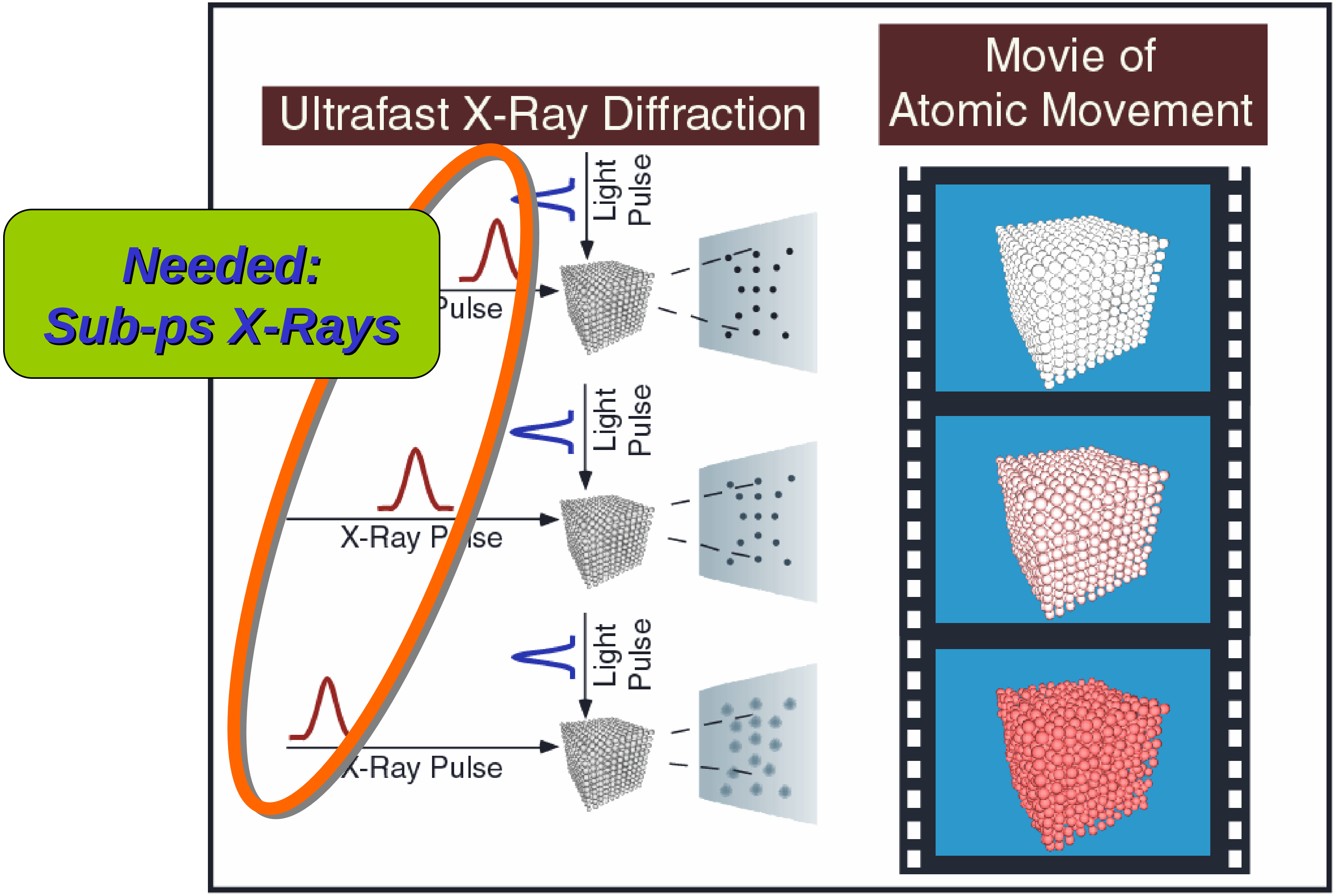
Under construction -Omega EP; LIL PW

Fast Ignition of Inertial Confinement Fusion, High Energy Density Matter

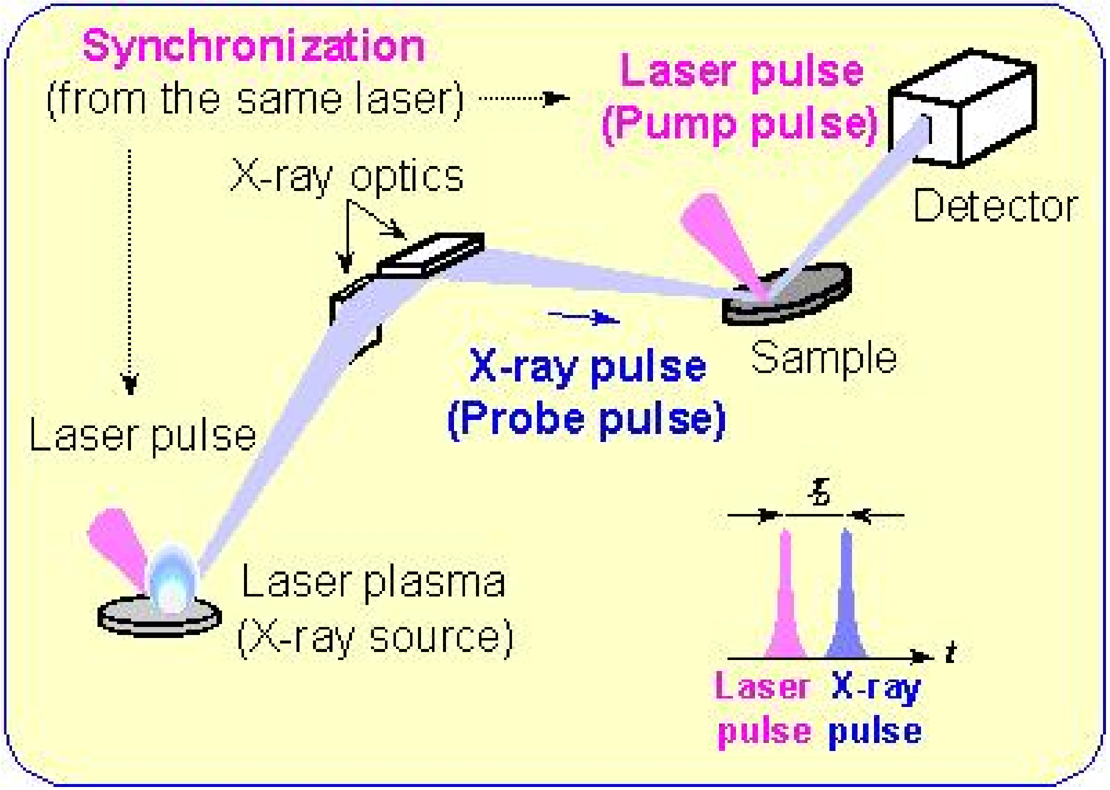
PW Ti:Sapphire lasers (2nd path)

- Many (>10) 100 TW Ti:sapphire lasers exist
- Short pulse, relatively low energy, much larger repetition rate, smaller compressor gratings, better focusability
- 1 PW - typically 30 fs, 30 J, 1 shot/1 minute, 30 cm compressor grating aperture, room 20 x 10 m
- Extensive shielding of interaction chamber necessary
- 0.5 PW laser at JAERI APRC – 2004
- Astra Gemini project at RAL, UK, user facility to be opened in summer 2007 – 2 synchronized 0.5 PW beams (<5 million Euro)
- Research in interaction physics, electron and ion acceleration, laser induced nuclear reactions, hard X-ray source etc.
- Many installations at construction start or planned

Application of sub-1 TW lasers
Time-resolved Crystallography



Scheme of x-ray pulse-probe measurement



Weak laser pulse – sample excitation

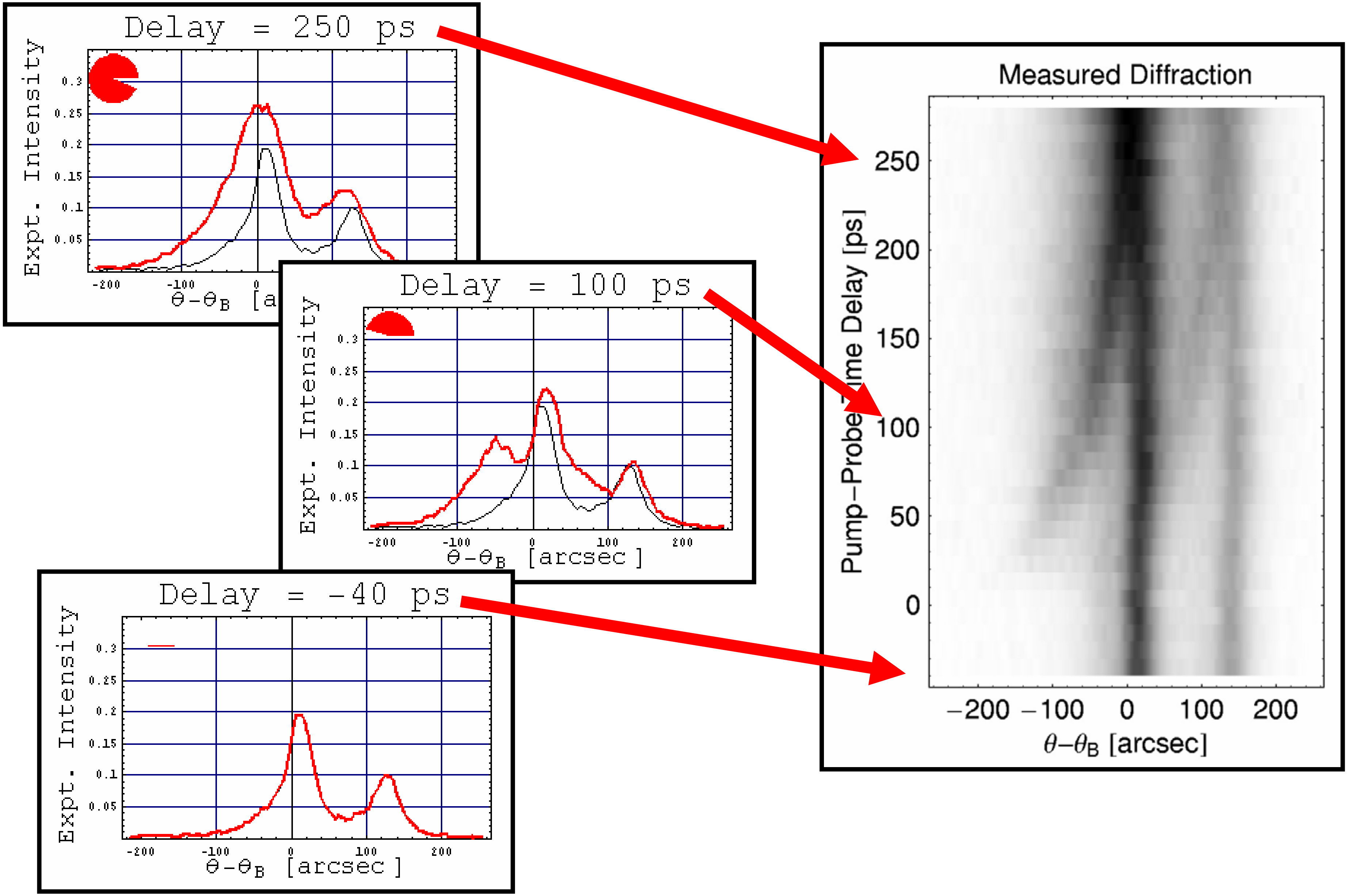
Main laser pulse – generates X-ray pulse incident with variable delay on sample

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

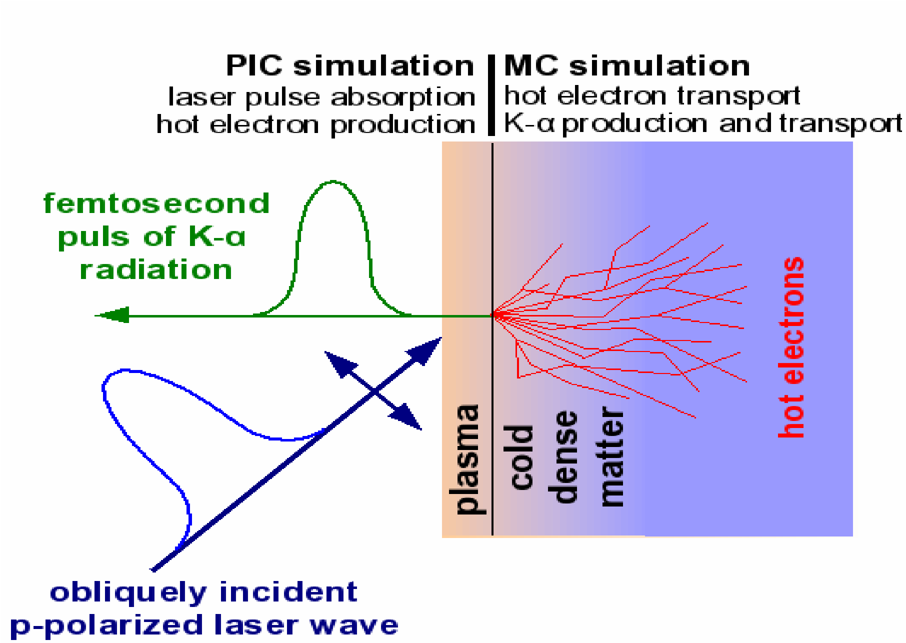
Moderate laser intensities – 10^{16} – 10^{17} W/cm^2 – preferable
higher intensities - fast electron fly longer distance, x-ray pulse longer

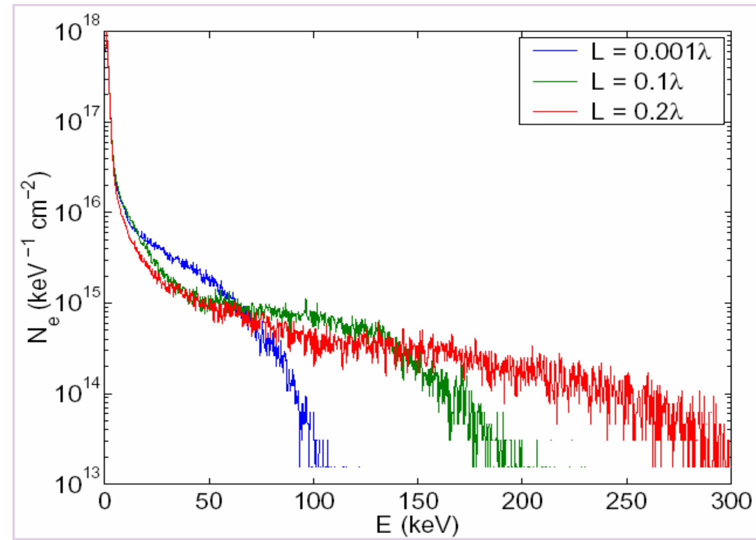
First application – Nature 1999, waves on crystal surface, 5 ps/5 μm
Best resolution – 250 fs – fast melting (2001)
Reversible changes – using 1 kHz repetition rate laser (Science 2004)

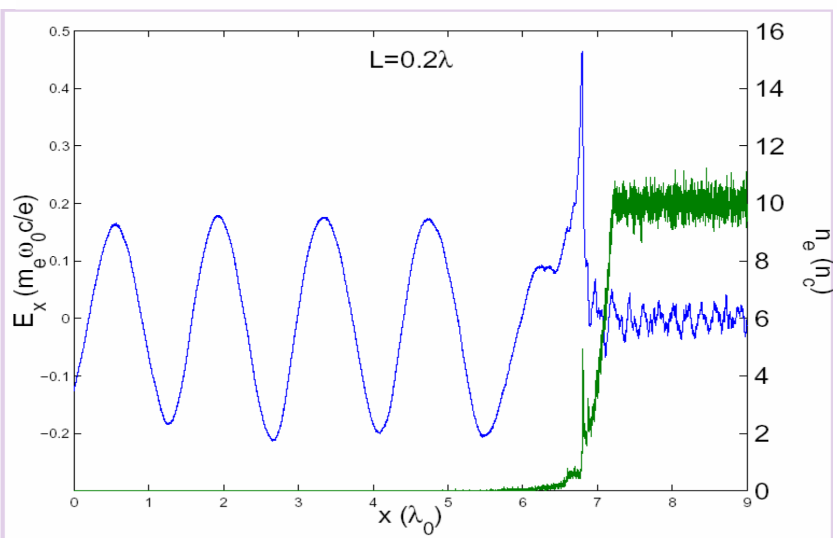
Ultrafast X-ray Diffraction: The Movie

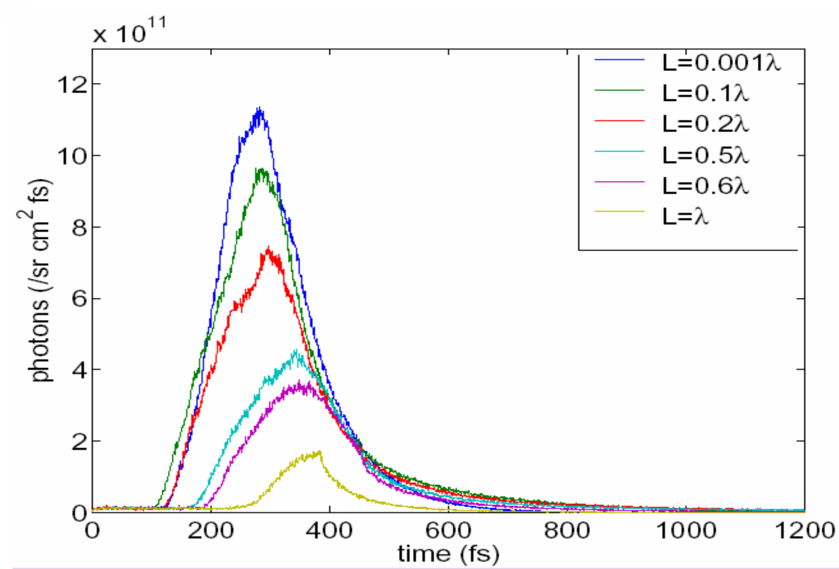


1D3V PIC + 3D time-resolved Monte Carlo simulations (J. Limpouch *et al*., LPB **22** (2004), 147–156)

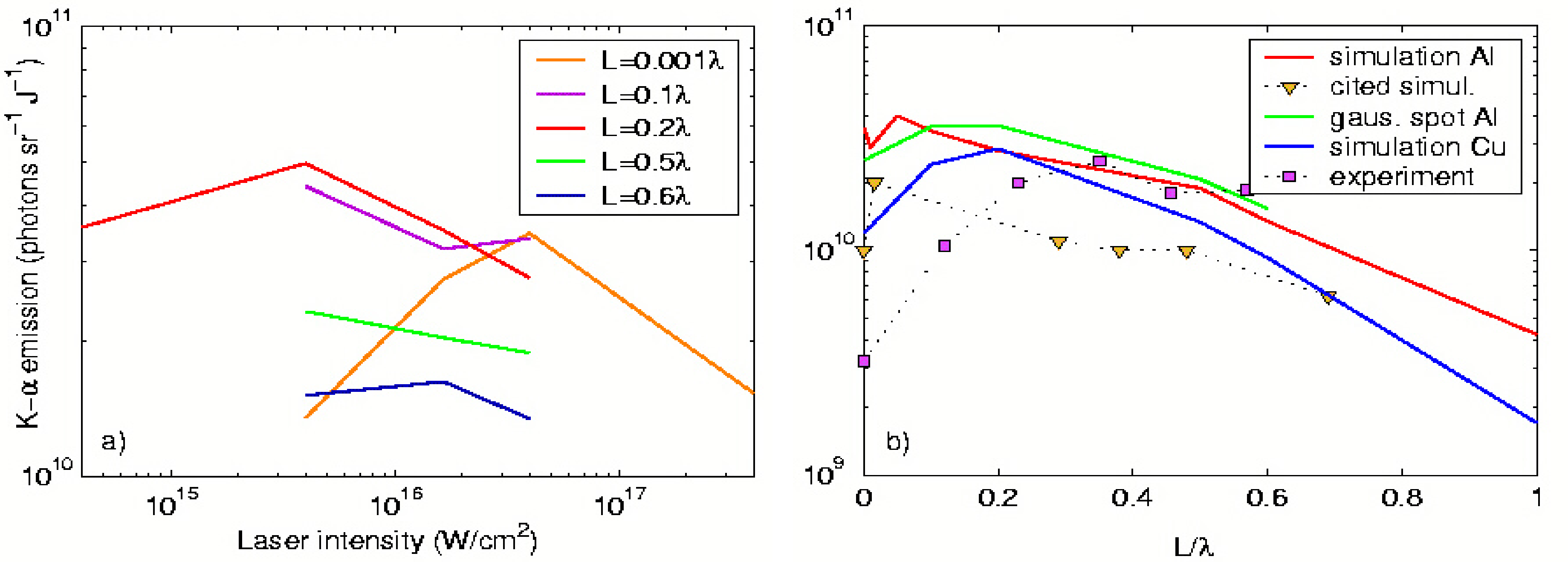








K-α versus laser intensity and density scale length



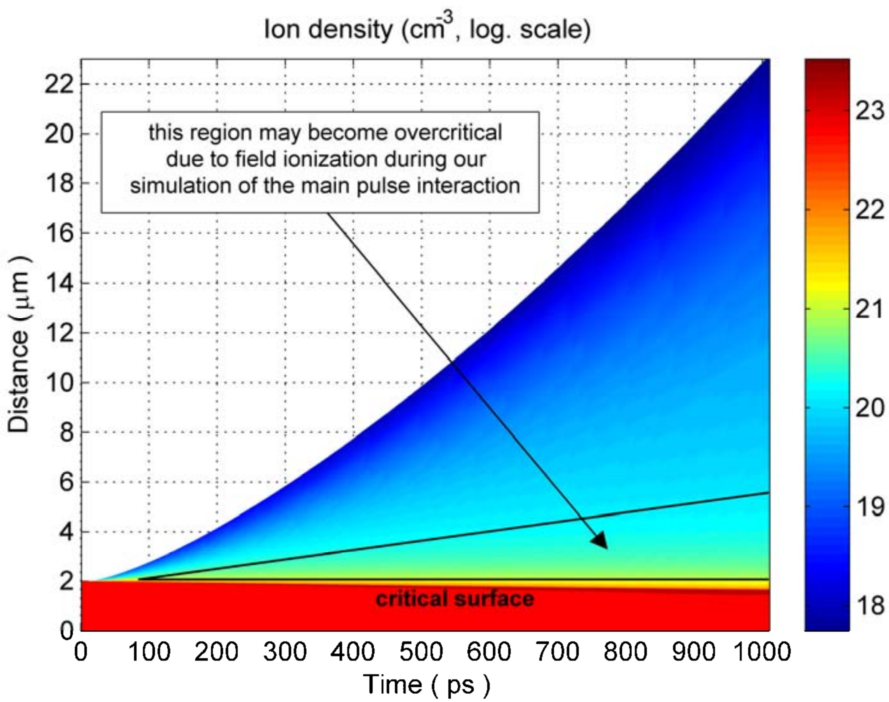
Optimum laser intensity for K-α emission exists for each density scale length L. The optimum intensity is minimal for L optimum for resonance absorption and this point seems to be absolute maximum of the conversion efficiency

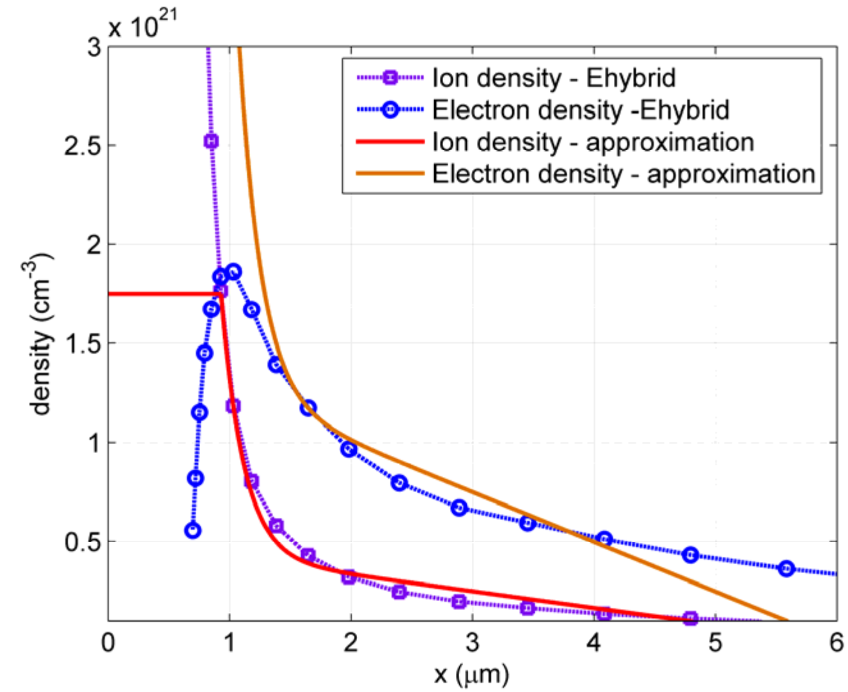
Optimum intensity grows with Z (here Al)

Simulation cannot reveal experimental decrease of K-α emission for small ***L***, for heavier elements maximum at resonance absolute optimum, integration over focal spot – the spot emitting K-α is wider for ***L*** optimum for resonance absorption

Impact of ASE and of ionization

(O. Klimo *et al*., J. Physique IV **133** (2006), 1181-4)

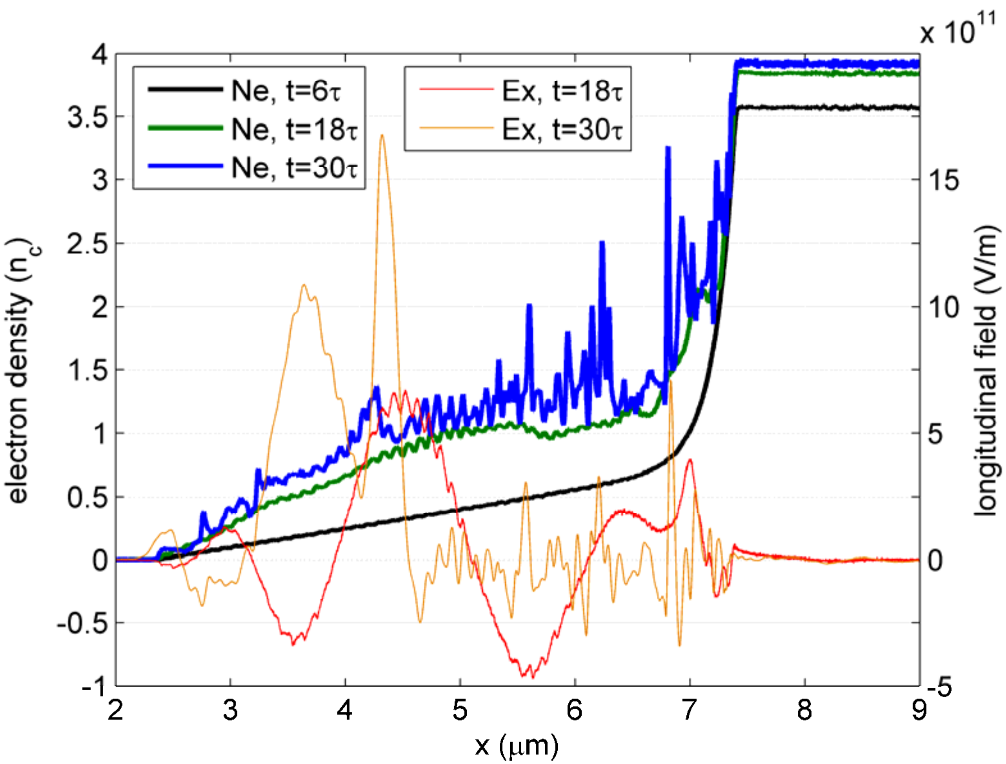


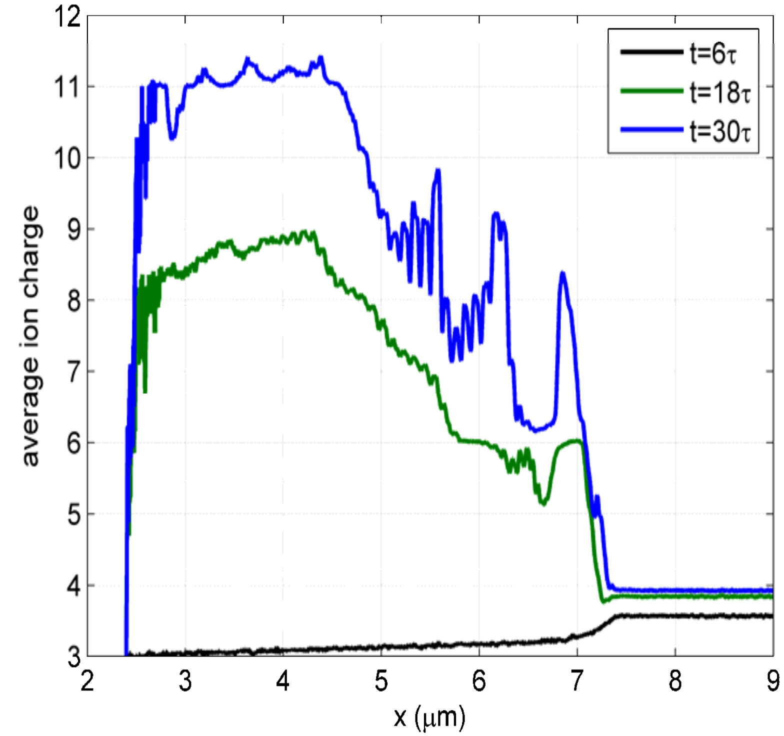


Optical field and collisional ionization added into PIC code
Initial profile for PIC taken from hydrocode Ehybrid simulation

Conditions for experiment in Max-Born (N. Zhavoronkov *et al*.)
Ti-sapphire 45 fs 5 mJ pulse, spot ∅ 6.7 μm, 10^{17} W/cm^2, Cu, ASE contrast 10^7 at 1 ns (left ion density evolution, constant *I*)

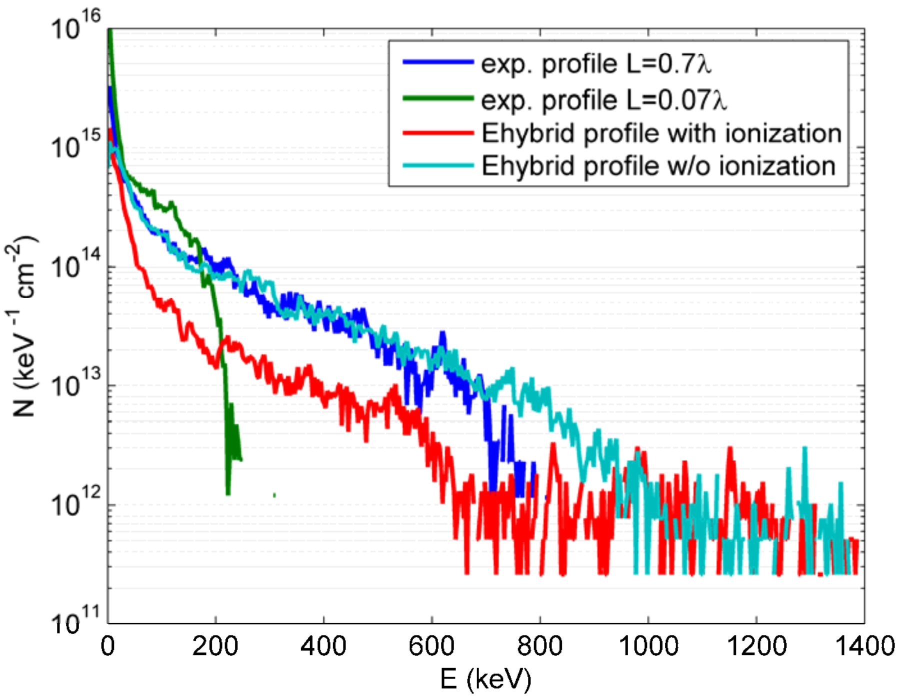
Profiles of electron density and Z in PIC

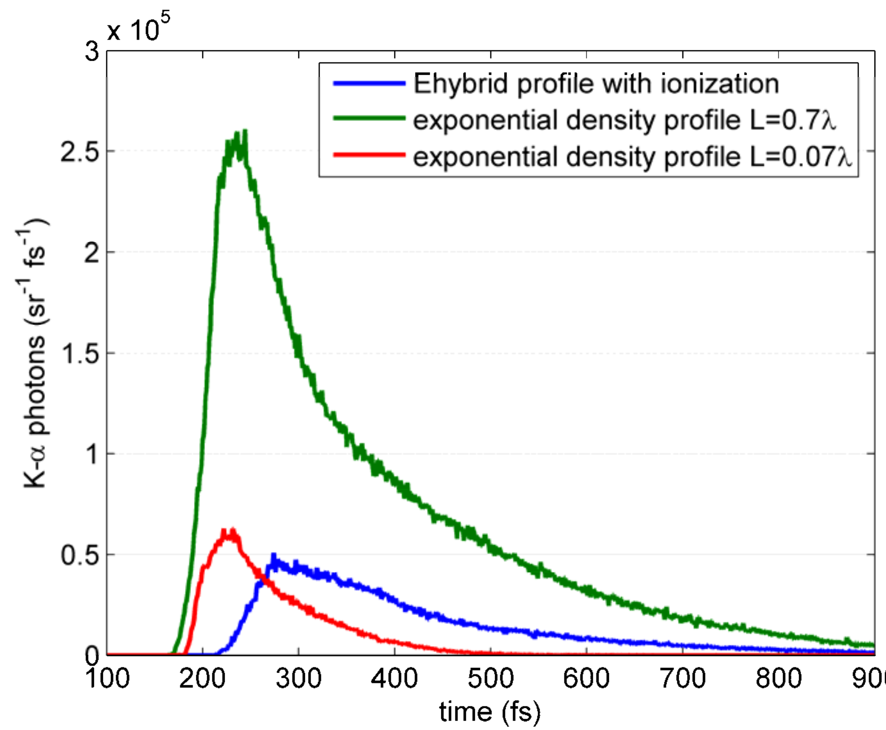




Profiles of electron density N_e and longitudinal electric field E_x (left) and of mean ion charge Z (right), Cu target. Maximum of $\sin^2$ laser pulse at t =27τ is in x=7, angle of incidence 25°. PIC starts from Ehydrid profile, T_{e0} = 50 eV, Z_0 = 3. (Z = 11 is Ar-like copper)

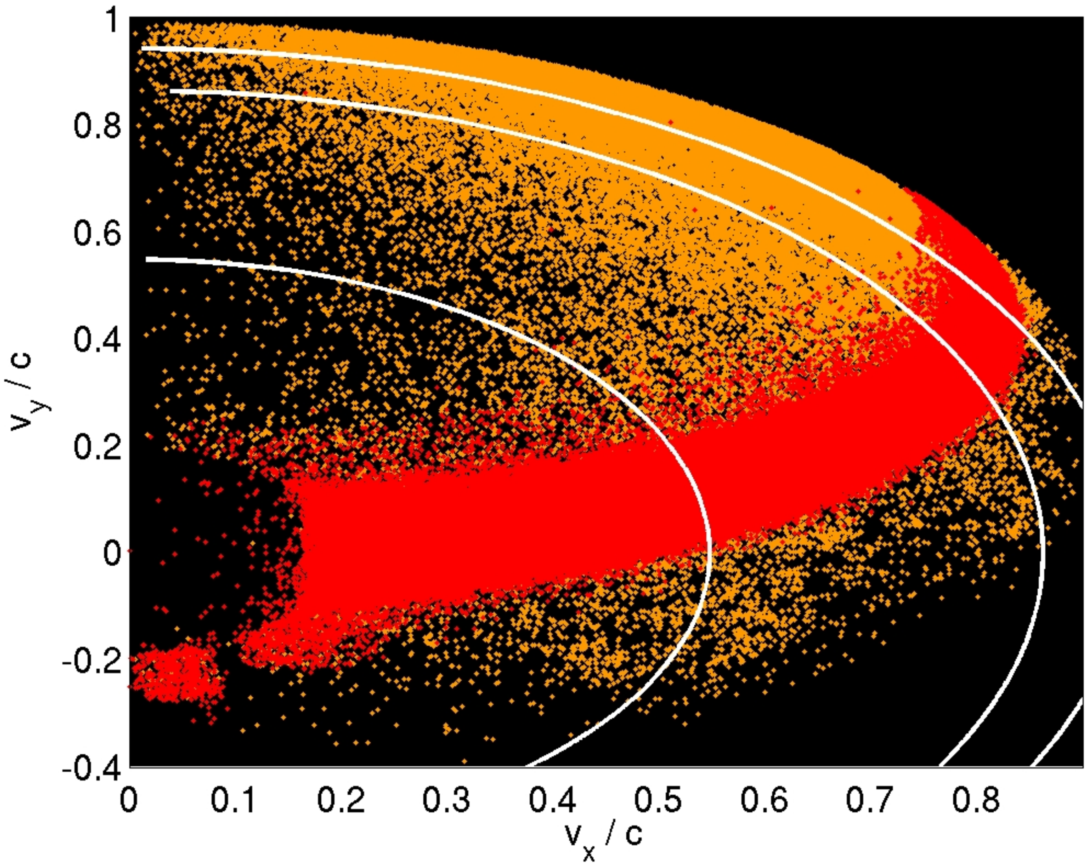
Fast electron spectrum and K-α emission





Sharp exponential profile (L=0.07 λ) leads to K-α emission near to experimental value, but emission does not maximize for angle 25°. Long profile (L=0.7 λ) leads to experimental value of optimum angle but it overestimates K-α emission, best Ehybrid profile with ionization

Fast electron angular distribution



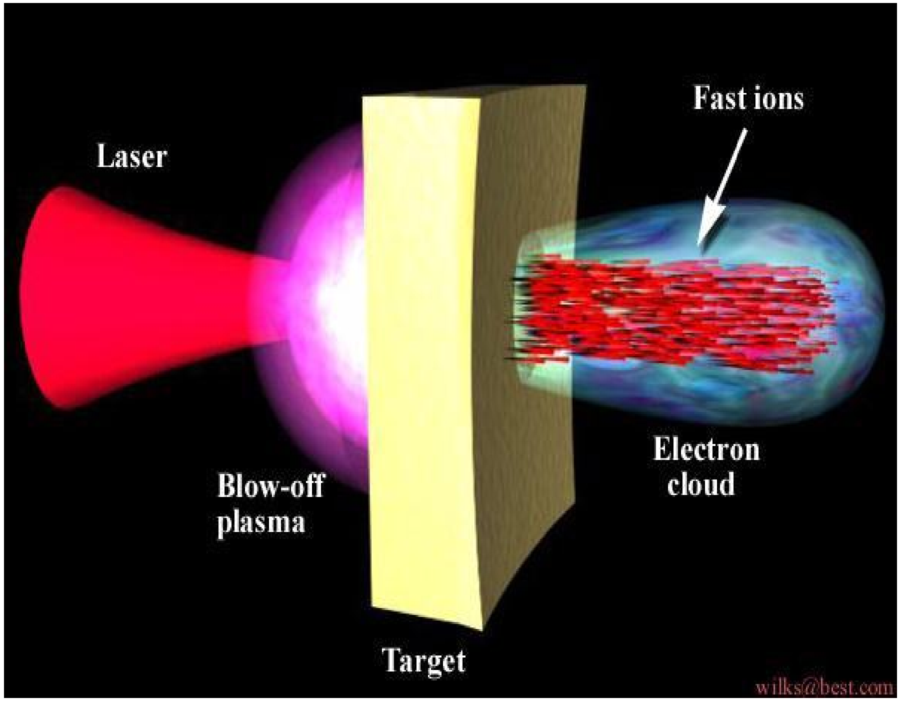
Orange electrons – from ionization of 2p shell, $I_p >$ 780 eV, field ionization occurs near to laser pulse maximum

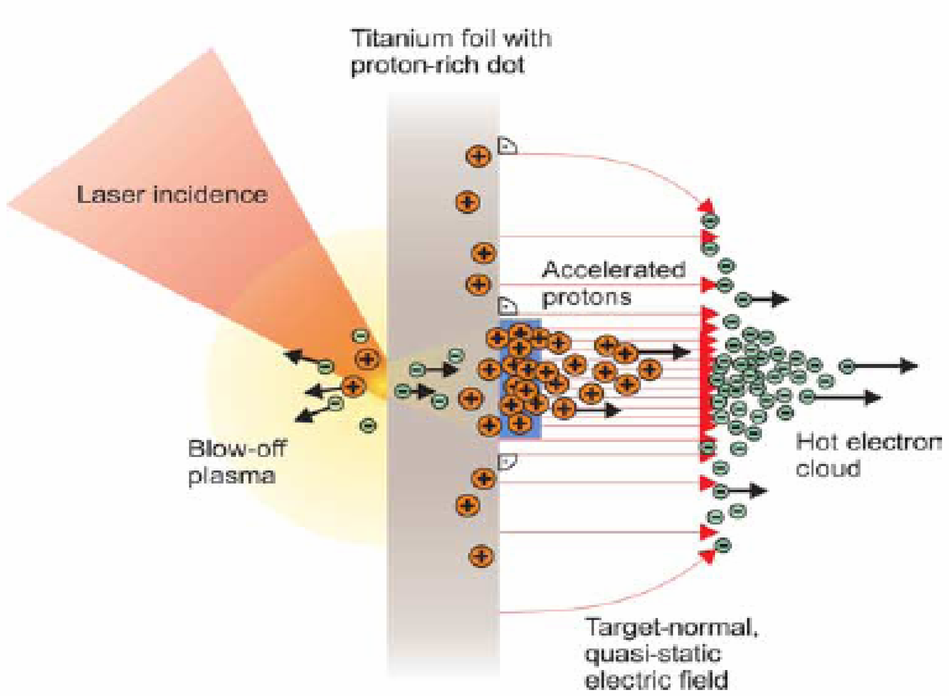
Red – all other electrons

Orange electrons have large angles to the target normal (red obey classic angle-energy law)

Angular distribution of fast electrons, Ti target, 65 fs laser pulse, $5\mathrm{x}10^{18}$ W/cm^2 (a_0 = 1.52), angle of incidence 45°, Z_0 = 3, T_{e0} = 1 keV, L=0.3 λ (with long pedestal L=7λ of $n_e < ¼\ n_c$ during whole simulation), white lines – 100, 500 and 1000 keV

Fast ions acceleration (nearly always protons)





More energetic ions observed at foil rear side, most energy to ions with best q/m, nearly always protons, difficult to get rid of surface water and hydro-carbon contamination

Accelerating fields up to 10^{13} V/m (6 order higher than in conventional accelerators), **Target Normal Sheath Acceleration** (TNSA)

Protons of energy up to 60 MeV (like in 100 m long accelerator)

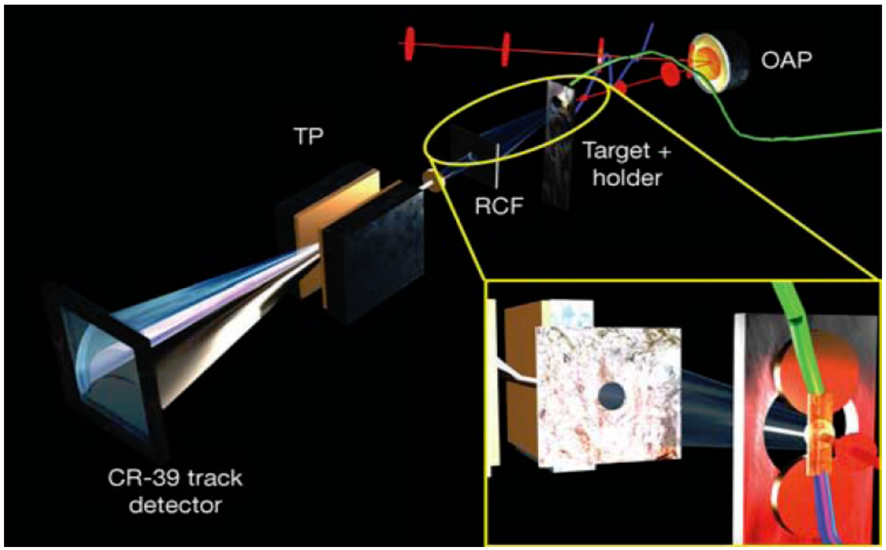
Up to 10^{13} protons/per pulse (10^8 A/cm^2), low emmitance $\varepsilon_\perp \leq 10^{-3}$ mm mrad

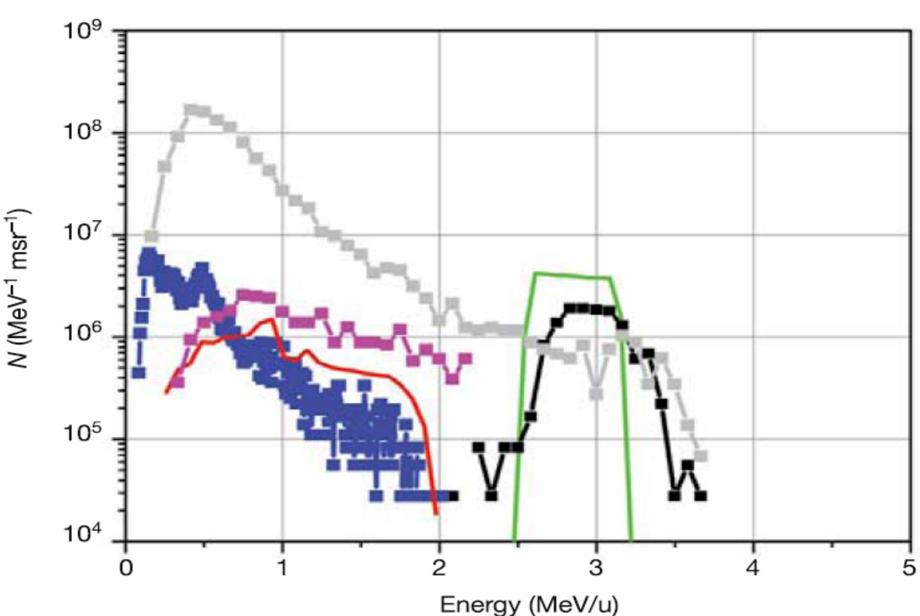
F ions up to 100 MeV, Pd ions up to 225 MeV (>2 MeV/nucleon)

Applications of high energy ion beams

- Intense source of very short (~1 ps) very energetic ion beams (mostly protons)
- It can heat macroscopic amount of matter to $\sim 10^6$ K before it can expand – conditions of star interiors
- It can probe extreme states of matter before it can dis-assemble (not possible via accelerators – low current)
- Electric fields in laser interactions are now often measured using laser generated fast protons
- Fast ignition of inertial fusion
- More applications need **monoenergetic ion beams**
  - Compact MeV accelerators
  - **Ion surgery** and other medical applications

Laser acceleration of quasi-monoenergetic ion beams (Nature, January 2006, 2 groups)





Hegelich *et. al.*, LANL, USA

Nd-laser Trident, 30 TW, 600 fs, 20 J

10 μm spot size, 10^{19} W/cm^2, 22.5°, contrast 10^{-6} (2 ns before pulse)

Pd-foil 20 μm thick heated to 1100 K

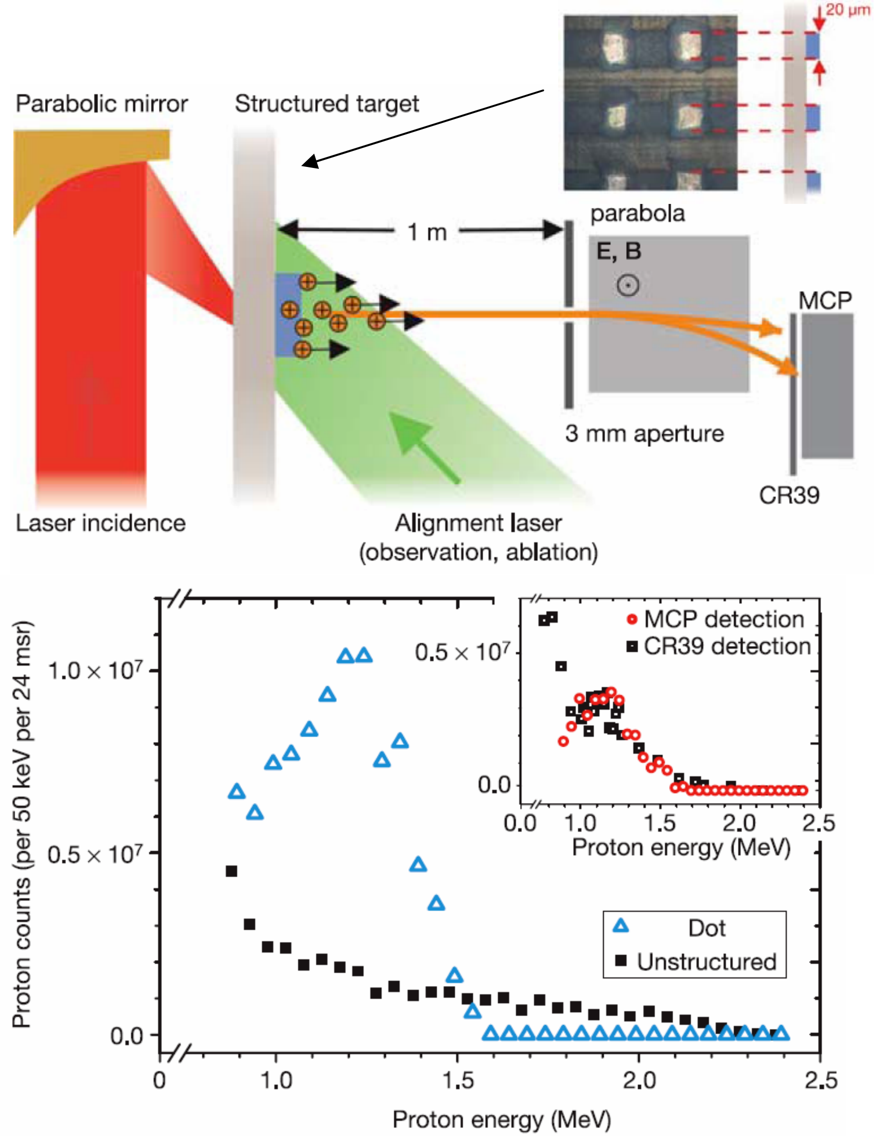
Catalytic surface chemistry forms from hydrocarbon deposits **pure carbon** layer (~1 nm thick) on surface

Beam of C^{5+} ions with energy 36 MeV = 3±0.5 MeV/nucleon (black curve, green curve PIC simulation), ~20 % of total ion energy

Longitudinal emittance <2×10^{-6} π eV s

3×10^{-5}/shot ions in 3.4 $\times10^{-5}$ milisterad input solid angle of Thomson parabola

Laser acceleration of quasi-monoenergetic proton beams – structured target



Schwoerer *et.al.*, Jena University, FRG

Ti-sapphire, ~10 TW, 80 fs, 600 mJ

3×10^{19} W/cm^2, 45°, contrast 10^{-8} (0.5 ps before pulse), spot radius 1.5 μm

Ti-foil 5 μm thick with PMMA dots thick 0.5 μm. Dots 20 x 20 μm with empty spaces in between

Protons 1.2±0.3 MeV, 10^8 protons/shot inside peak in angle 24 milisterad (input angle of Thomson spectrometer)

Both online MCP detector and CR-39 detector measure the same spectra

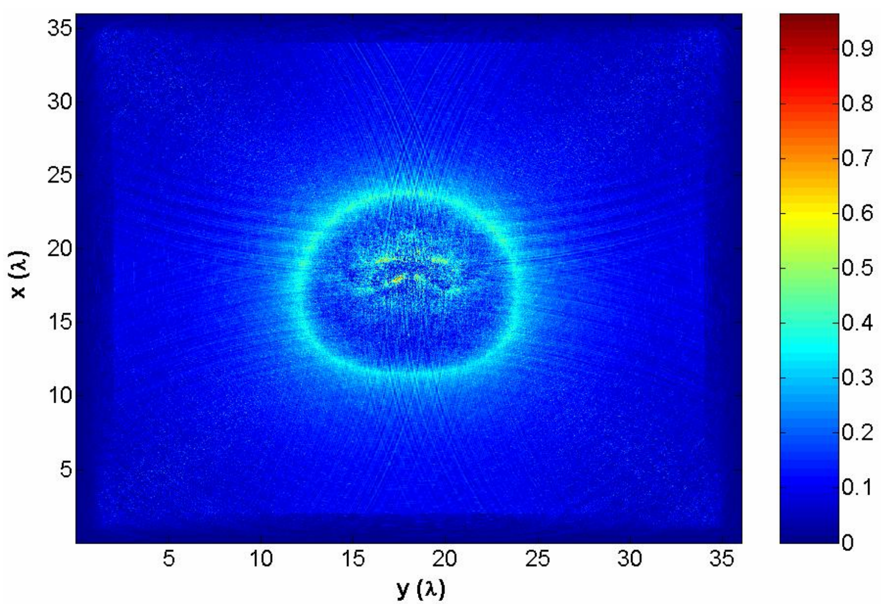
Monoenergetic proton spectra due to uniform sheath field in the centre and due to very thin proton-containing layer

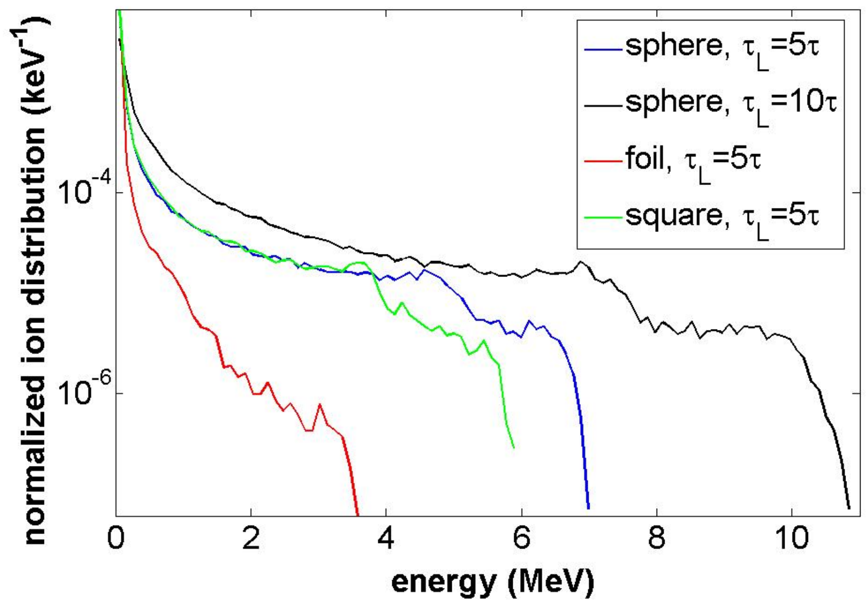
When laser focused outside dot – black spectra - broad

PIC simulations reproduce peak and predict 170 MeV for 10^{21} W/cm^2

Laser interactions with mass-limited targets

- Mass-limited (MLT) targets (droplets, clusters, foil sections) eliminate energy spread to many secondary particles
- Experiment M. Schnurer, S. Ter-Avetisyan *et al.*: Laser and Particle Beams **23** (2005) 337 (Max-Born Institute, Berlin, Germany)
- 2D3V PIC simulations of ion acceleration in laser interaction with water droplet (4λ diameter) – 2x increase of proton energy as compared with foil of the same thickness (Pšikal et al., SPPT 2006, Poster We-64)
- $I=10^{19}$ W/cm^2, Left – sheath electric field after laser, Right – proton spectra



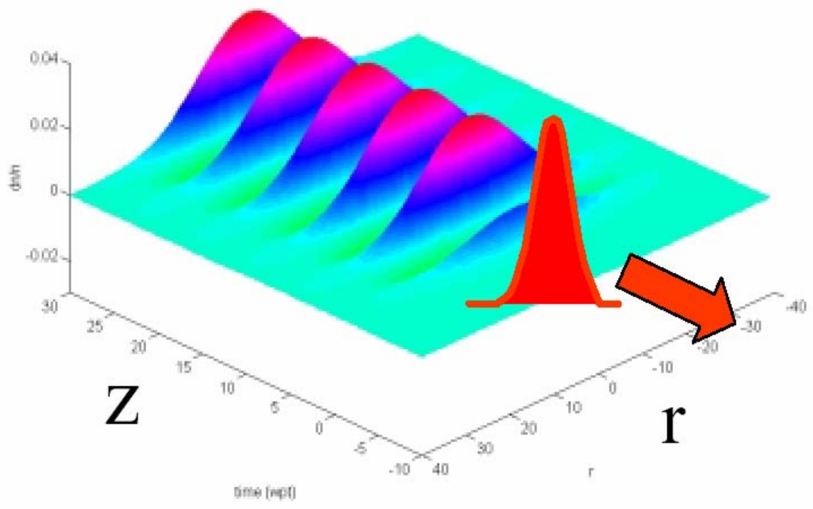


Electron acceleration

- Many possibilities of electron acceleration
- Most common acceleration mechanism – laser wakefield accelerator
- Acceleration by plasma waves in short pulse interaction
- Accelerating electric fields – **200 GV/m**

  compared with 20 MV/m in conventional RF linacs

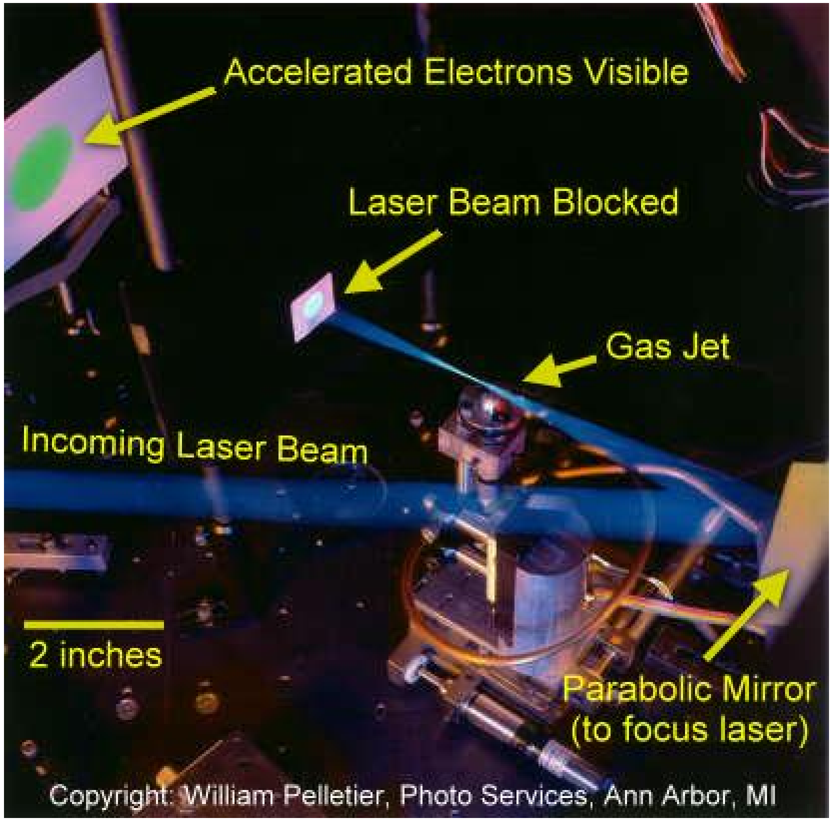
  so 1 m instead 10 km - **CERN on a table**

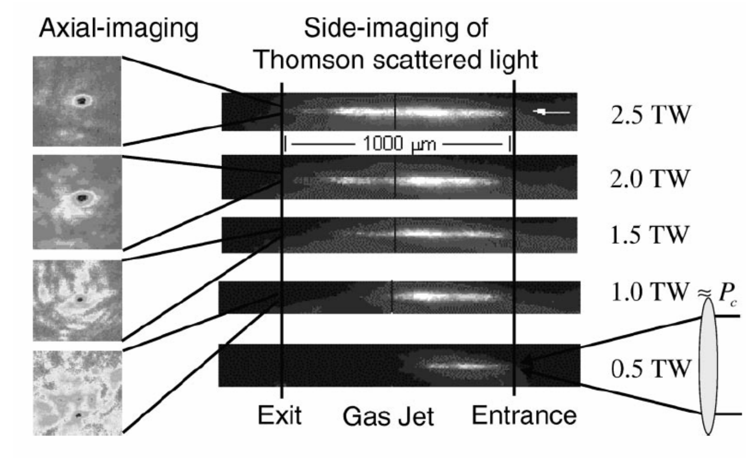


Wakefield accelerator

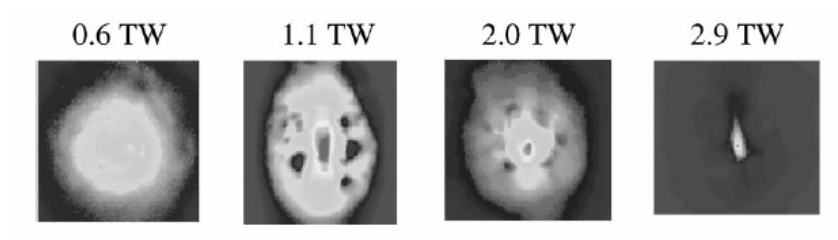
when short pulse propagates in underdense plasma electrons are displaced by ponderomotive force and when laser pulse is away they oscillate with respect to ions – plasma wave (called wakefield) is formed

Experiment – CUOS, Univ. of Michigan, USA, 2000





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

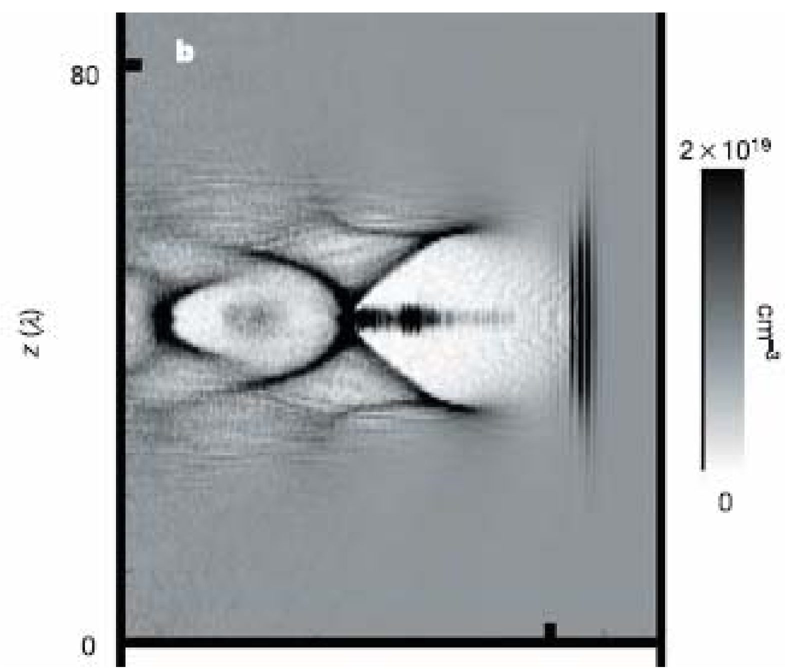
(1 order better than in best electron guns !)

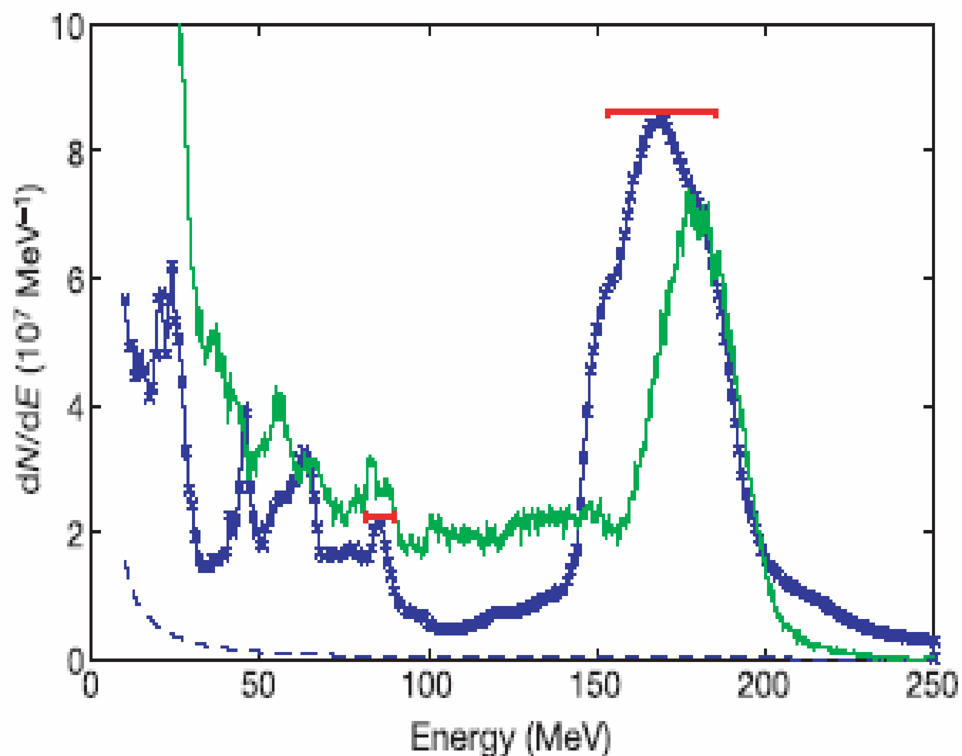
High number 10^{10} electrons/per bunch, but energy spread 1 – 50 MeV

Monoenergetic electron beams

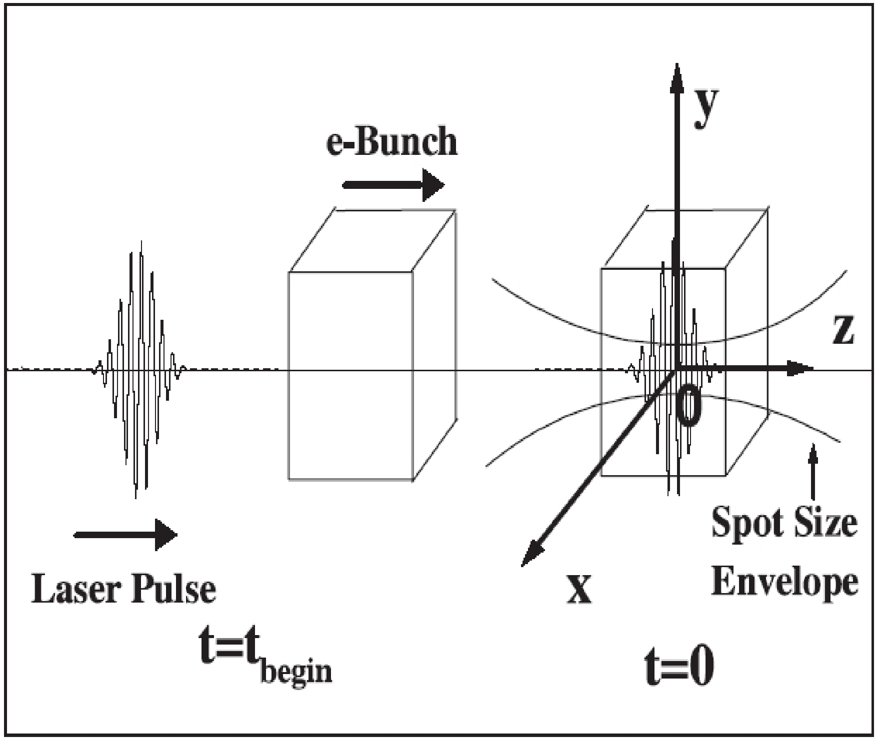
(Nature 2004, 3 independent groups)

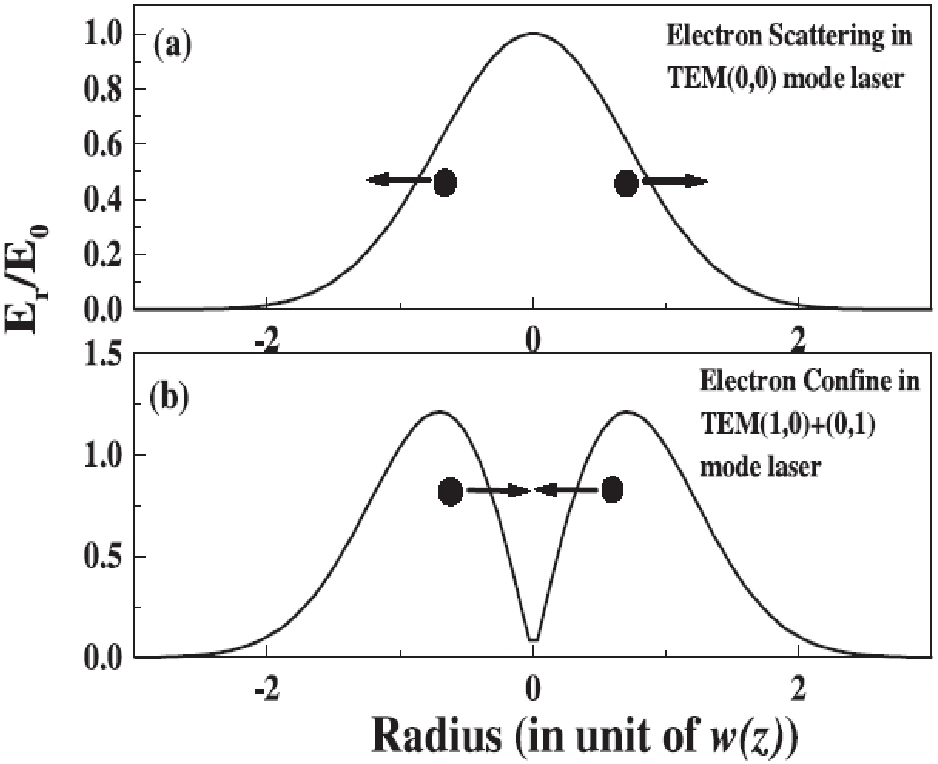
- Bubble wakefield regime (predicted by 3D PIC code VLPL)
- Left – calculated electron density in bubble, Right – measured (green) and calculated (blue) fast electron spectra
- Laser 1J, 30 fs, 10^{19} W/cm^2, He gas jet, $n_e=6\times10^{18}$ cm^{-3}, electron beam divergence 10 mrad, 170±20 MeV, 20 nC in spectral peak





Other mechanisms - Electron acceleration in vacuum by laser beams with central intensity minimum

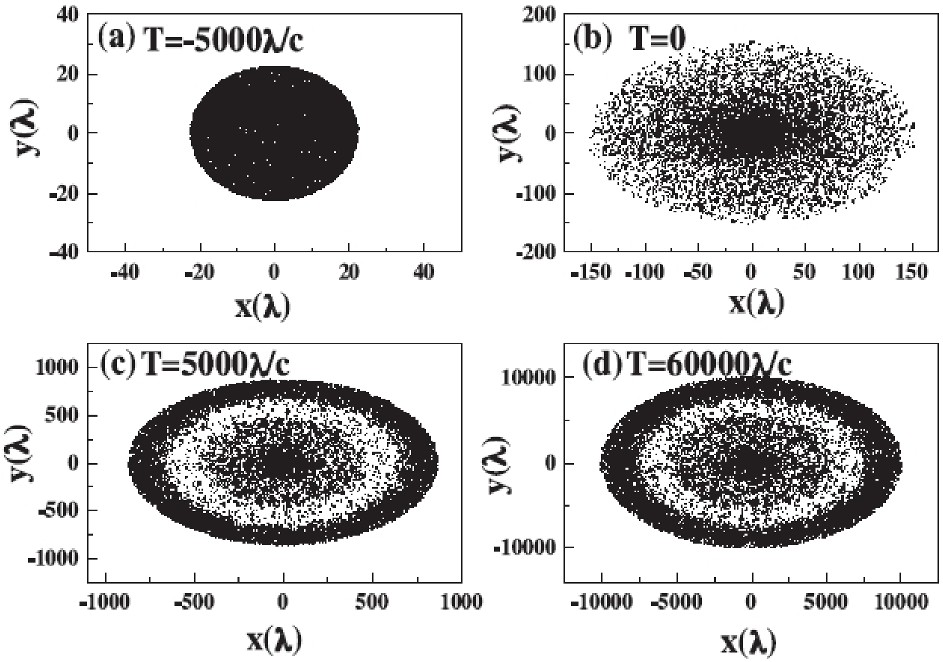


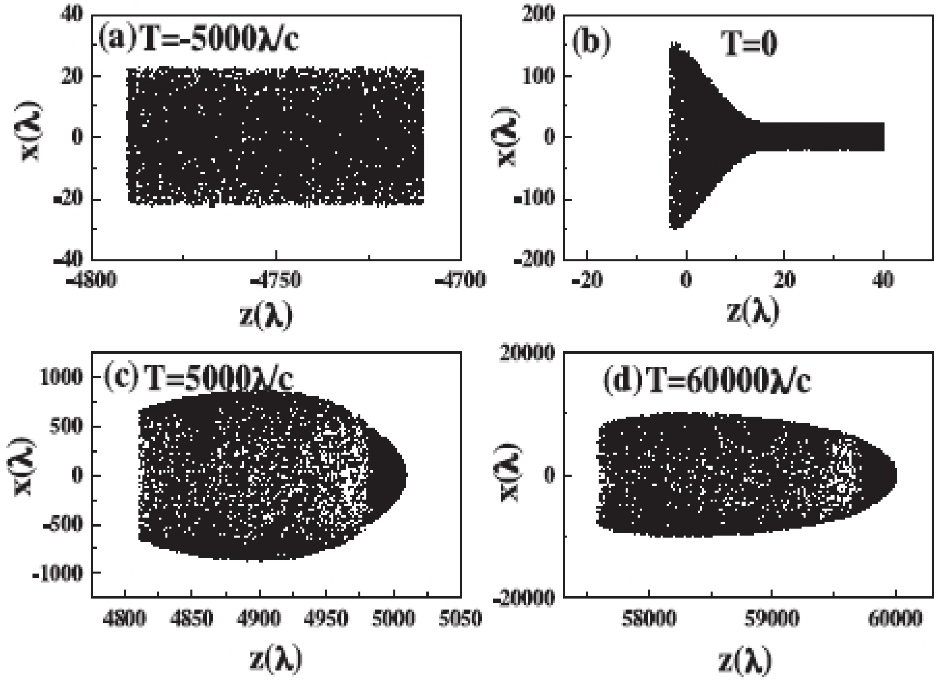


Laser pulse and electron bunch propagate in parallel and they coincide in best laser focus

Idea of prof. Kawata– for sum TEM(1,0)+TEM(0,1) modes ponderomotive confinement

Transverse and side-on profiles of electron beam



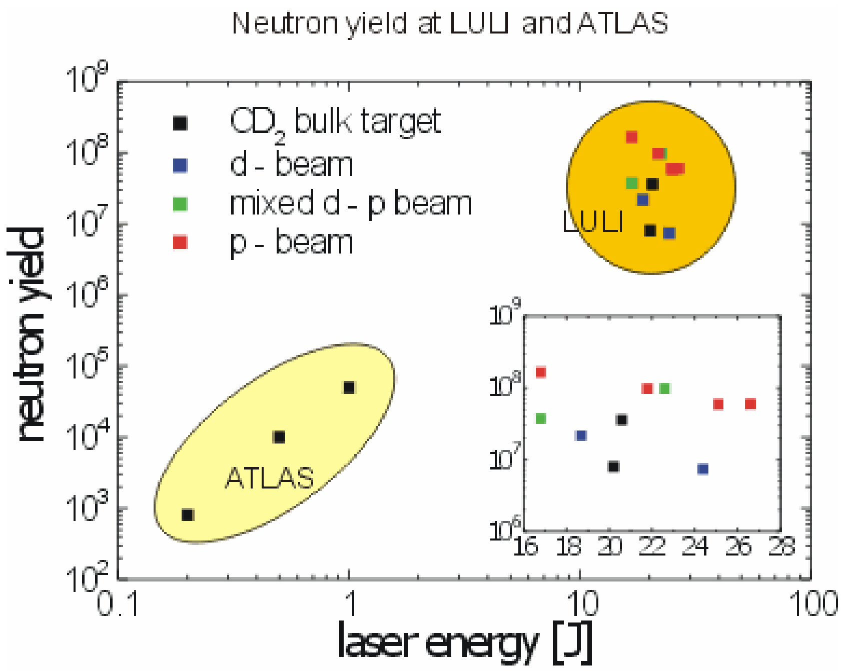


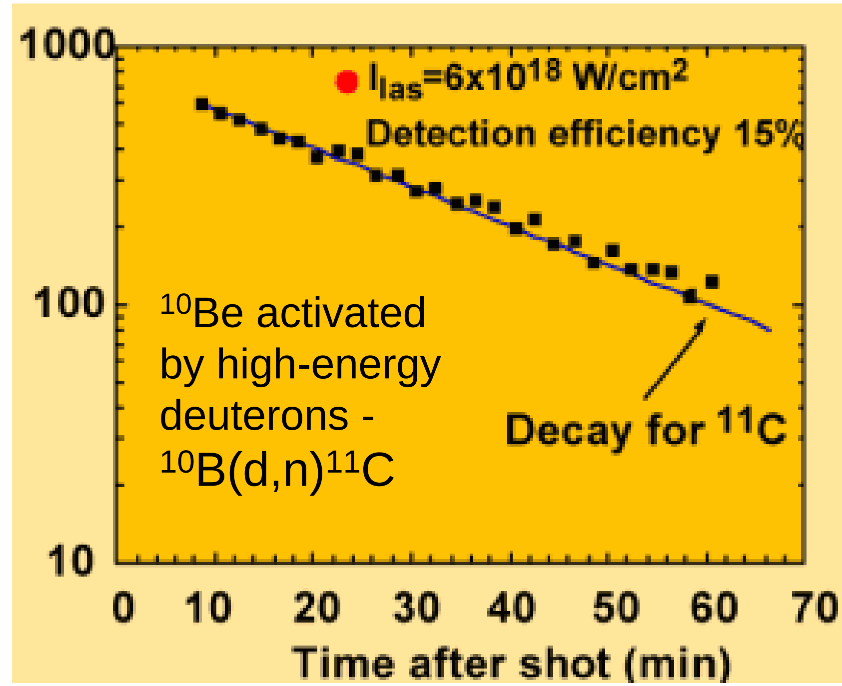
Electron beam transverse profile for a_0 = 10, waist w_0 = 15λ, laser pulse duration 10τ, electron bunch β_z = 0.95, β_x = β_y = 0, uniform bunch of radius 10λ and length 80λ

Acelerated part of electron bunch is confined in central forward position at the rising part of laser pulse

Simulation of electron motion in vacuum fields

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.

Fast ignition (FI) of inertial nuclear fusion (ICF)

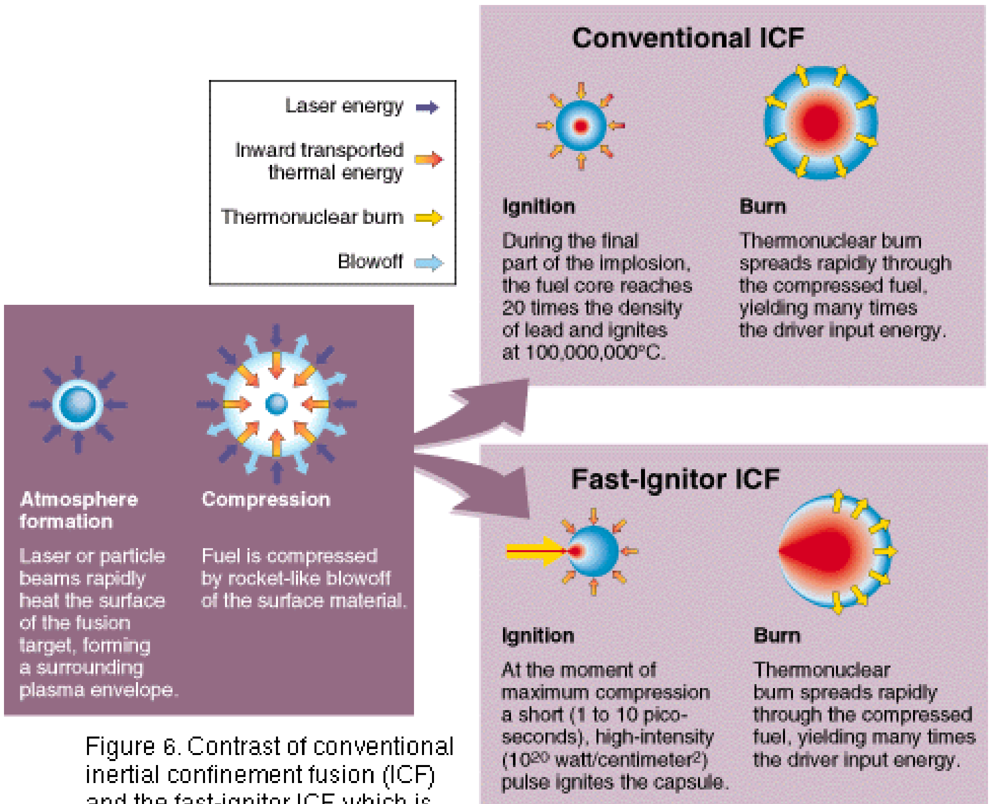
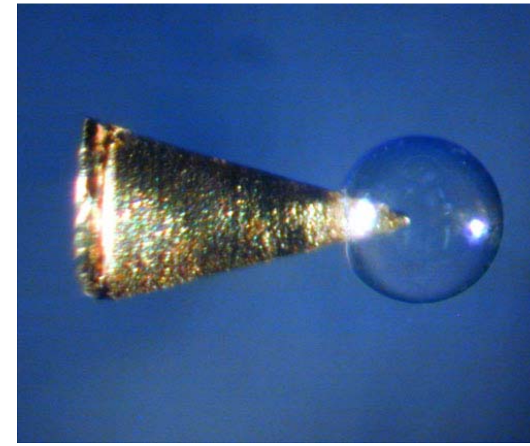


Figure 6. Contrast of conventional inertial confinement fusion (ICF) and the fast-ignitor ICF, which is used on the Petawatt laser.



Target for cone guided FI

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

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 DT fuel (in 1D simulations it works fine)