

APPLICATIONS OF SUPER-HIGH INTENSITY LASERS IN NUCLEAR ENGINEERING

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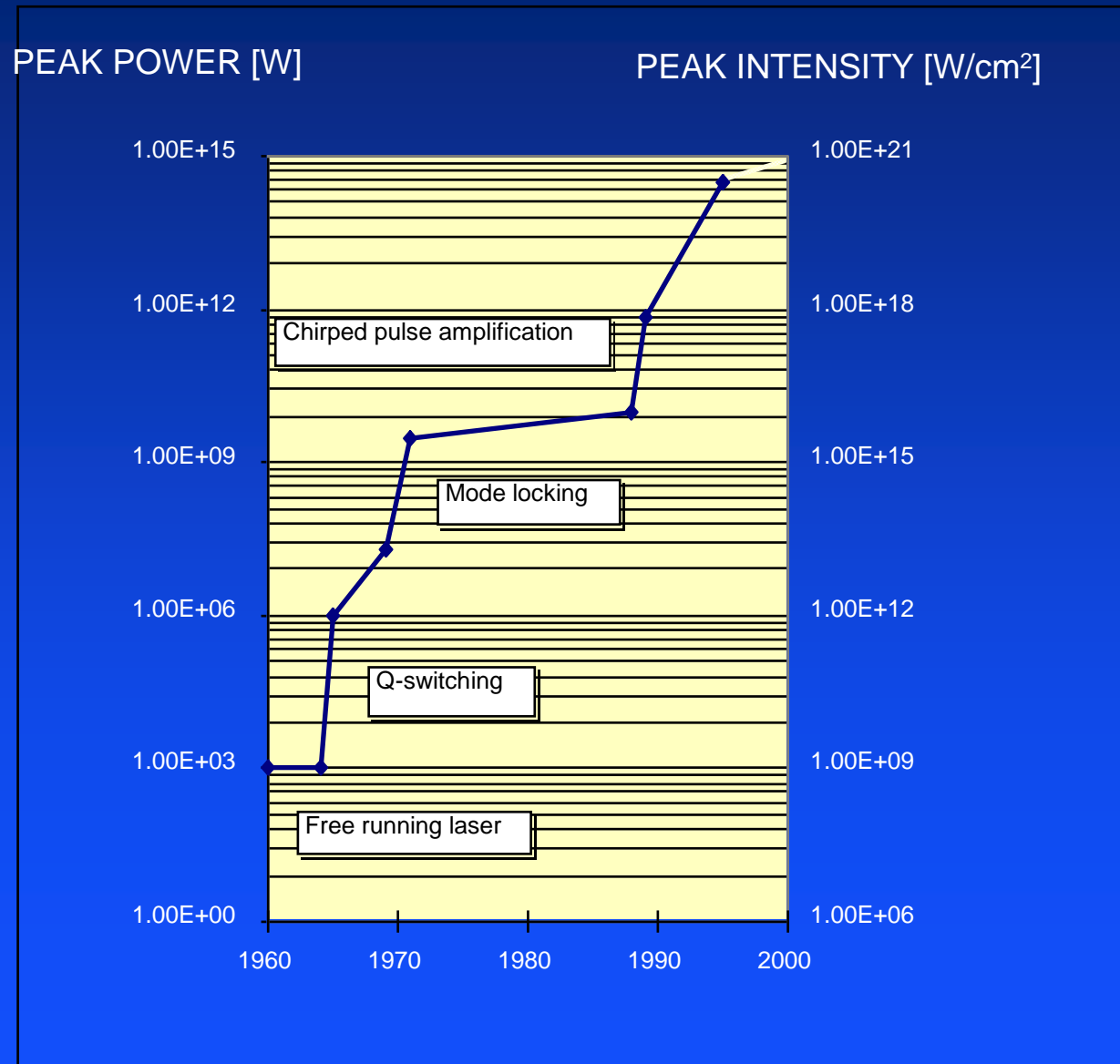
OUTLINE

- Ultraintense laser pulses, T³ -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)

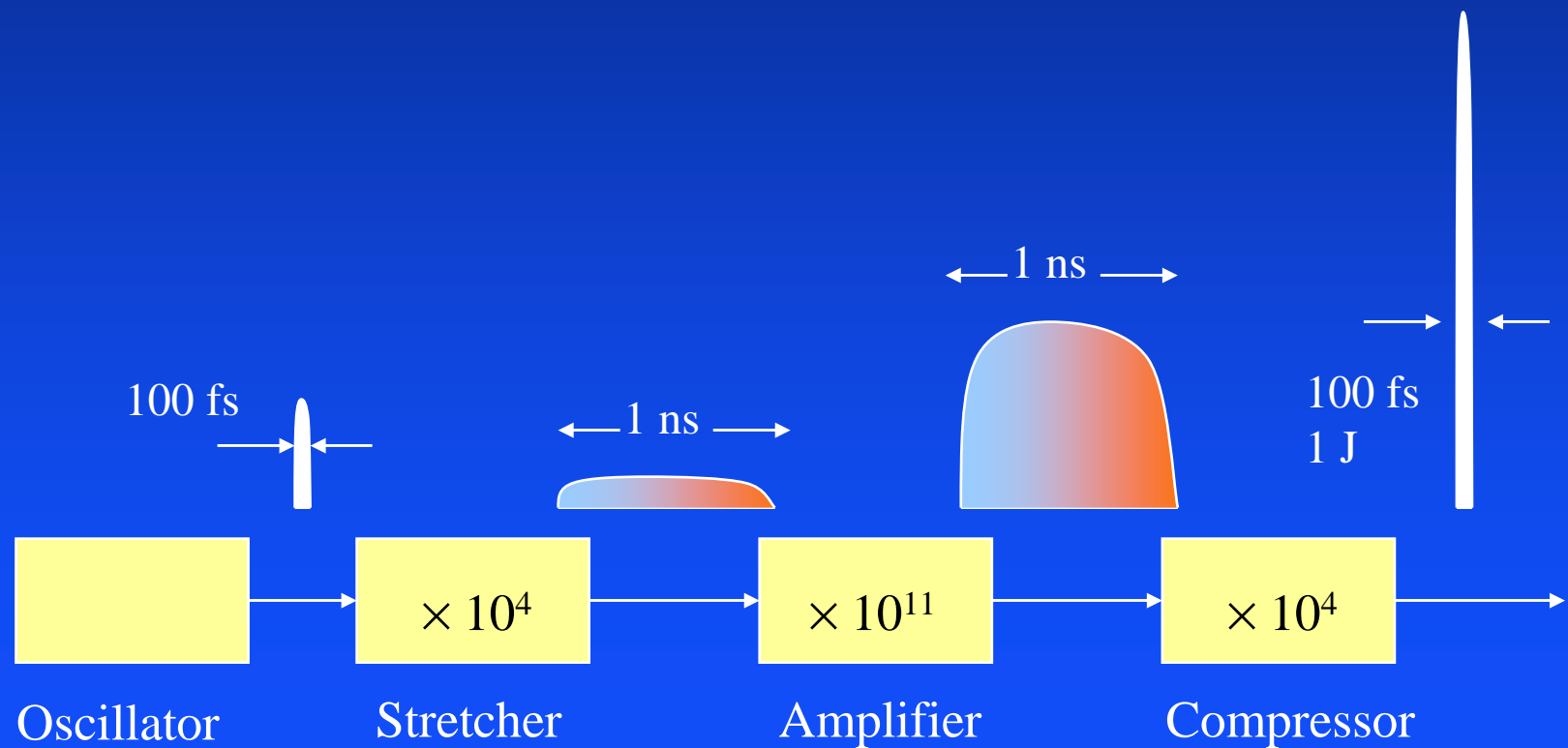
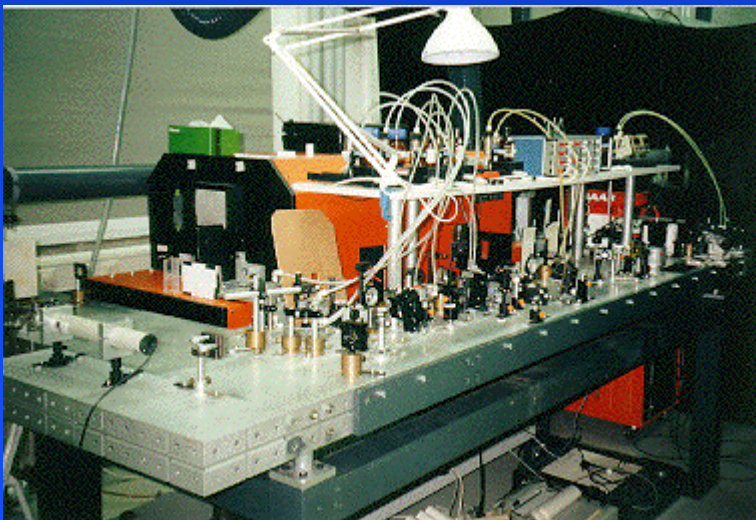
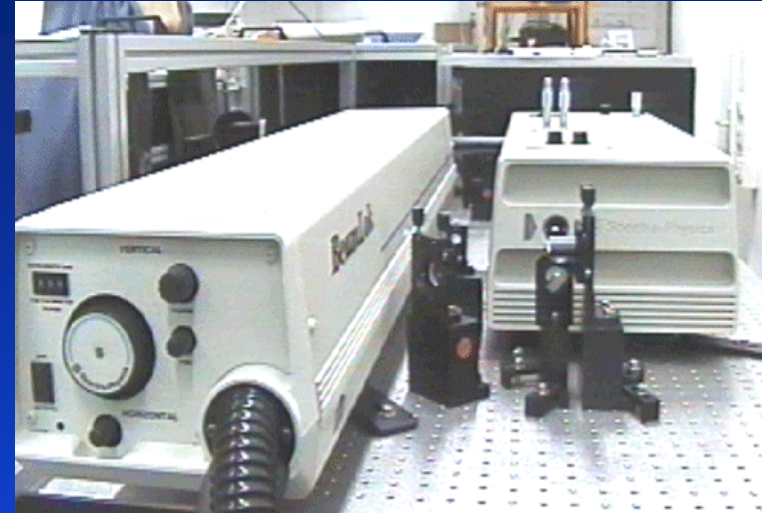
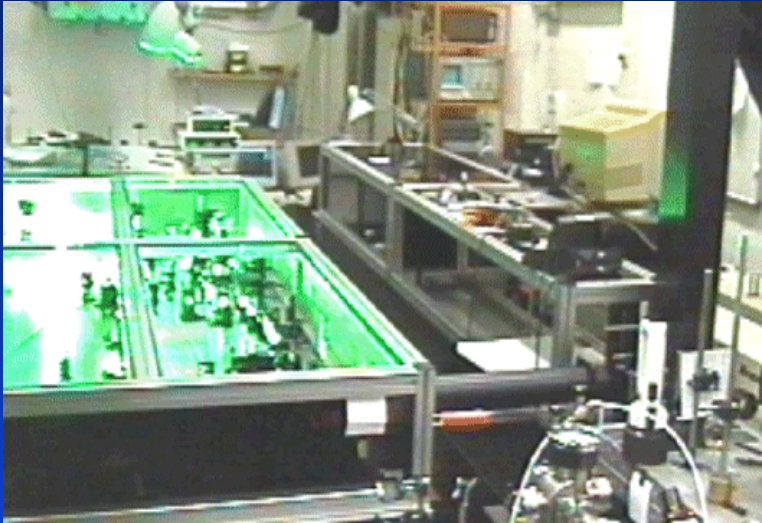


Table Top Terawatt (T³) Lasers



↙ ↗
Ti:Al₂O₃ (Continuum/Spectra Physics)
240 mJ, 100 fs, 2.4 TW, 10 Hz, 795 nm

↙ KrF
20 mJ, 700 fs, 1Hz, 248.5 nm

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/cm²

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/cm² and beyond
- Repetition rate 1 h⁻¹...100 s⁻¹
- Near UV-IR wave length range (fundamental)

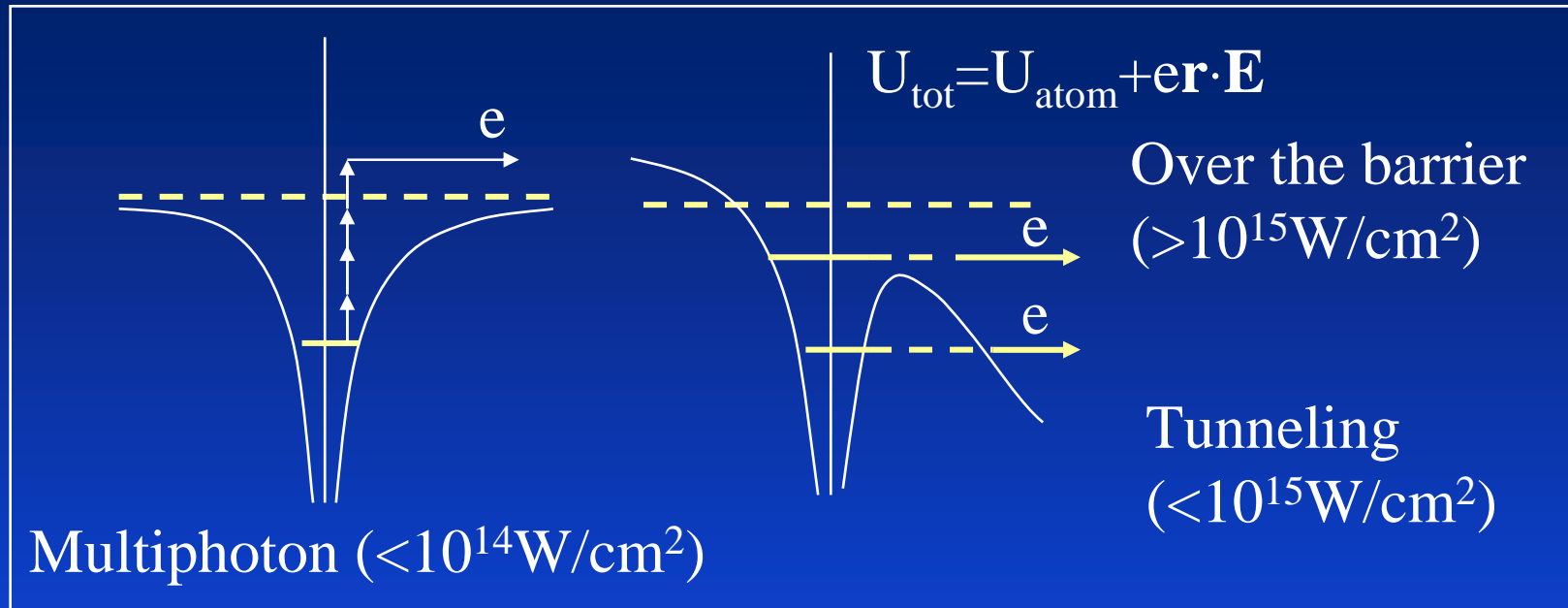


Extremely interesting physics

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 $10^2 \dots 10^5$ T
- Gbar light and Hohlraum pressures
- Extreme acceleration (of bulk)
- Laboratory astrophysics

Ultrafast ionization & other atomic issues



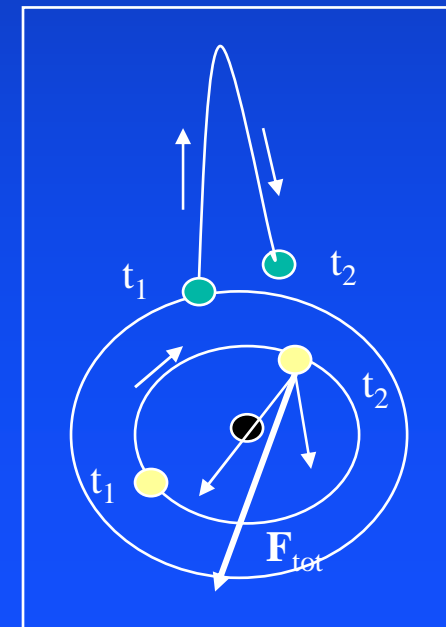
Ultrafast ionization within one laser cycle:

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

$$E_{\text{atom}} = e/4\pi\epsilon_0 a_0^2 = 5.142 \times 10^{11} \text{ V/m}$$

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+} : $r_{\text{nucl}} = 8.7 \text{ fm}$, $r_{\text{Bohr}} = 645 \text{ fm}$



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

Relativistic electron physics

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

- Multi-MeV electrons \rightarrow 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 $\lambda_{\text{Compton}}^3 \epsilon_0 E^2 \approx m_0 c^2 \rightarrow I \approx 10^{25} \text{ Wcm}^{-2}$
- 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

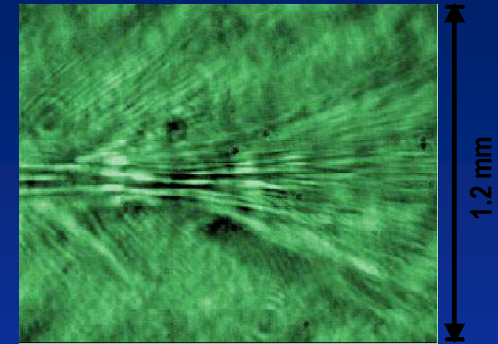


Solid and gas target experiments

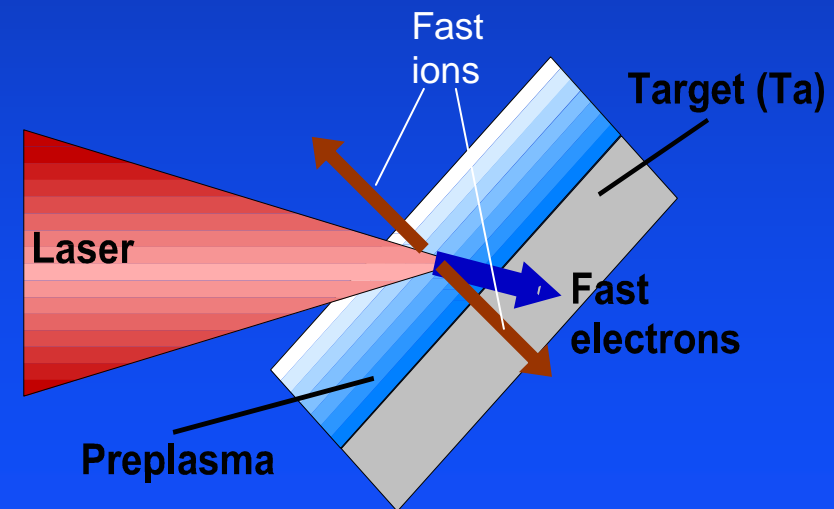
Laser-solid interaction

- 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

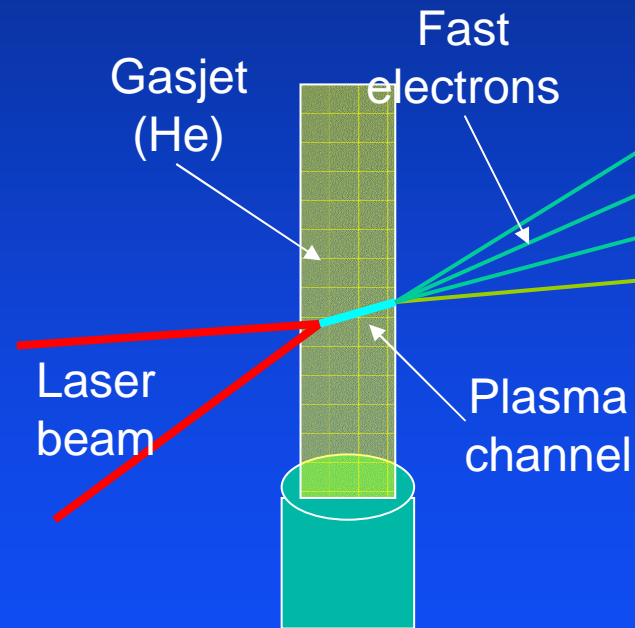


Laser-plasma interaction imaged from side



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

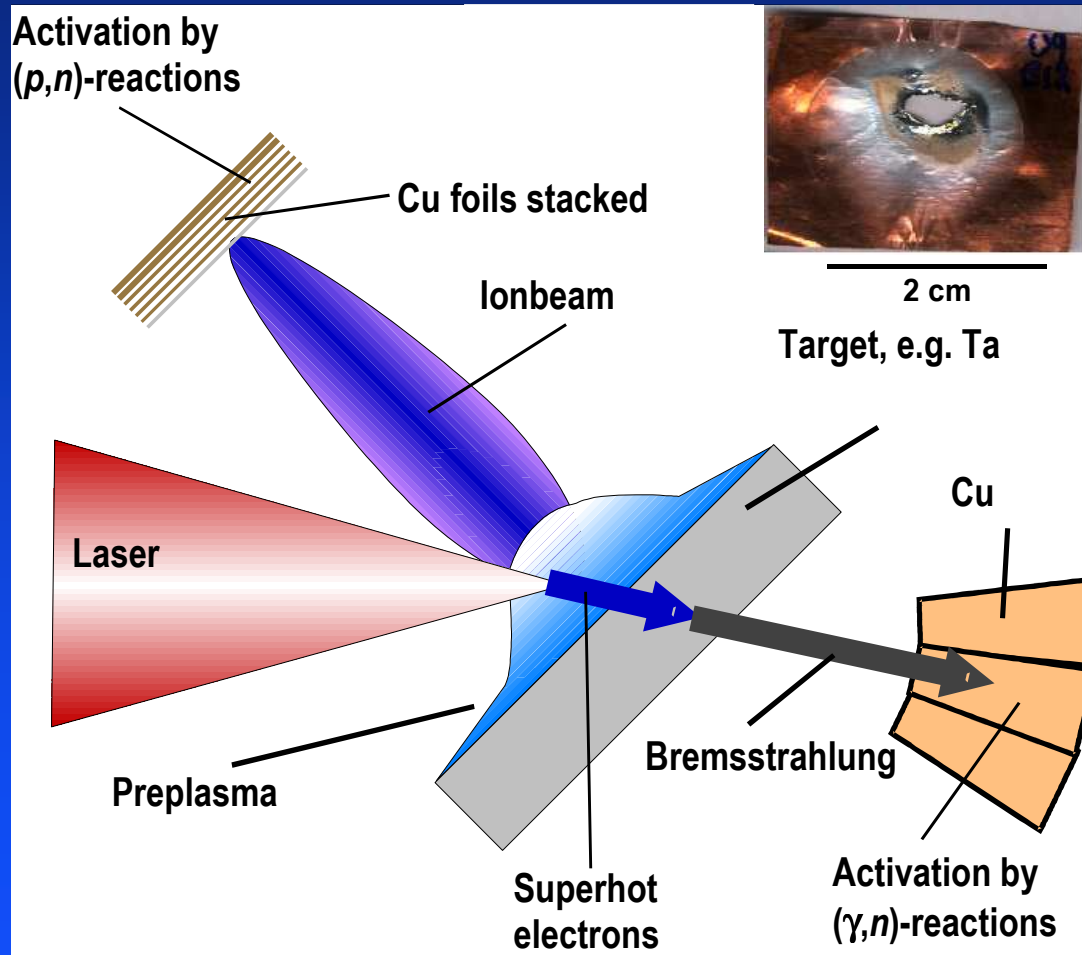
- Plasma acceleration (in gas jets):
 - ◆ Electrons up to >100 MeV
 - ◆ Ions to several MeV
 - ◆ Dedicated accelerator schemes
- Laser-solid interaction
 - ◆ Electrons up to ‘tens of MeV’
 - ◆ Protons up to ‘tens of MeV’
 - ◆ Heavy ions up to ‘hundreds of MeV’



Nuclear reactions & diagnostics

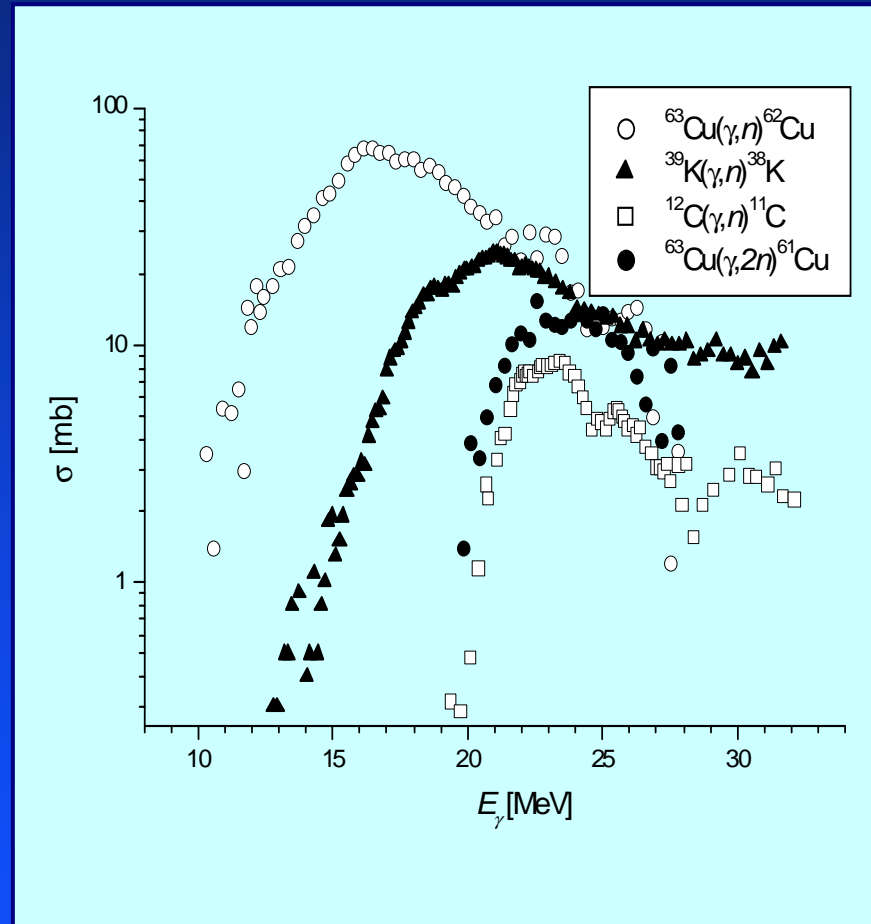
Santala et al. at Vulcan (IC&RAL)

Diagnostics by activation, Ta-Cu



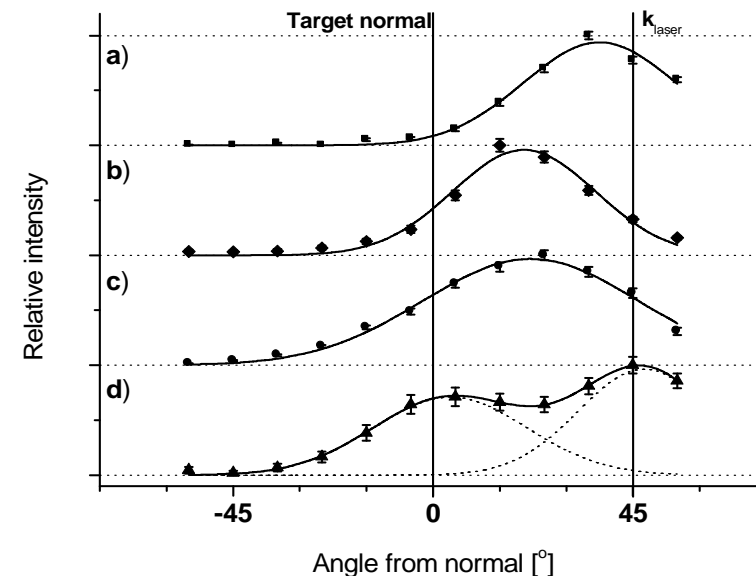
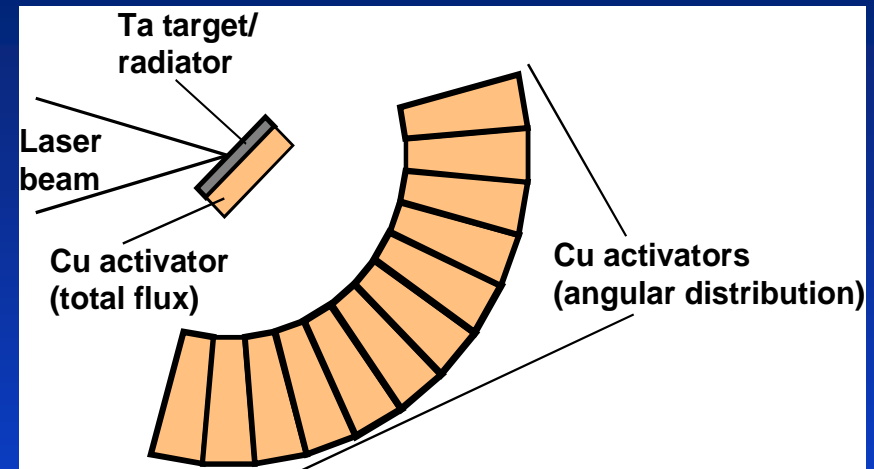
Photonuclear reactions

- 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

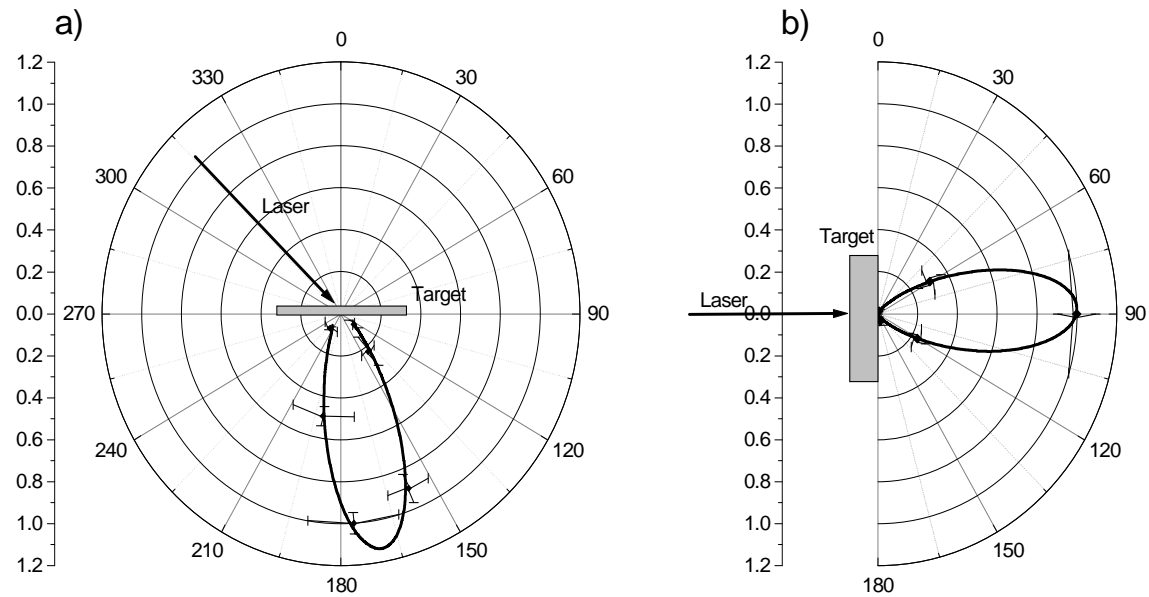


Electron angular distribution

- 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



Some potential applications?

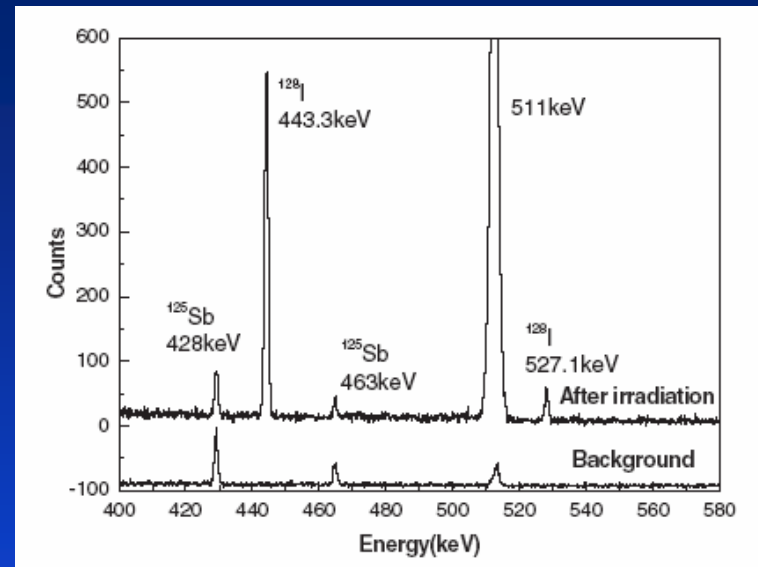
Applications of ultrashort superintense laser pulses:

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

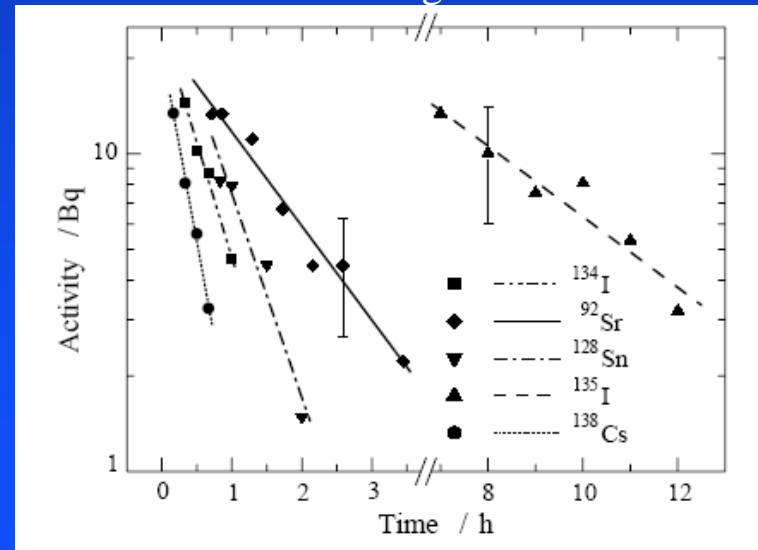
- **Materials processing, microstructures, surface treatment by T³-lasers**
- **Ultrafast optical switching**
- **THz-sources**
- **Nonlinear microscopy, in-vivo nonlinear spectroscopy**

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
- ...



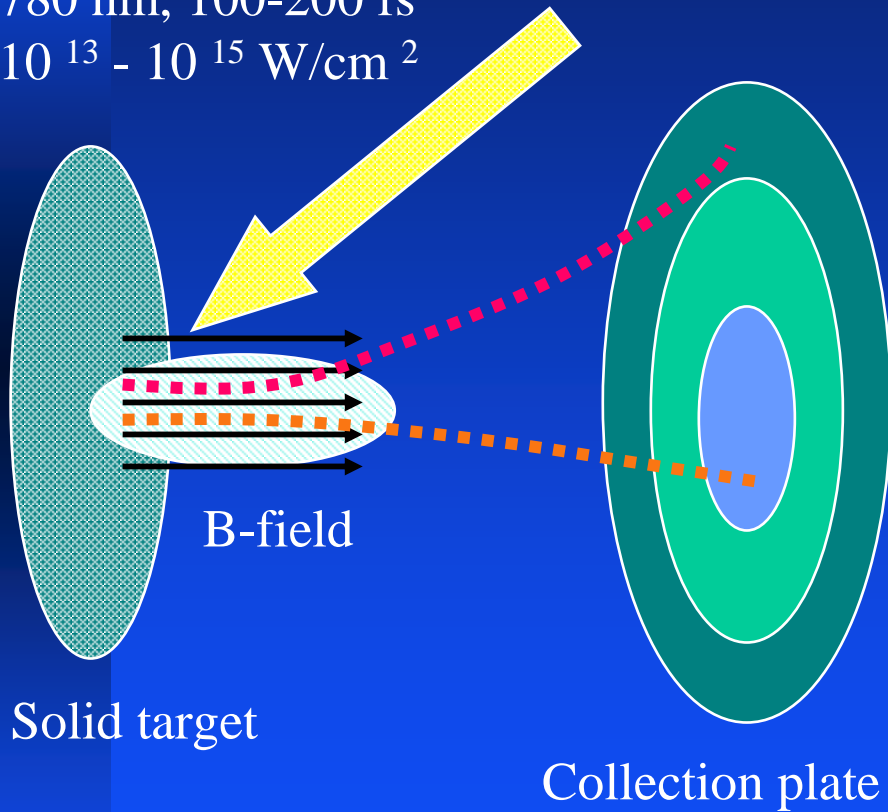
Ledingham et al 2003



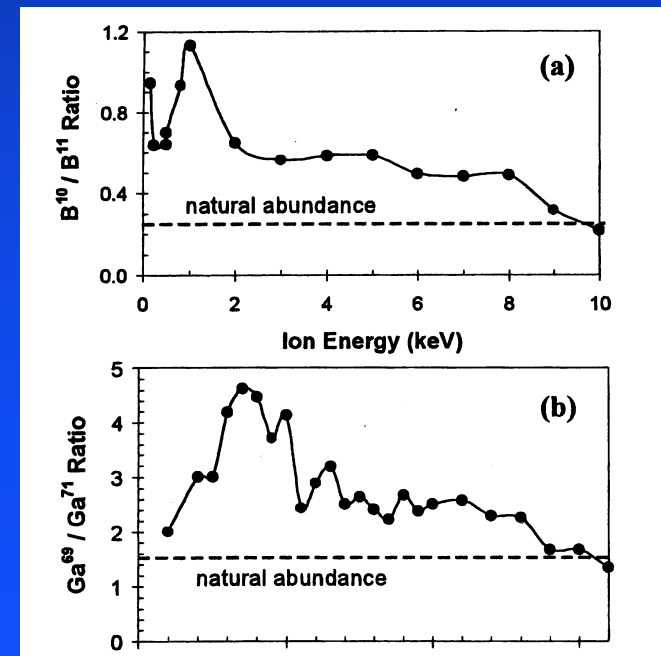
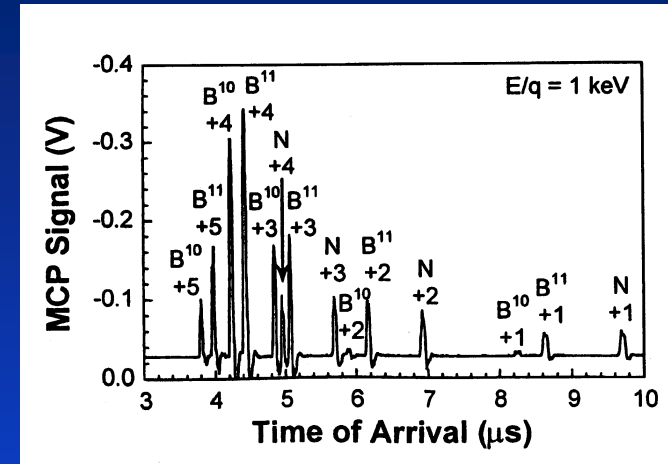
Schwoerer et al 2003

Laser isotope separation by fs-laser ablation

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



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 tailoring
- New possible innovations: e.g. exploiting the time resolution, breaking the attosecond barrier, ...