APPLICATIONS OF SUPER-HIGH INTENSITY LASERS IN NUCLEAR ENGINEERING

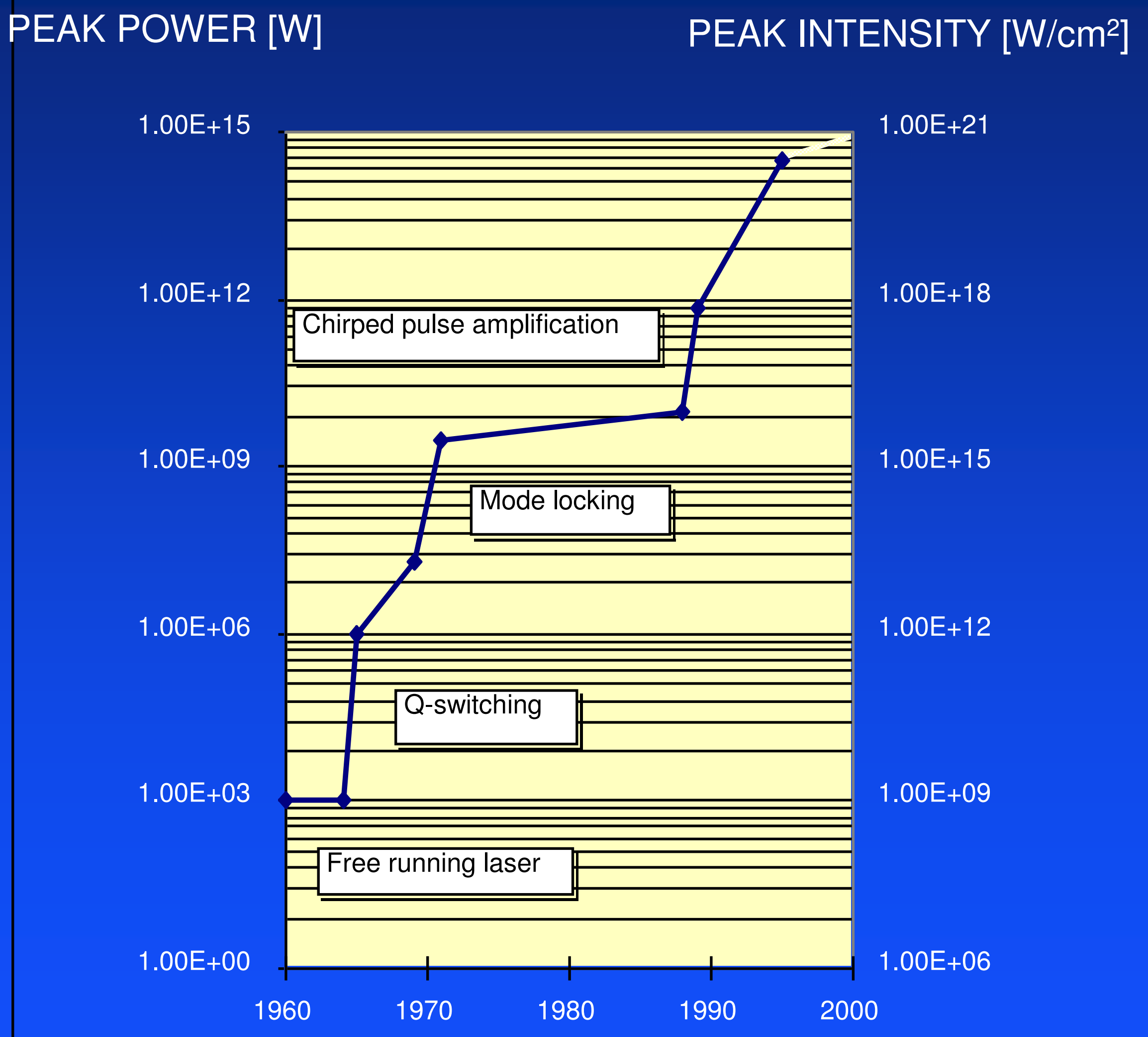
Rainer Salomaa, Antti Hakola, and Marko Santala
Helsinki University of Technology
Advanced Energy Systems
Finland

OUTLINE

- Ultraintense laser pulses, T^3 -lasers
- Plasma physics under extreme conditions
- Generation of photons and particles
- Particle diagnostics
- Potential applications for nuclear technology

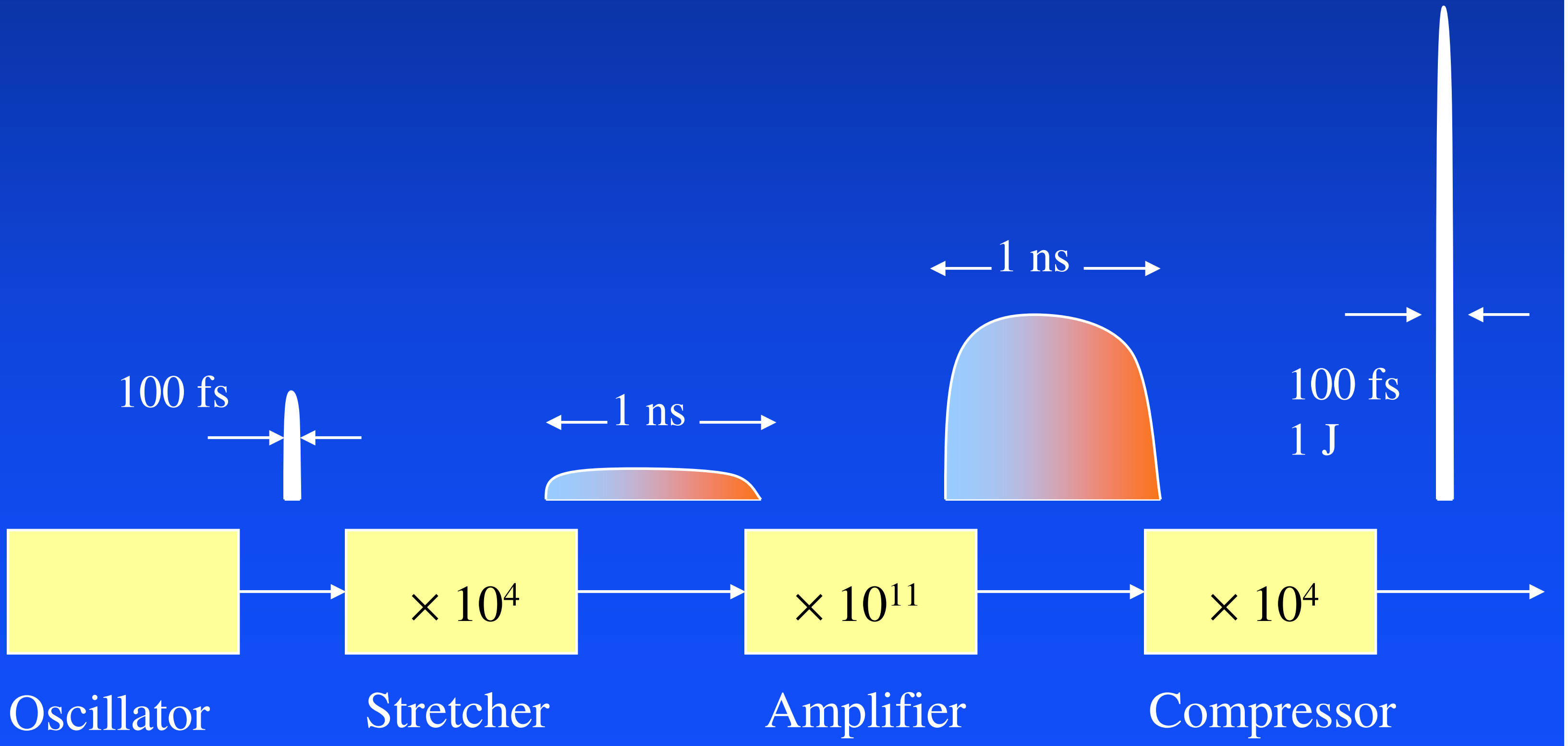
How to make ultraintense ultrashort laser pulse?

Dramatic increase in pulse-laser peak power has enabled laser-matter interaction studies in a fully new regime



Chirped Pulse Amplification

- Short pulse generation: 1) compensation of dispersion and 2) self phase modulation (e.g. Kerr lens mode locking)
- Efficient energy extraction requires a high fluence (J/cm^2)
- Undesired optical nonlinearities limit the intensity (W/cm^2)



100 fs

1 ns

1 ns

100 fs
1 J

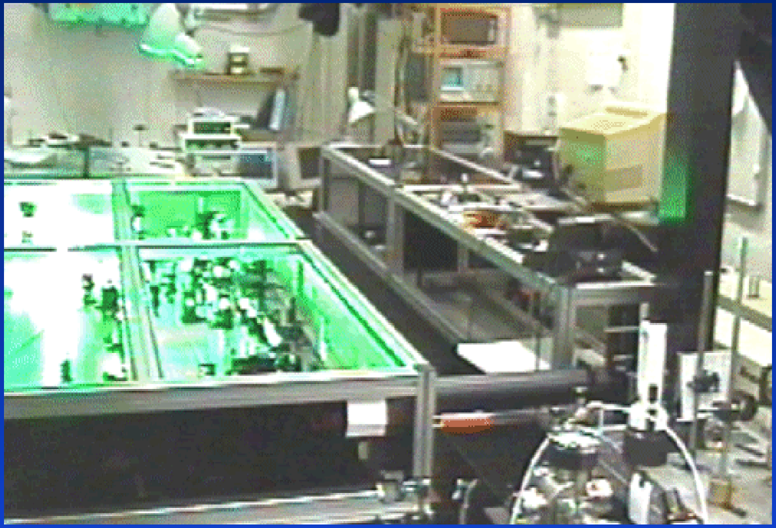
Oscillator

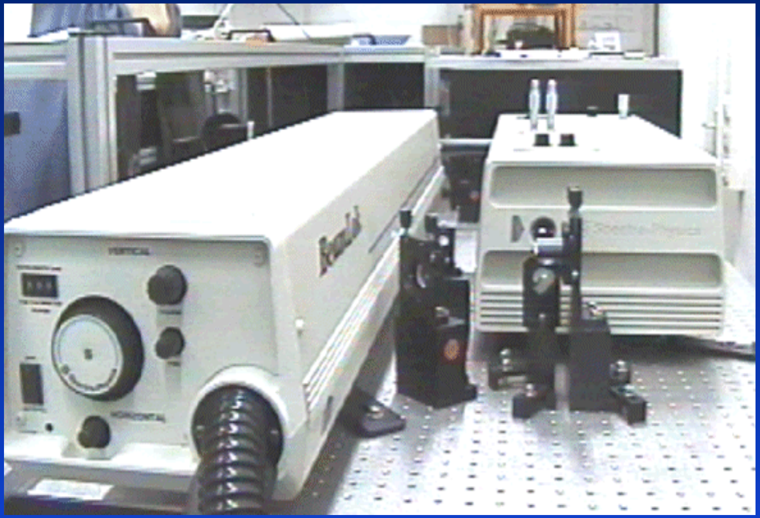
Stretcher $\times 10^4$

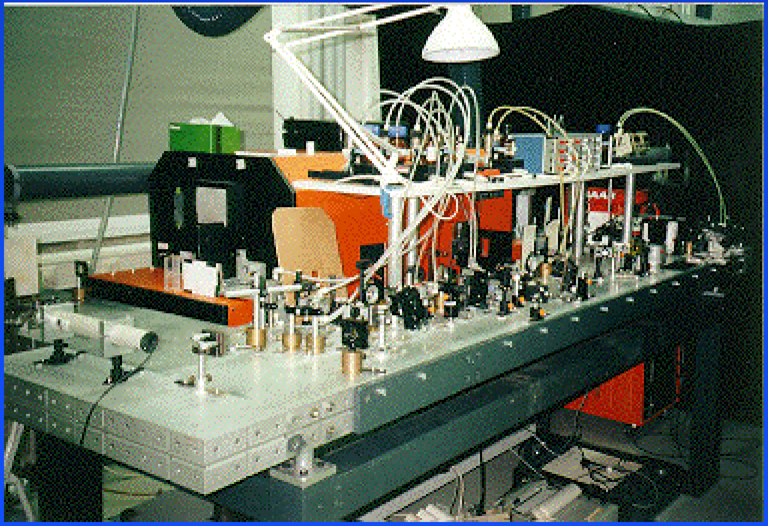
Amplifier $\times 10^{11}$

Compressor $\times 10^4$

Table Top Terawatt (T^3) Lasers







↖ ↑

Ti:Al_2O_3 (Continuum/Spectra Physics)
240 mJ, 100 fs, 2.4 TW, 10 Hz, 795 nm

← KrF
20 mJ, 700 fs, 1Hz, 248.5 nm

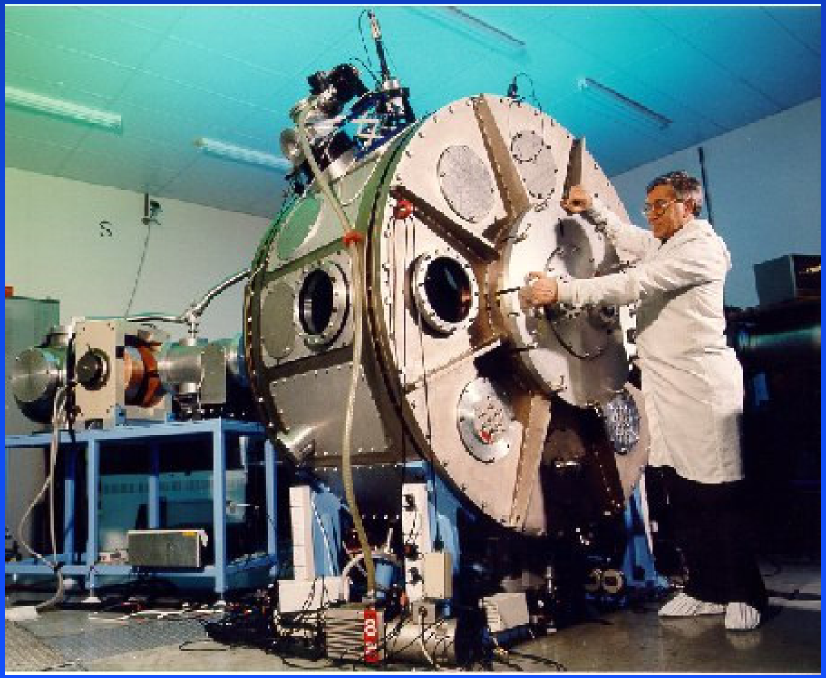
IOQ FSU-Jena

Vulcan (Rutherford Appleton Labs)

- Central Laser Facility with user support, TMR-funding possibilities, loan pools
- Nd:glass: 2.6 kJ/100 TW+ at 1054 nm, 700 fs / 5 ns pulses or 1kJ at SHG 527 nm
- On target intensity 10^{20} W/cm^2

Disc amplifiers

Target chamber



Petawatt laser (LLNL)

- Ti:Sapphire oscillator
  100 fs, 1054 nm
- Nd:YAG amplifiers
  over 600 J in 430fs
  1.25 PW peak power
- Fast ignitor test bed

Performance

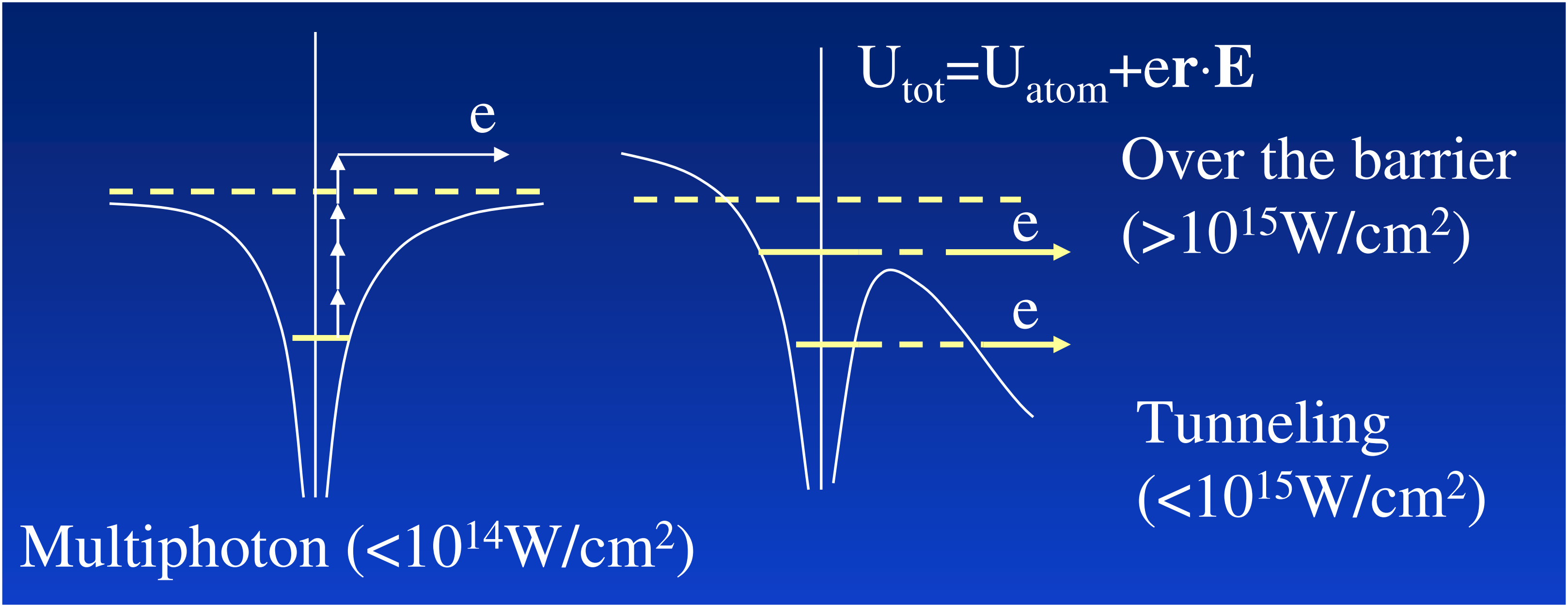
- Energy 100…1000 J and beyond
- Pulse length 0,1…1 ps
- Peak power 100TW…1PW
- Spot diameter 10…100 µm
- Intensity 10^{20}…10^{21}W/cm^2 and beyond
- Repetition rate 1 h^{-1}…100 s^{-1}
- Near UV-IR wave length range (fundamental)

Extremely interesting physics

Physics under extreme conditions

- Laser field comparable to atomic binding
- Ultrafast ionization, up to 100th harmonic, VUV and X-rays, highly stripped ions
- Relativistic electron plasmas
- MeV-range particles and radiation
- Magnetic fields in the range $10^2 \ldots 10^5$ T
- Gbar light and Hohlraum pressures
- Extreme acceleration (of bulk)
- Laboratory astrophysics

Ultrafast ionization & other atomic issues



$U_{tot}=U_{atom}+e\mathbf{r}\cdot\mathbf{E}$

Over the barrier ($>10^{15}$W/cm^2)

Tunneling ($<10^{15}$W/cm^2)

Multiphoton ($<10^{14}$W/cm^2)

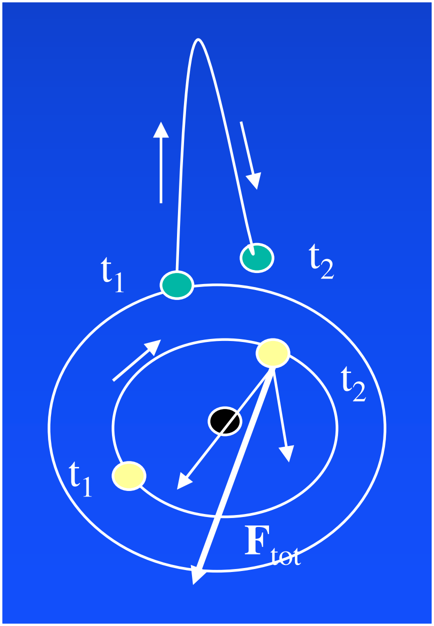
Ultrafast ionization within one laser cycle:

$E_{laser}= 2.745\times10^{11}$ V/m $(I/10^{18}\ \mathrm{Wcm}^{-2})^{1/2}$

$E_{atom}= e/4\pi\varepsilon_0 a_0^{\ 2} = 5.142\times10^{11}$ V/m

Sequential ionization: primary electron together with the ion kicks out a second electron half a cycle later

Relativistic electron orbitals in highly stripped atoms like U^{82+}: r_{nucl}=8.7 fm, r_{Bohr}=645 fm



*For a review see M. Protopapas et al, Rep.Prog.Phys. **60**, 389 (1997)

Relativistic electron physics

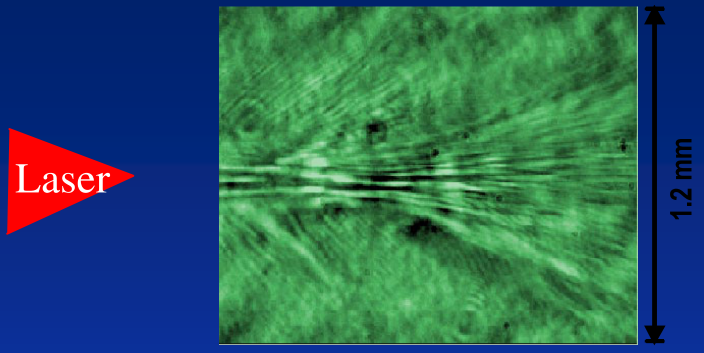
$$\boxed{p_{max}/mc = 0.854\ (I\lambda^2/10^{18}\mathrm{Wcm}^{-2}\mu\mathrm{m}^2)^{1/2}}$$

- Multi-MeV electrons → intense UV- and X- and γ-emission up to 10 MeV, significant neutron emission (n, γ)
- Bulk electron temperature several 100 eV
- Pair production: QED theories needed, ultimate case for $\lambda_{Compton}{}^3\ \varepsilon_0 E^2 \approx m_0 c^2 \rightarrow I \approx 10^{25}\ \mathrm{Wcm}^{-2}$
- Ultrafast photoionization creates B-fields up to 10^5T, somewhat weaker fields by $(\nabla n \times \nabla T)$ –mechanism and electron jets (in the range 10^2-10^4T in a longer time scale)
- Energy transport by hot electrons is a challenge (jets to vacuum, magnetic field inhibition, etc.)
- Due to short pulse duration ions are partly frozen

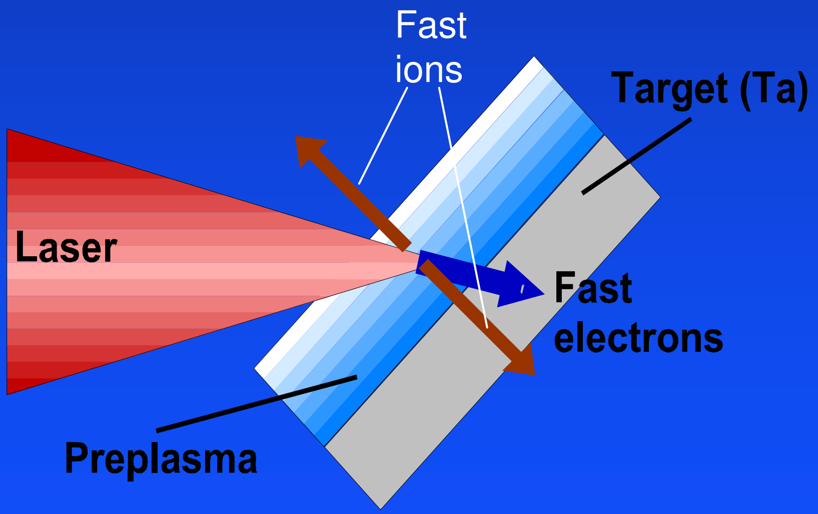
Solid and gas target experiments

Laser-solid interaction

- Pre-ionization at surface
  - inhomogeneous plasma
  - under/overdense plasma
- Several electron and ion acceleration processes
  - energies to ‘tens of MeVs’
- 50 % conversion efficiency to electrons
  - enormous currents and ***B***

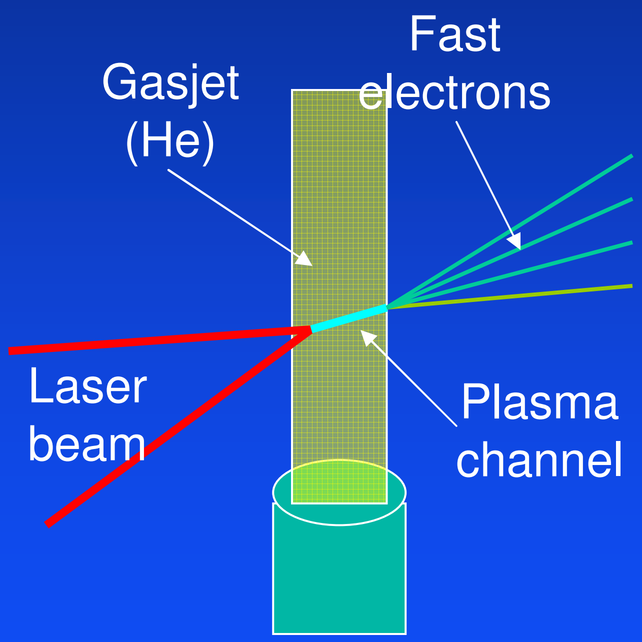


Laser-plasma interaction
imaged from side



Gas targets, plasma accelerators

- Gasjet experiment
  - homogeneous plasma
  - underdense plasma
  - intense plasma waves
- Extended interaction length due to channeling
- Electron acceleration to >100 MeV
- Two methods: Beat wave (BWA) and Wake Field Acceleration (WFA) 10 GV/m field



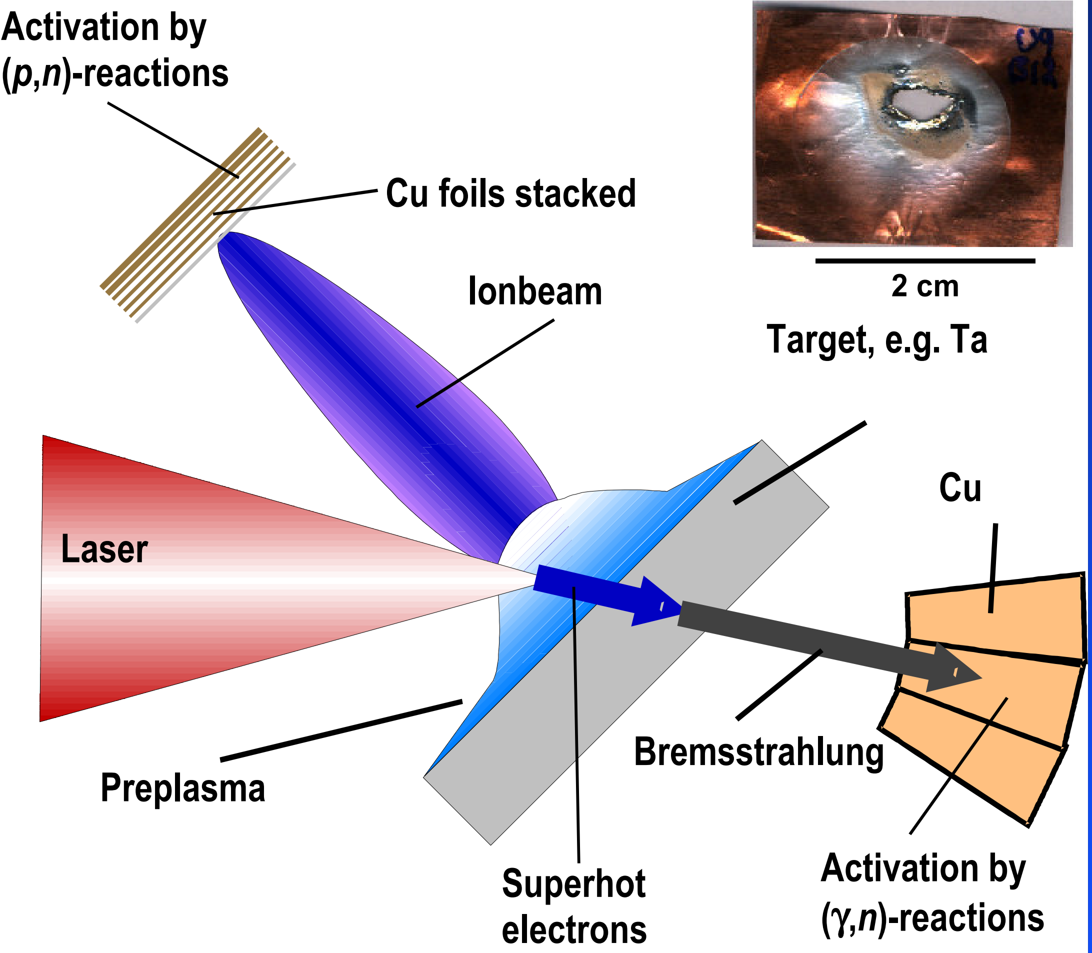
Particles from laser-plasmas

- Plasma acceleration (in gas jets):
  - Electrons up to >100 MeV
  - Ions to several MeV
  - Dedicated accelerator schemes
- Laser-solid interaction
  - Electrons up to ‘tens of MeV’
  - Protons up to ‘tens of MeV’
  - Heavy ions up to ‘hundreds of MeV’

Nuclear reactions & diagnostics

Santala et al. at Vulcan (IC&RAL)

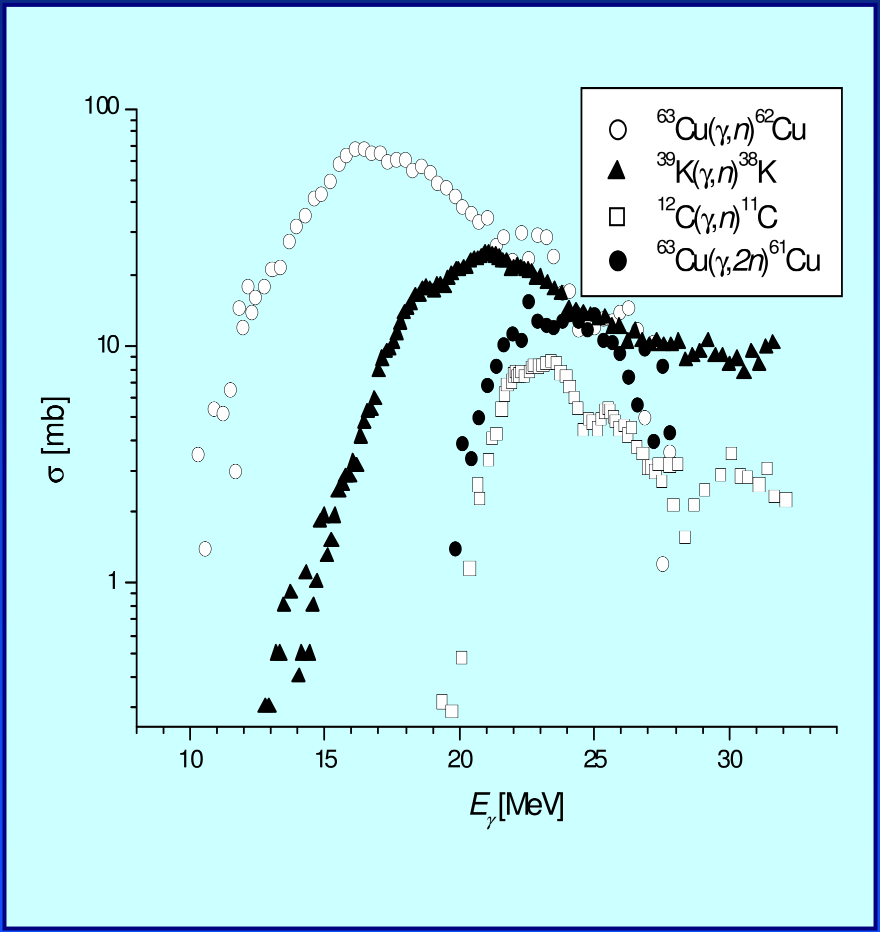
Diagnostics by activation, Ta-Cu



←Top Cu-foil

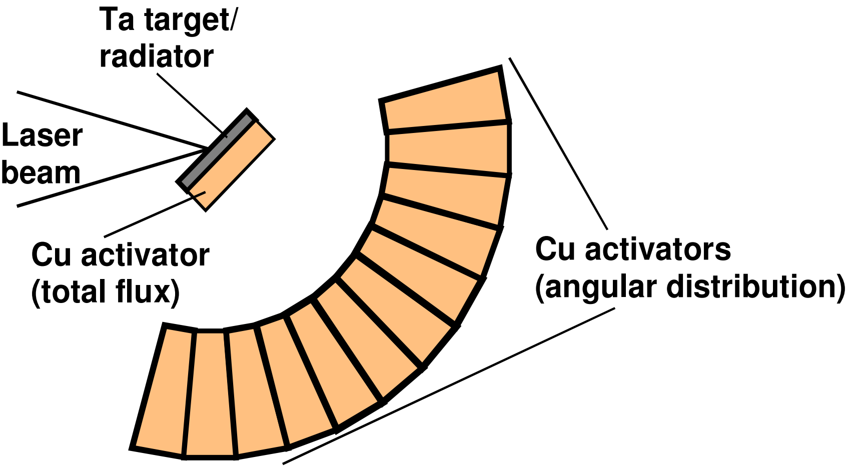
Photonuclear reactions

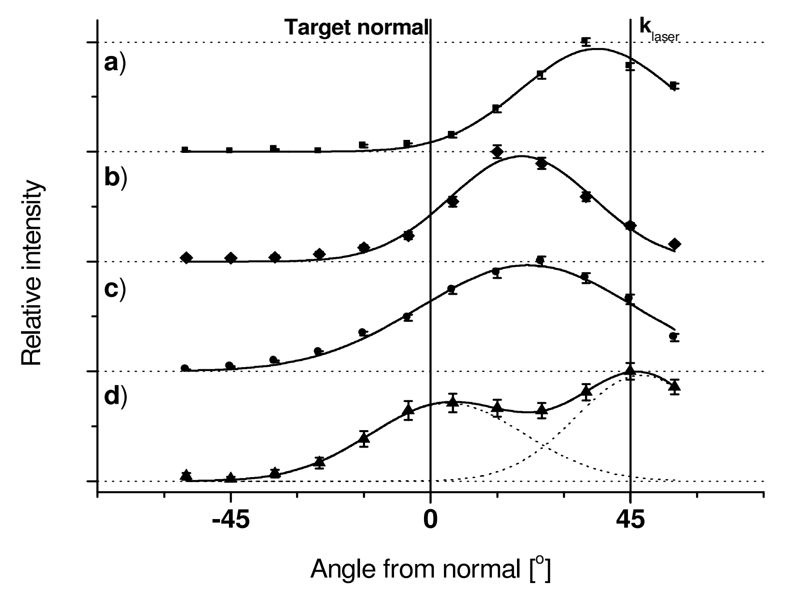
- Bremsstrahlung γ-rays knock off neutrons
- Reaction products are often radioactive
  - ◆ ^{62}Cu, $T_{1/2}$=9.7 min, β^+
- Activity proportional to the energy spectrum and the intensity of bremsstrahlung
- Multiple reactions enable resolving the spectrum



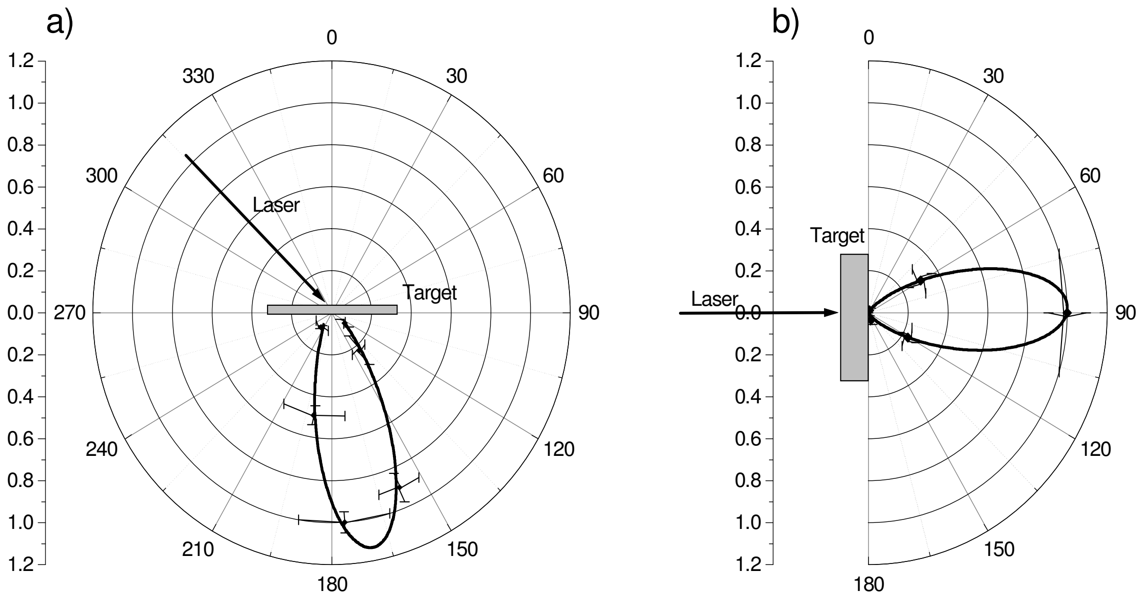
Electron angular distribution

- Laser-solid experiment
- Ta target/converter
  - 12 Cu activators
- Activation distribution measured
  - related to fast electrons





Directed radiation pattern, “gamma torch”



Over 10 MeV gammas

Vulcan, Norreys et al, Ph.Plasmas 1999

Some potential applications?

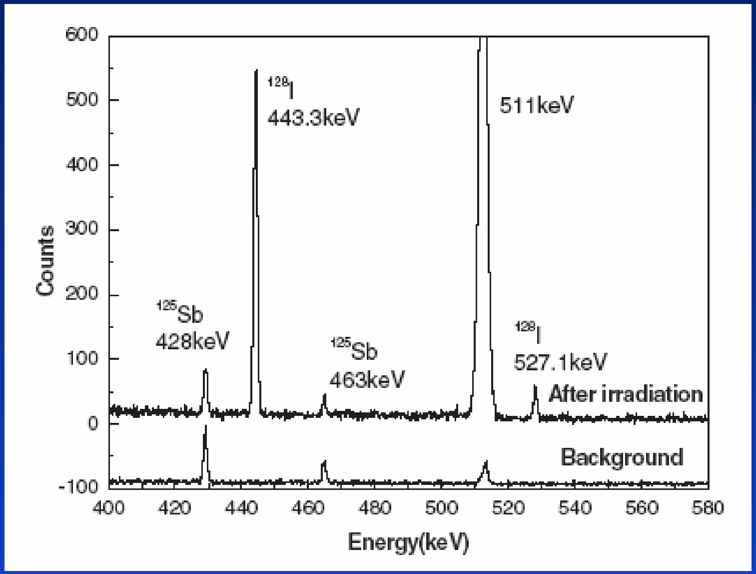
Applications of ultrashort superintense laser pulses:

- **Table-top particle accelerators**
- **Nuclear reactions, transmutation**
- **Isotope separation, PET isotopes, …**
- **Ultrashort radiation sources (UV,X, γ, n)**
- **Inertial confinement fusion, fast ignitor**

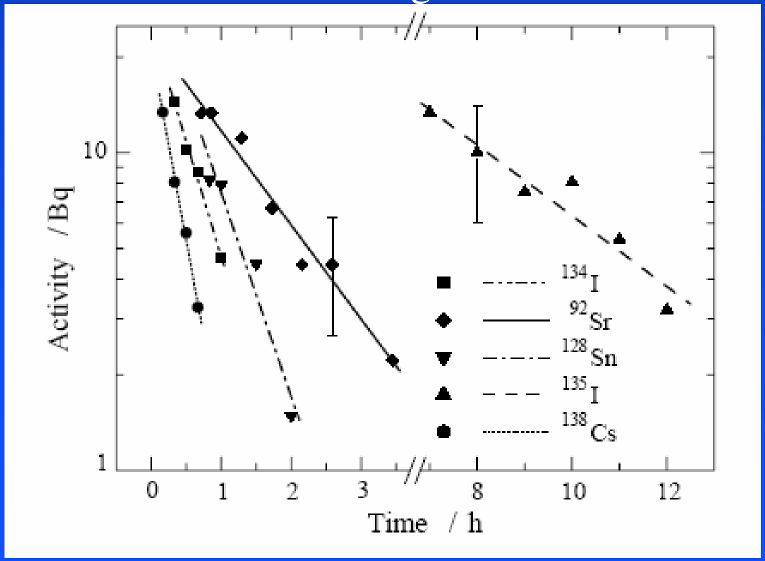
- Materials processing, microstructures, surface treatment by T^3-lasers
- Ultrafast optical switching
- THz-sources
- Nonlinear microscopy, in-vivo nonlinear spectroscopy

Laser induced nuclear reactions

- Photon-induced reactions, γ´s up to 10MeV range
- p-induced reactions, proton energy above 50 MeV
- Nuclear transmutation, case I-129
- Photon induced fission case Th-232, U-238
- Isotope production, PET cases C-11, F-18, …
- Heavy ion reactions: C, Al,Pb in 100 MeV range
- …



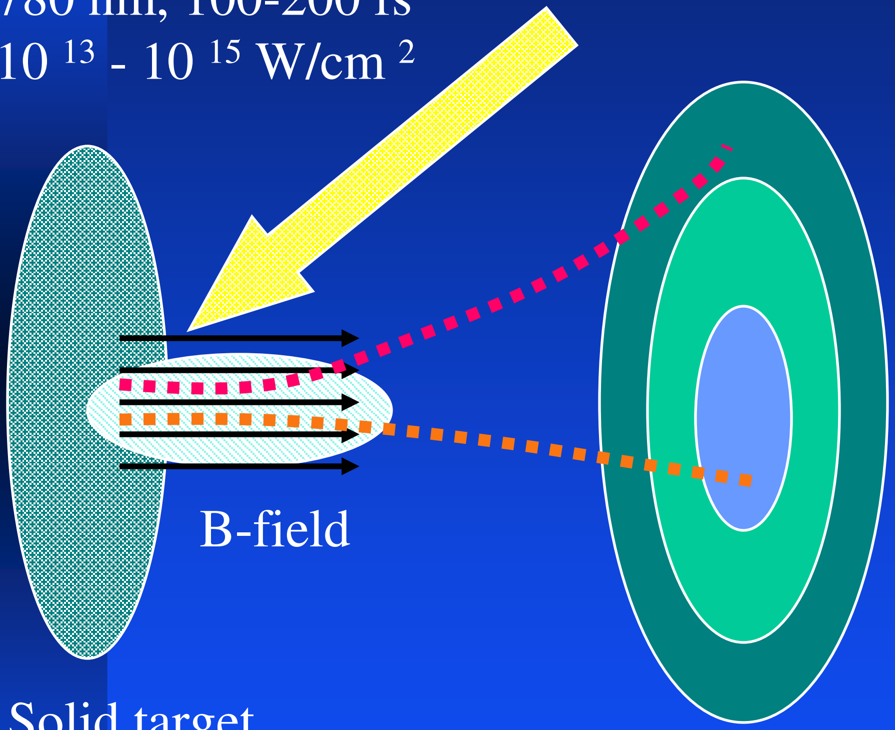
Ledingham et al 2003



Schwoerer et al 2003

Laser isotope separation by fs-laser ablation

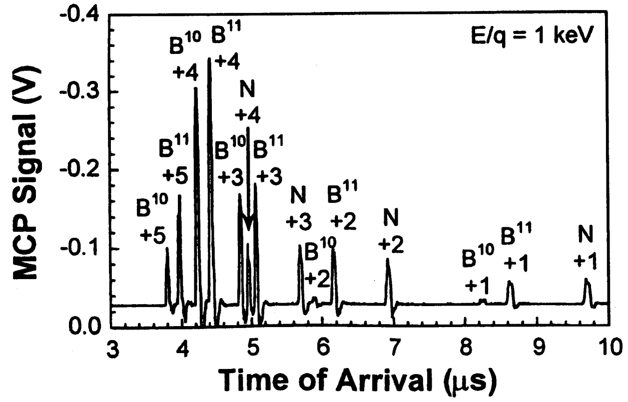
Laser pulse
780 nm, 100-200 fs
$10^{13} - 10^{15}$ W/cm ^{2}

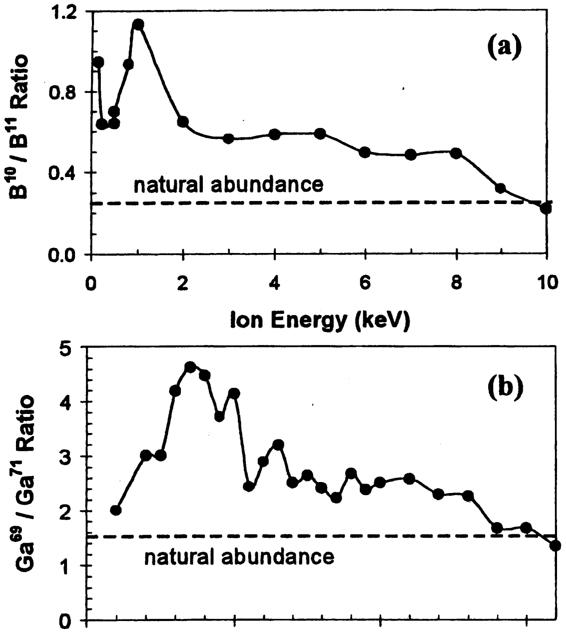


B-field

Solid target

Collection plate





Pronko et al. PRL 83 (1999) 2596

In summary

Final remarks

- Super intense laser irradiation: a novel exciting new tool for nuclear physics
- Experimental requirements: within reach of university level funding, not yet turn-key operation
- Get to shorter wave lengths
- X-ray sources in the water window
- Several demonstrations done, some may be moving to practical applications
- Niches for nuclear technology: no waste transmutation but perhaps PET isotopes, Mössbauer sources
- Technical optimization and tayloring
- New possible innovations: e.g. exploiting the time resolution, breaking the attosecond barrier, …