Workshop on Ions for Cancer Therapy, Space Research and Material Science
26 -30 August 2017, Chania, Crete, GREECE

Coherent soft X-rays from ultra-intense lasers
The future of nanoscale imaging

PROF. NEKTARIOS **PAPADOGIANNIS**, NPAPADOGIANNIS@STAFF.TEICRETE.GR

CENTRE FOR PLASMA PHYSICS AND LASERS

SCHOOL OF APPLIED SCIENCES

TEI OF CRETE, GREECE

Evolution of laser Intensity and pulse duration

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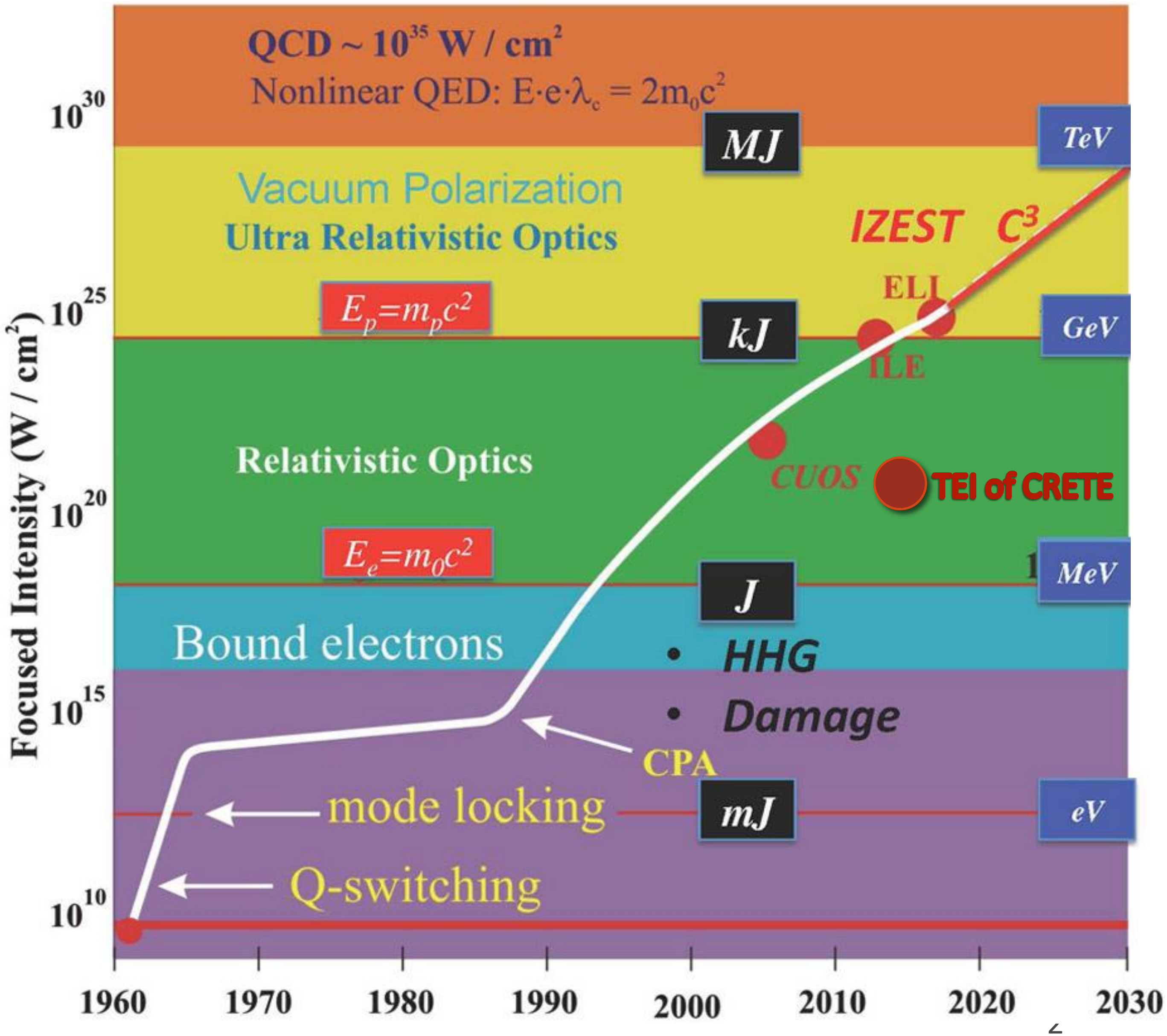

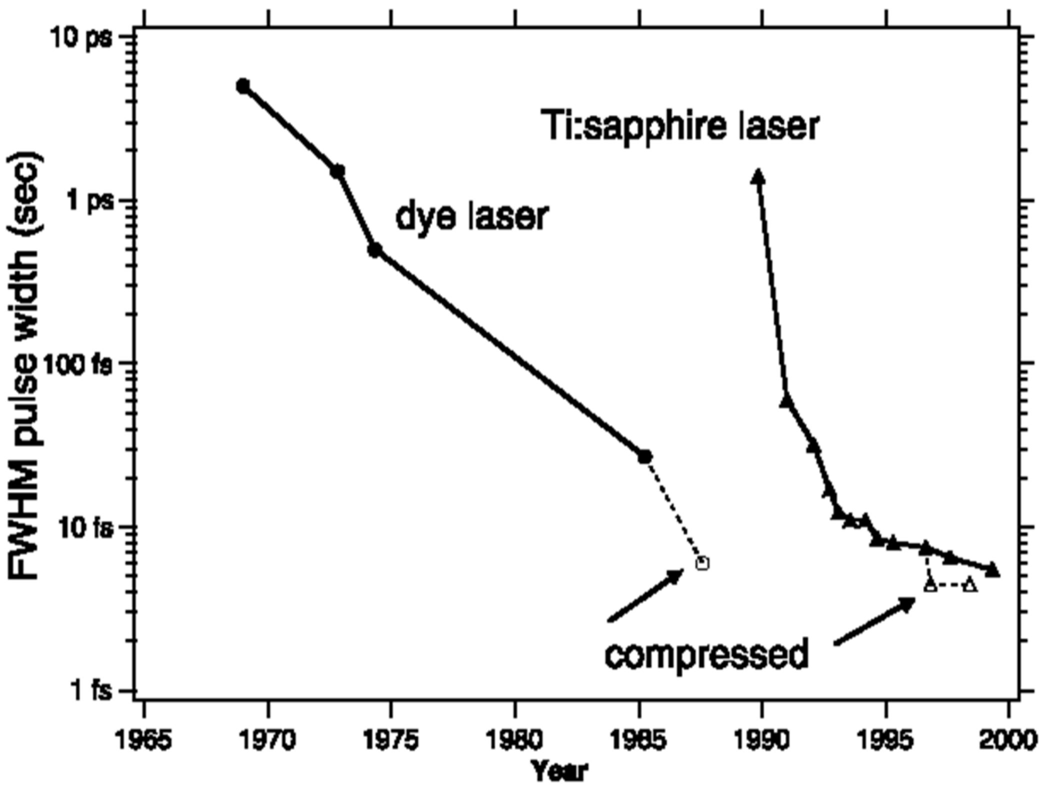

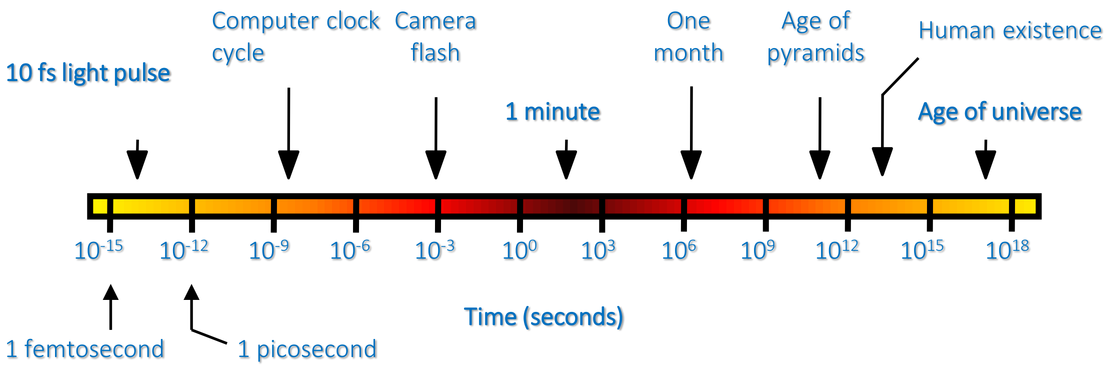

Ultrafast laser pulses: the light synthesizer!

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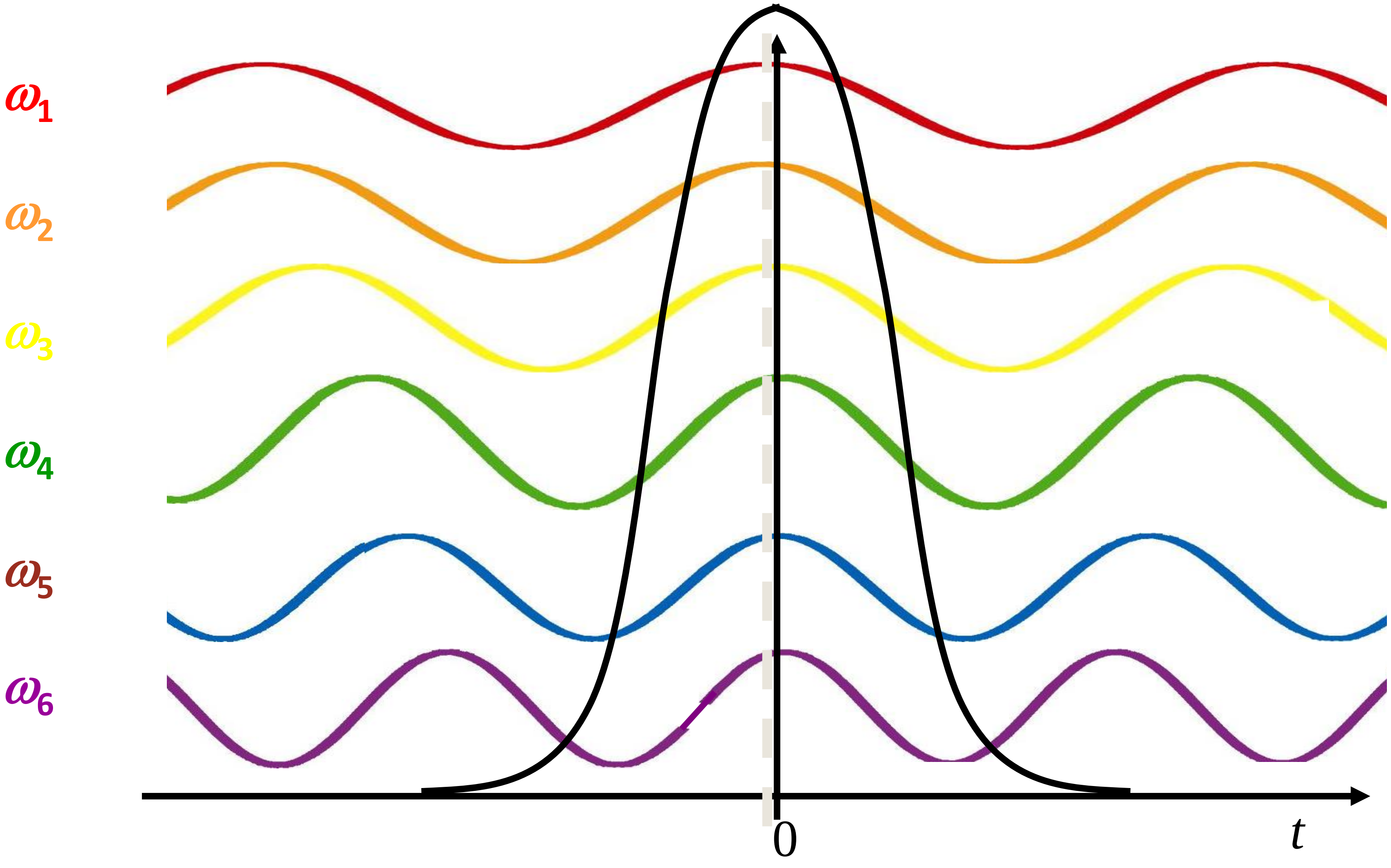
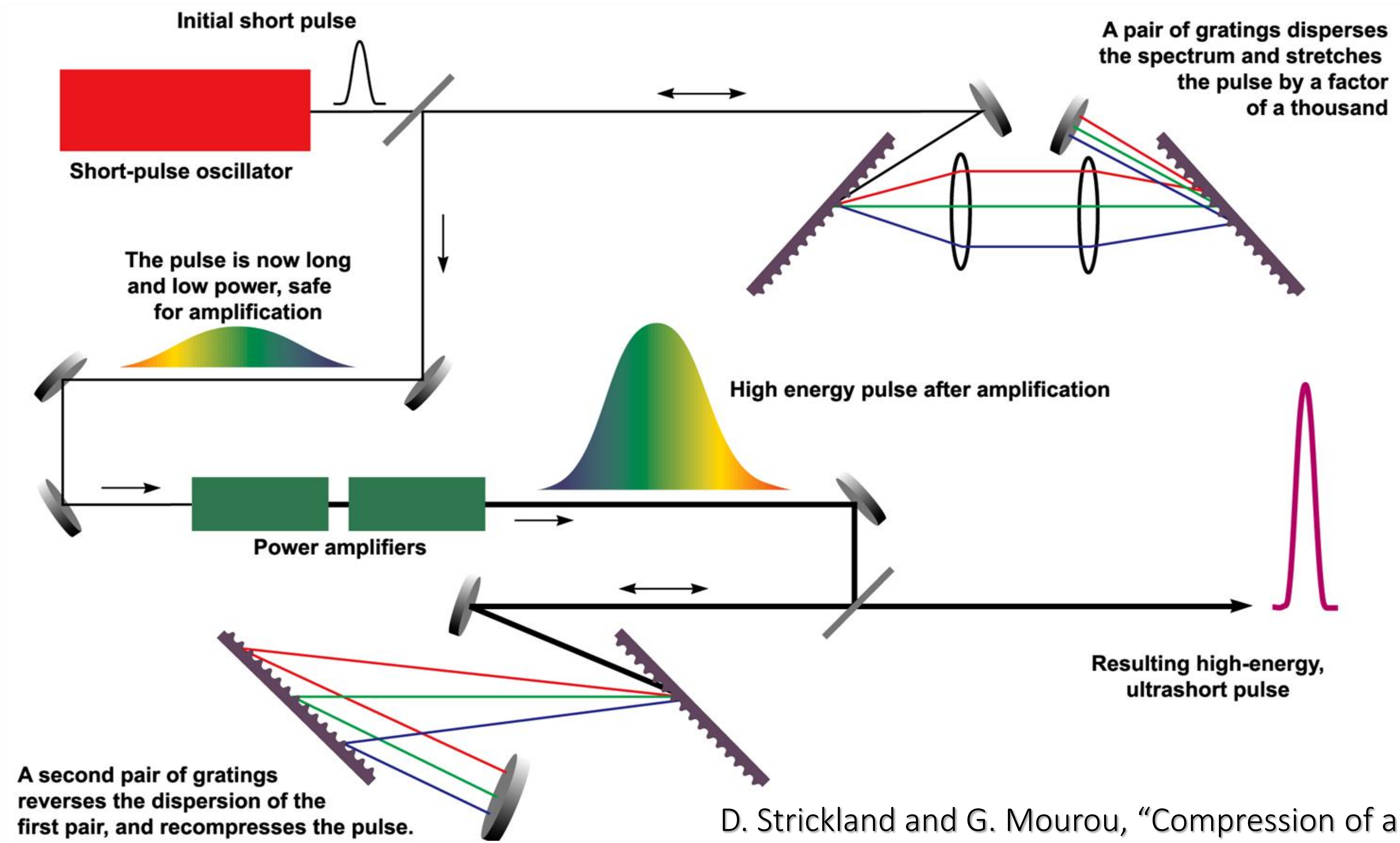
Light -Synthesizer



Ultra-Intense LASERs – The CPA scheme



D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses", Opt. Commun. 56, 219 (1985)

~50 TW LASER at CPPL / Crete

The highest intensity in Greece

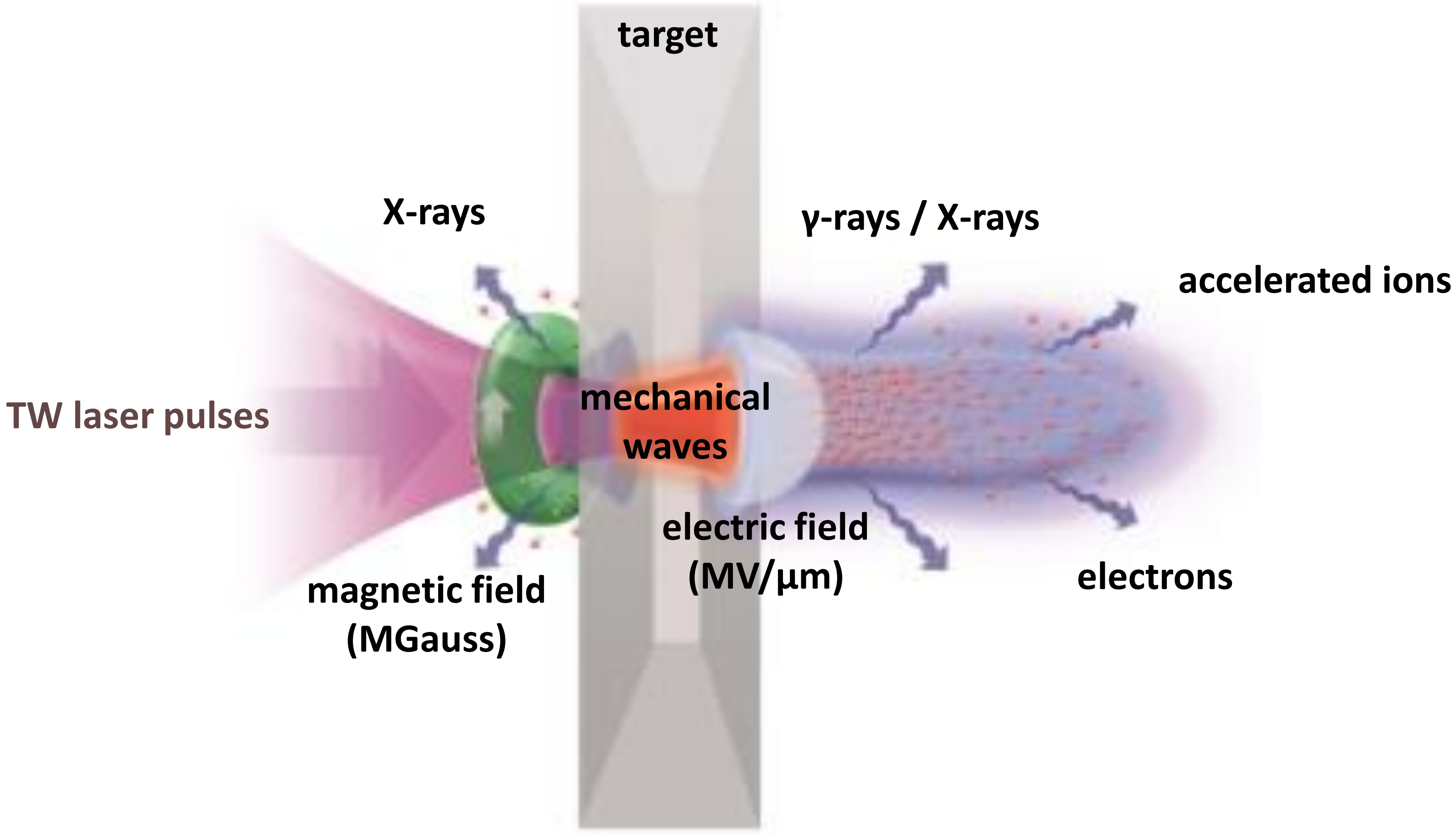
- Peak Power~10^{14} W (×10 000 the power of a fusion plant)

- Peak Intensity ~10^{20} W/cm2 (for comparison Sun light intensity in earth ~0.1 W/cm2)

- Electric Field (RMS ~10^{13} V/m (50× Coulomb field in hydrogen)

- Acceleration gain of a single electron ~10^{23} g (close to that in a black hole!)

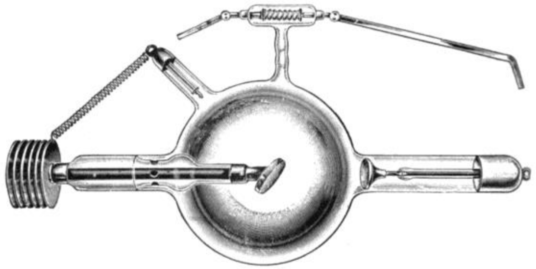
Ultra-Intense laser secondary sources



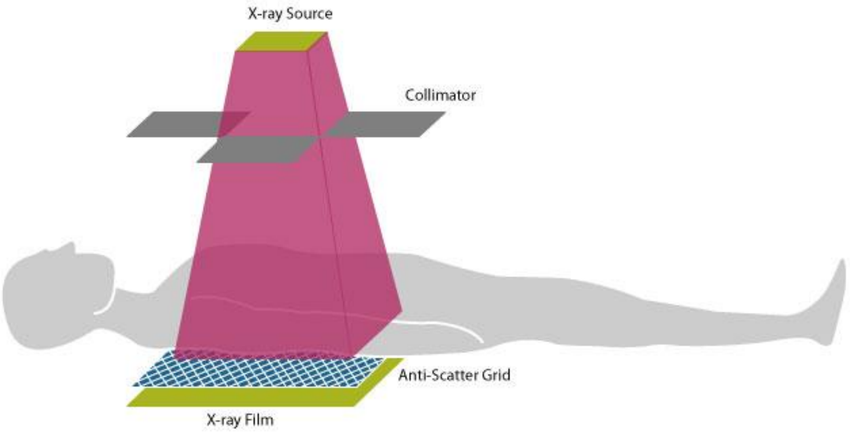
Ultrafast & Coherent X-rays

Evolution of X-ray imaging

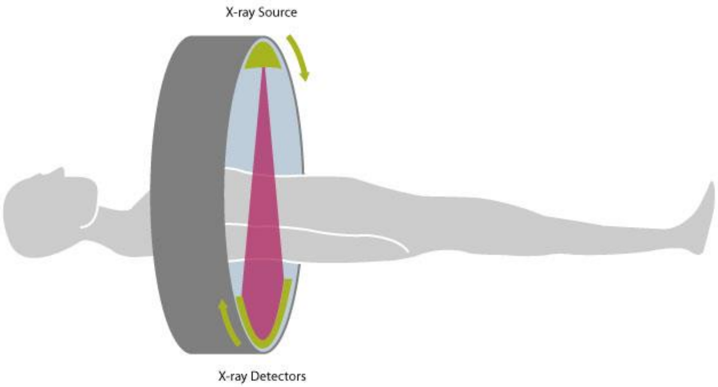
Wilhelm Röntgen

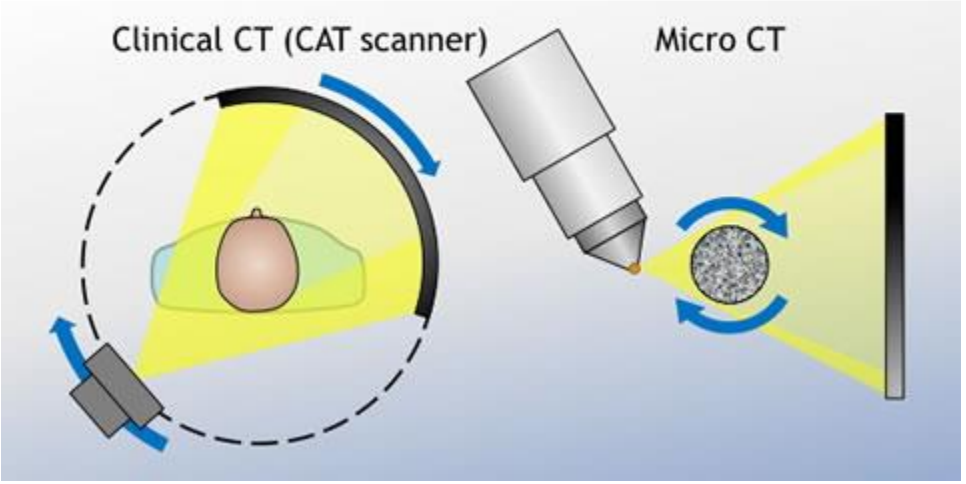


Radiography



Computed Tomography (CT)





The goal

Build a cost-effective and reasonably sized X-ray laser that could provide ultra high-resolution imaging:

▷Generate a ultrashort laser-like beam that contains a broad range of X-ray wavelengths coherently summed all at once focused both in time and space

▷This source of coherent light spans a huge region of the electromagnetic spectrum be able to make the highest resolution light-based tabletop microscope in existence that could capture high resolution images in 3-D

The goal practically

- The X-rays in the hospital now are limited. They can't detect really sub-mm cancers because the X-ray source in your doctor's office is more like a light bulb than a laser.

The goal practically is:

- **To improve X-ray imaging resolution at your doctor's practice by a thousand times.**

Needs/Solutions in X-ray Imaging

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Needs in X-ray imaging

▷Increase of resolution→ real 3D imaging with sub-mm resolution

▷ Increase the photon flux in table-top systems

▷ Decrease the radiation dose

Suggested Solutions with new X-ray coherent sources:

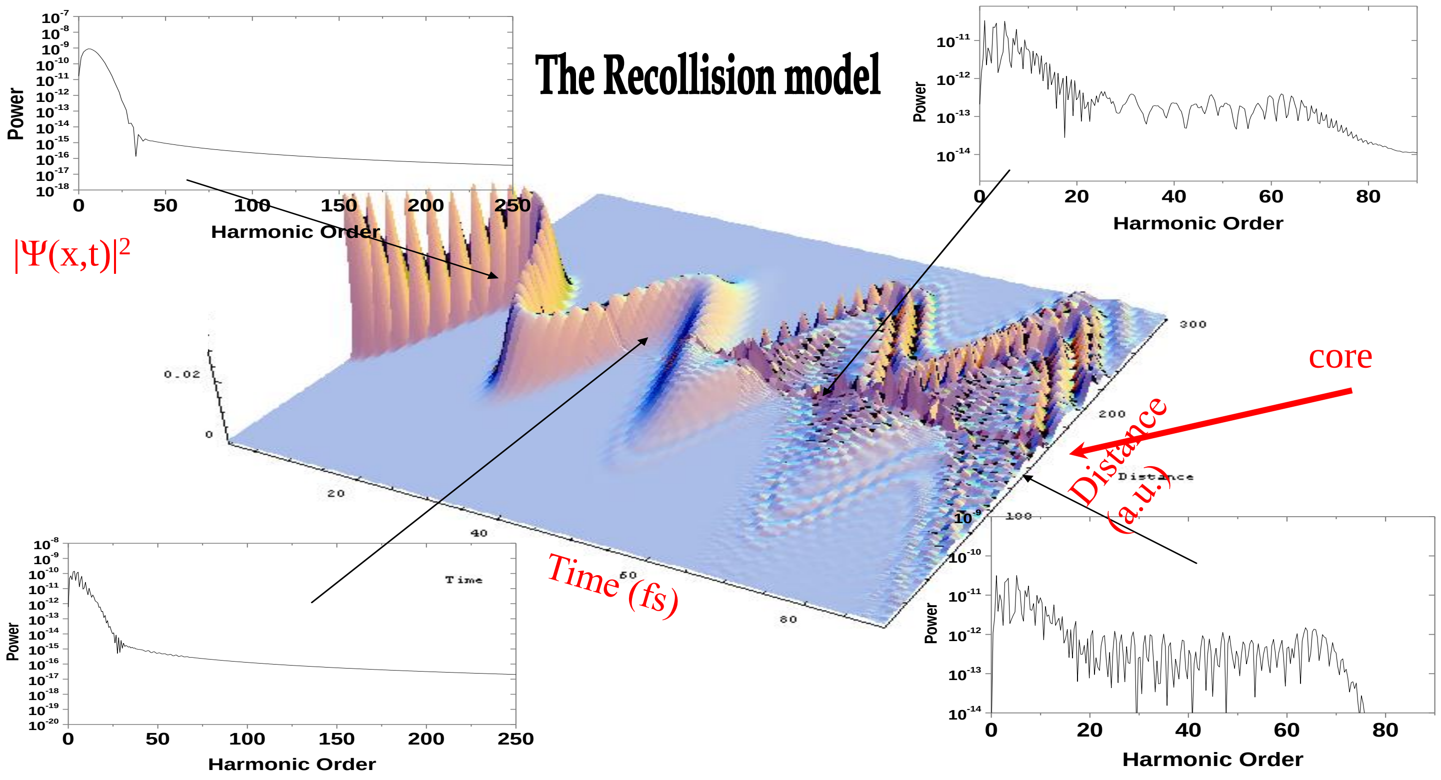
▷ Generation of coherent X-rays: High Harmonic Generation (HHG) from ultrafast and ultra-Intense laser systems or X-ray point sources (X-pinch devices).

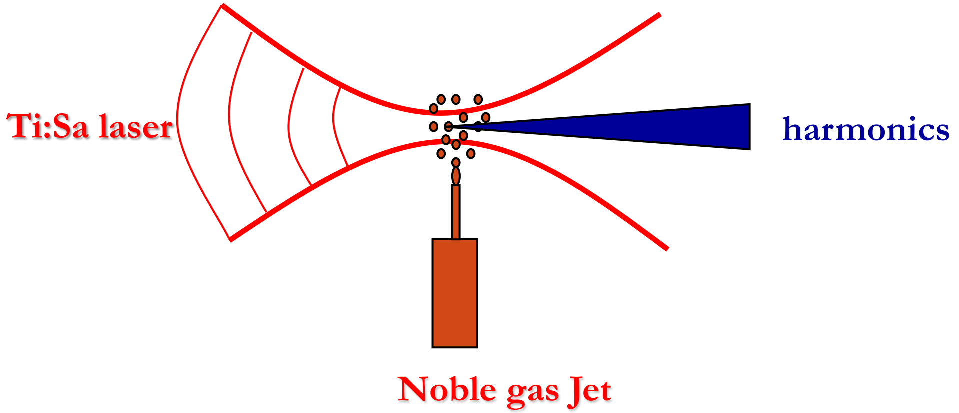
▷ Betatron type coherent light source from ultra-Intense laser accelerated relativistic electrons.

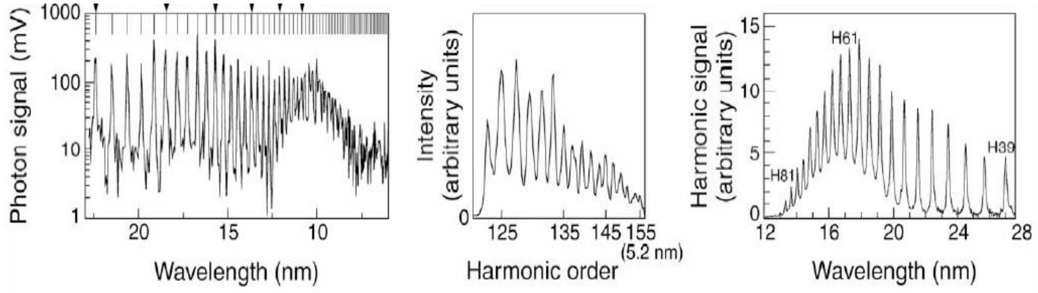
Semi-classical theory for Laser HHG

$$-\frac{\partial^2\Psi(x,t)}{2\partial x^2}+V(x)\Psi(x,t)+xE(t)\Psi(x,t)=i\frac{\partial\Psi(x,t)}{\partial t},\qquad V(x)=\frac{-1}{\sqrt{1+x^2}}$$

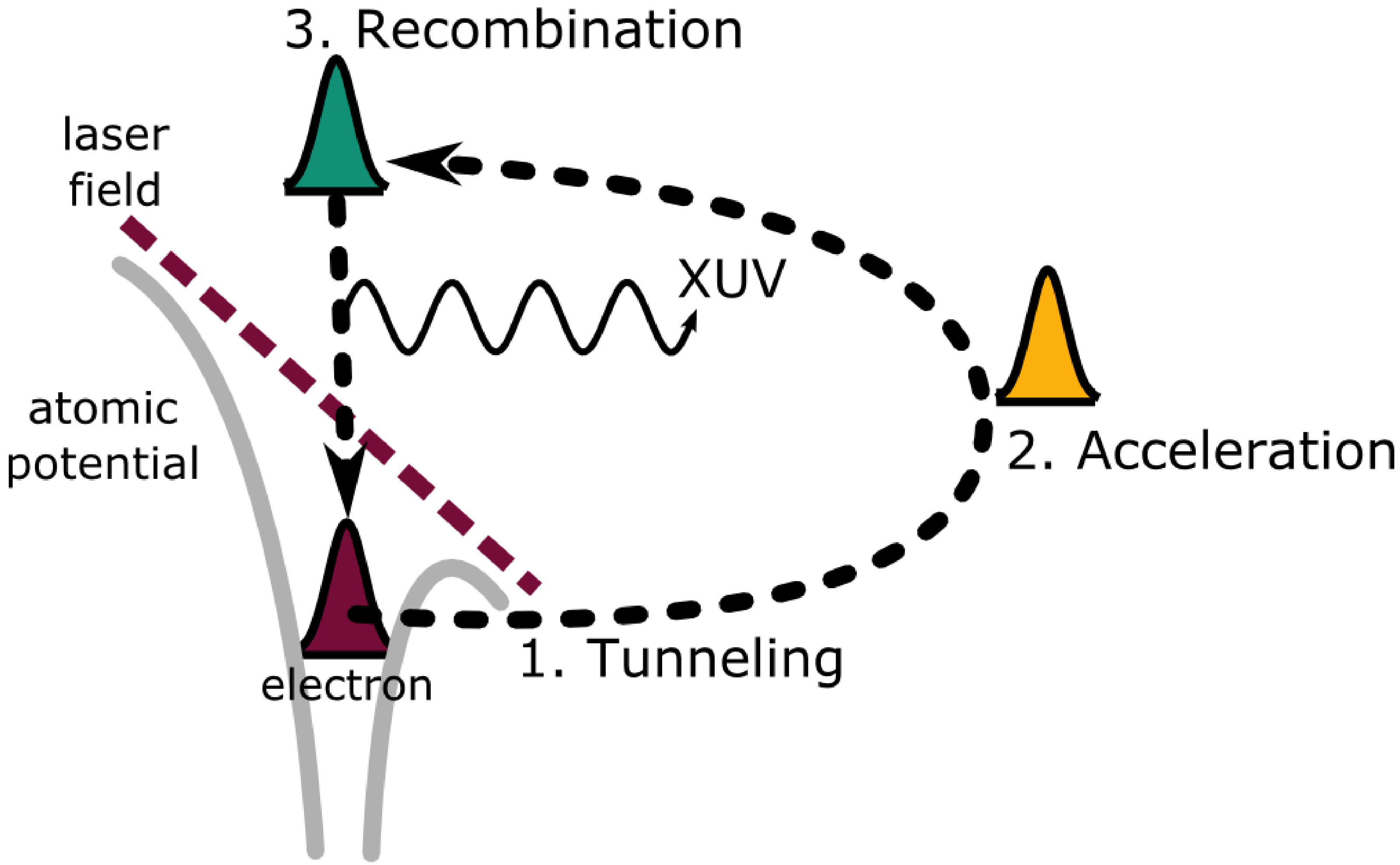
Soft Potential



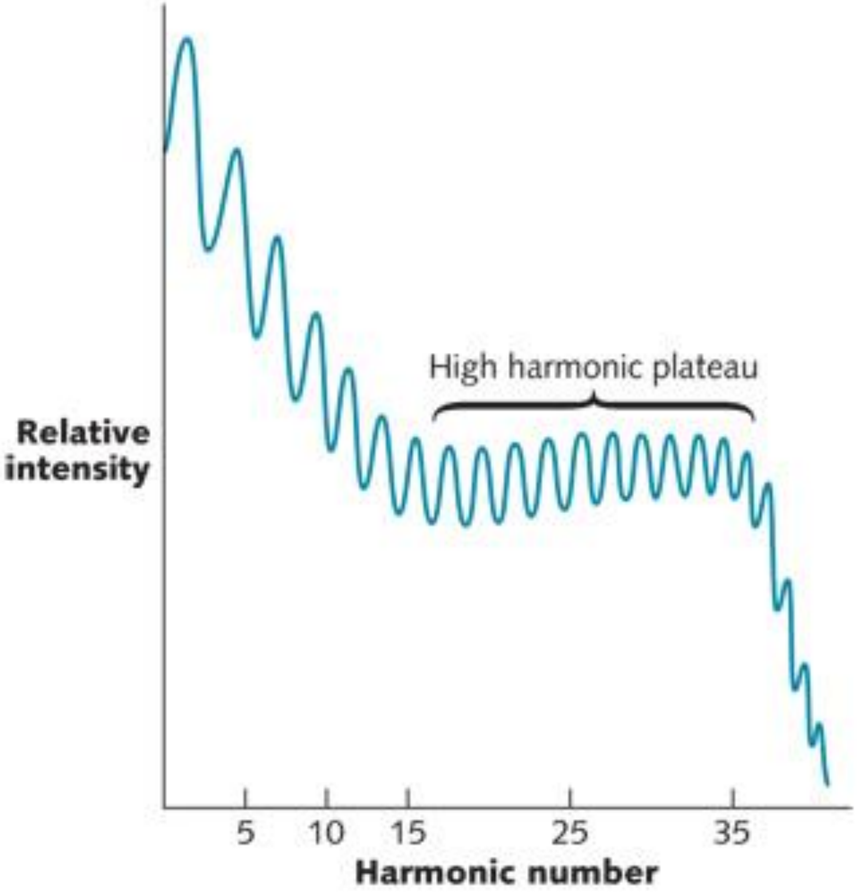




The re-scattering Model

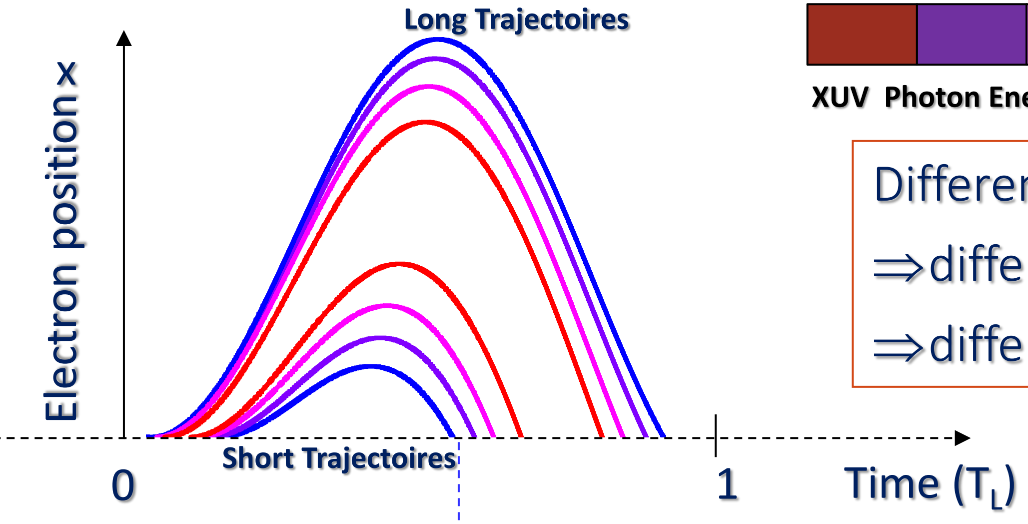


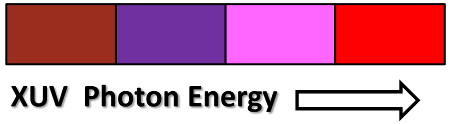
$$E_{cutoff} \approx I_P + 3.17\,U_p$$



The electron recombination physics

(Image taken from Benoît MAHIEU,CEA)





$x(t_i)=0$

$v(t_i)=0$

Different harmonic orders

$\Rightarrow$different trajectories

$\Rightarrow$different emission times t_e

Mairesse *et al.* Science 302, 1540 (2003)

Kazamias and Balcou, PRA 69, 063416 (2004)

$$F = m_e \frac{dv}{dt} = eE_0 \sin(\omega t) \Rightarrow$$

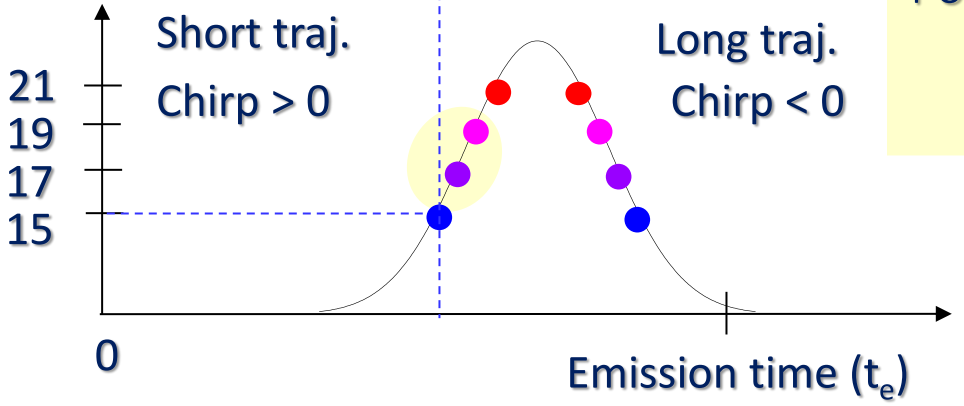
$$v = \int_{t_0}^{t} \frac{eE_0}{m_e} \sin(\omega t) dt =$$

$$= \frac{eE_0}{\omega m_e} \left[\cos(\omega t_0) - \cos(\omega t) \right]$$

$$= v_{drift} - \frac{eE_0}{\omega m_e} \cos(\omega t)$$

$$x = \int_{t_0}^{t} \frac{eE_0}{\omega m_e} \left[\cos(\omega t_0) - \cos(\omega t) \right] dt =$$

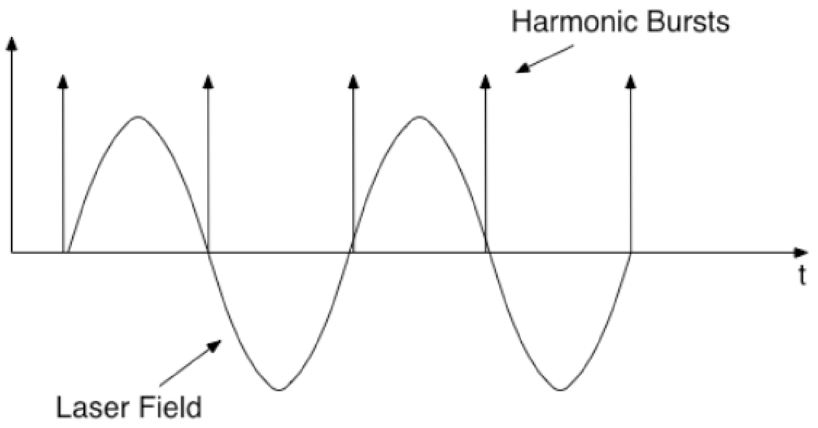
$$= \frac{eE_0}{\omega^2 m_e} \left[\sin \omega t_0 - \sin \omega t + (t - t_0) \omega \cos \omega t_0 \right]$$



Positive chirp of output LASER beam on attosecond timescale: the atto-chirp

Only odd harmonics

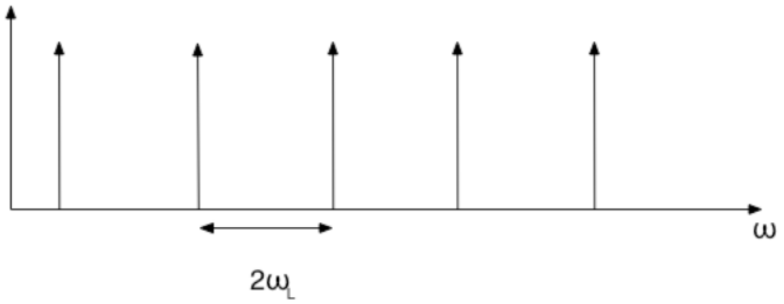
Harmonics are produced twice per laser cycle:



$$I_{harm}(t) = Ce^{+i\omega t}\sum_{n}\delta\left(t - n\frac{T_L}{2}\right)$$

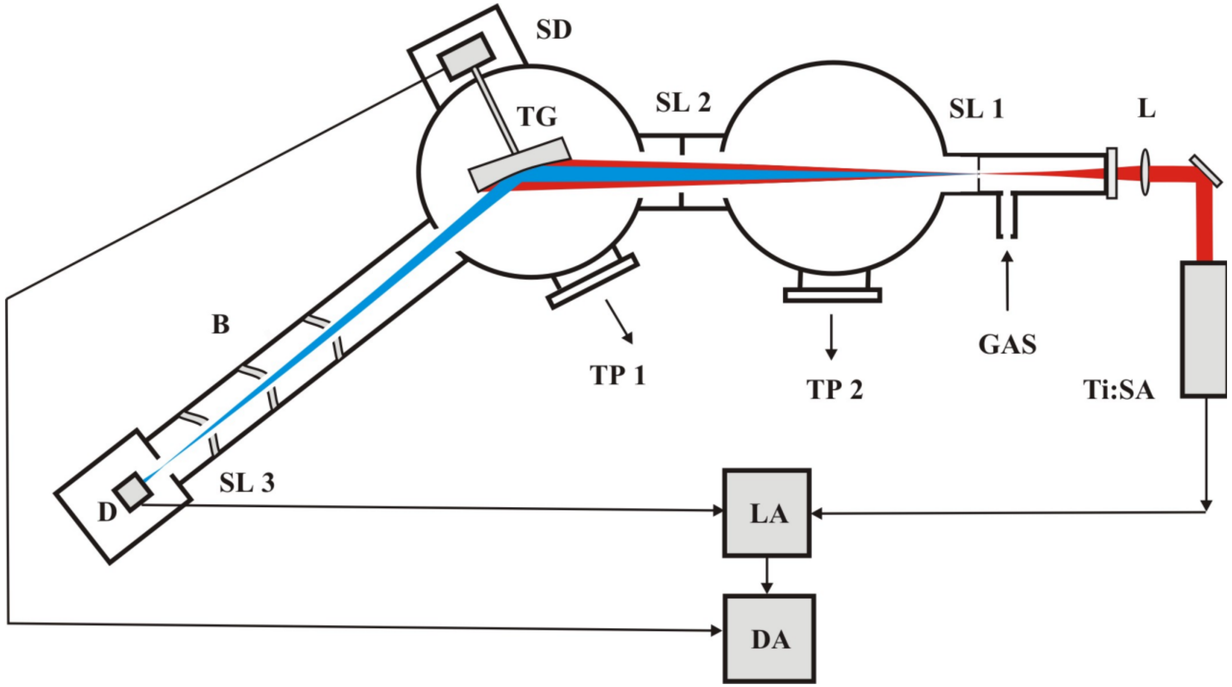
Fourier Transform of “spark” train is given by a comb in freqency space:

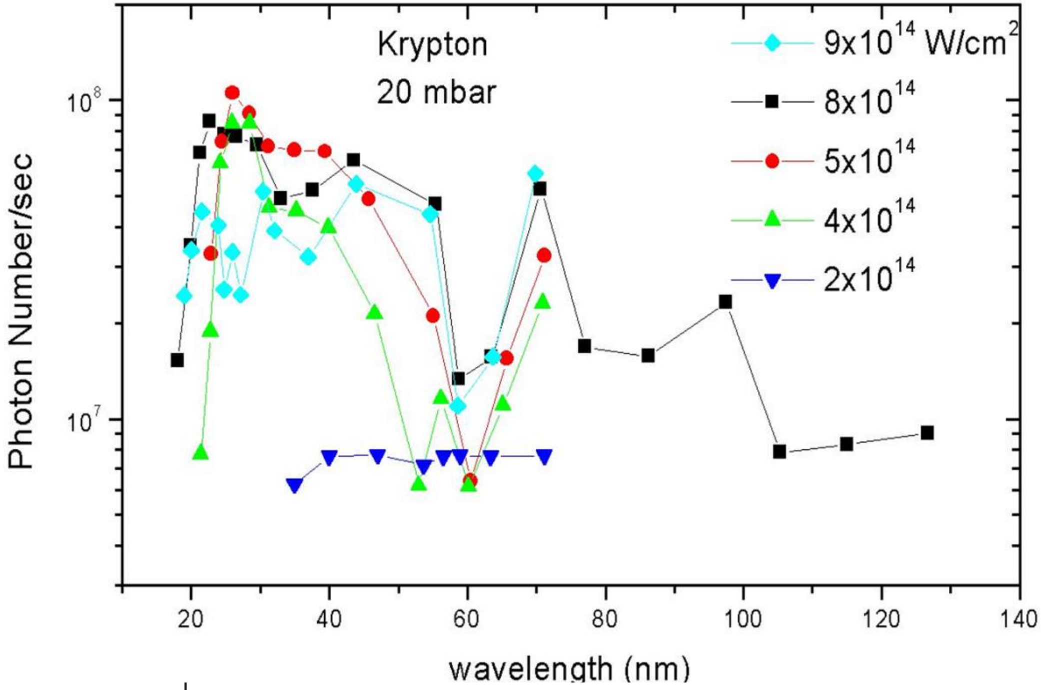
$$I_{harm}(\omega) = 2\frac{\sqrt{2\pi}}{T_L}C\sum_{n}\delta\left(\omega - \left[(2n)\frac{2\pi}{T_L} + \omega_L\right]\right)$$

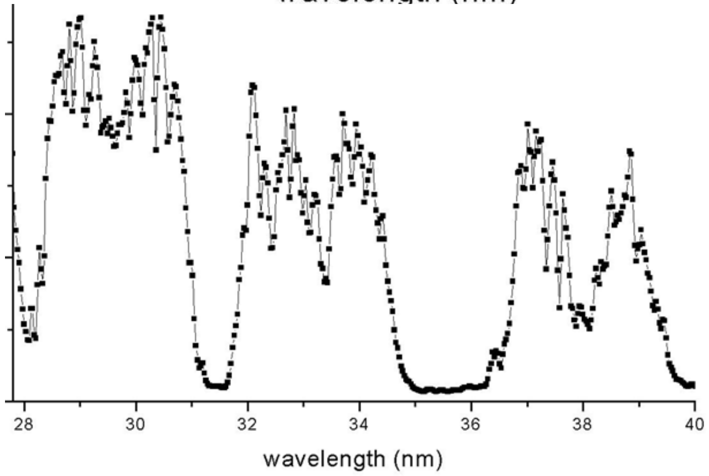


Since a gas is centrosymmetric (inversion symmetry!) any induced polarization of the gas must be an odd function of the Electric field →only odd harmonics!

Example of table-top KHz XUV Source







N. A. Papadogiannis et. al., Applied Physics B 73, 687 (2001)

Attosecond duration of HH

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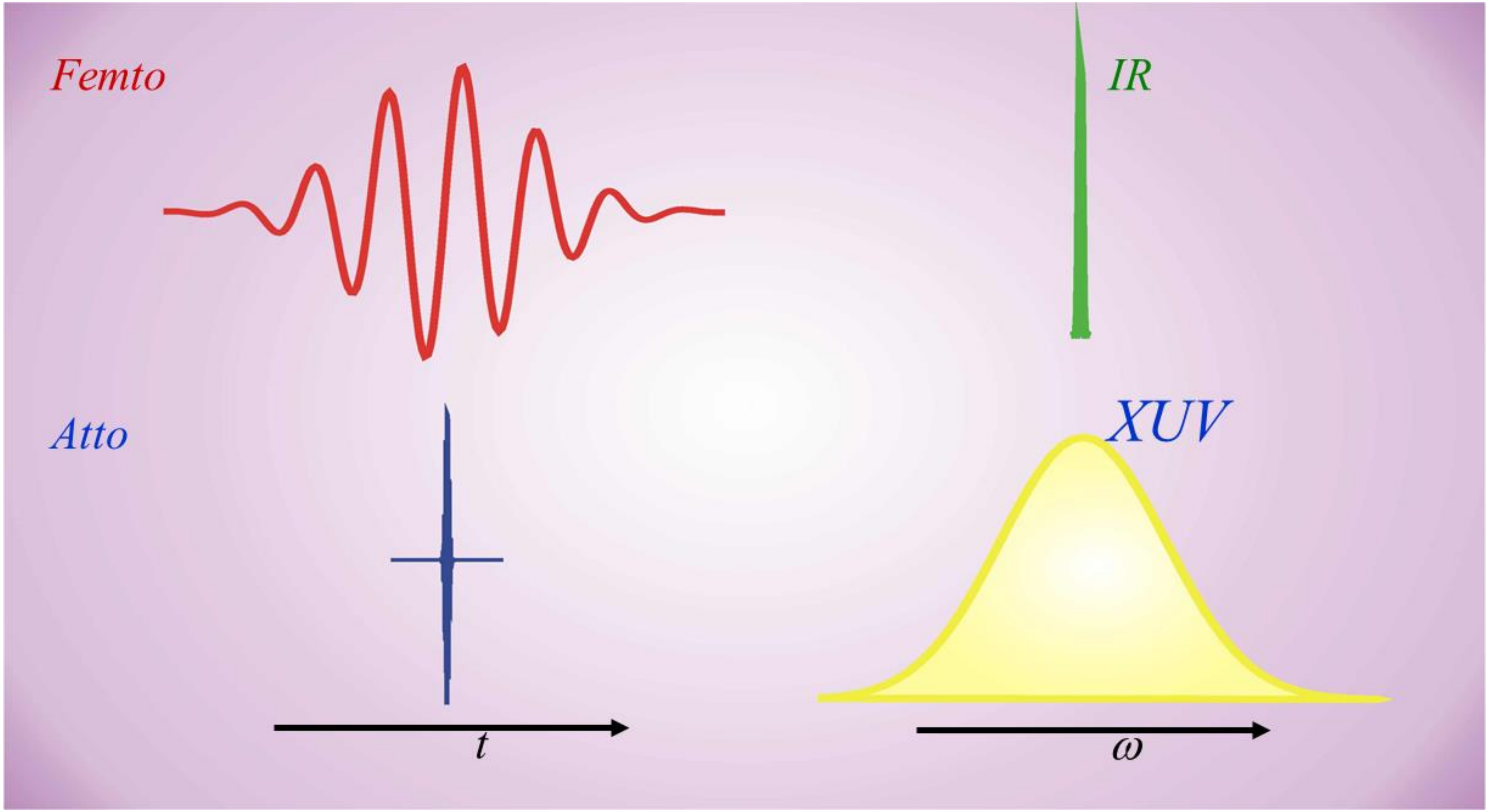
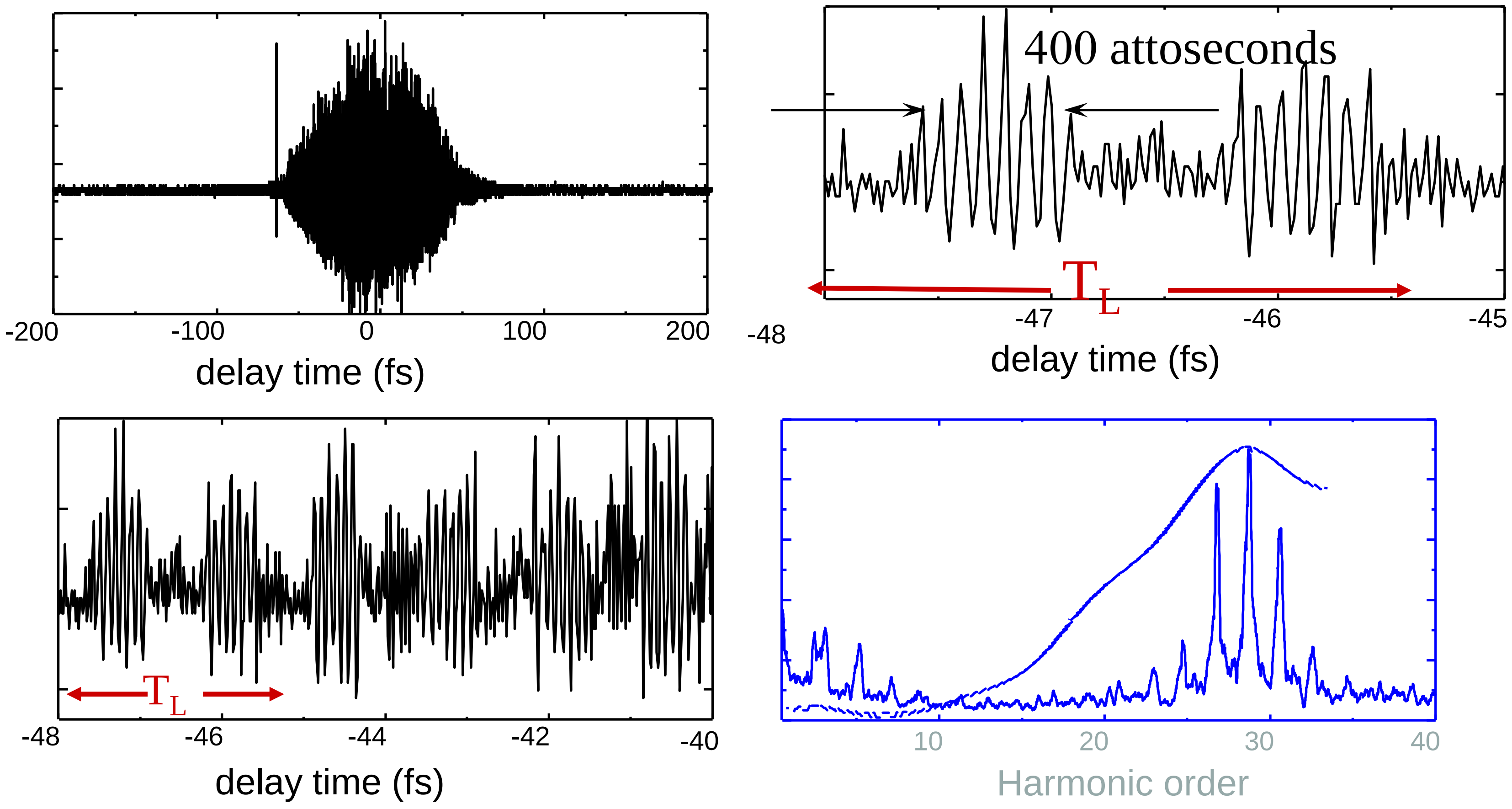


The first proof for atto pulses



N. A. Papadogiannis. *et al*. Physical Review Letters **83**, 4289 (1999)

The publicity

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Laser physics

Attosecond pulses at last

Paul Corkum

For the past five years, scientists have stood on the threshold of generating attosecond laser pulses but have been unable to cross it. (An attosecond — 10^{-18} s — is to one second as one second is to the age of the Universe.) This may have finally changed with the publication of a paper by Papadogiannis *et al.* (*Phys. Rev. Lett.* **83**, 4289–4292; 1999), who claim to have measured trains of attosecond pulses. The previous record for the shortest laser pulse was 4.5×10^{-15} s (4.5 femtoseconds). Pulses in the femtosecond range led to the development of femtochemistry — making it possible to study chemical reactions in real time — for which the 1999 Nobel Prize in Chemistry was awarded to Ahmed Zewail. But the new science that will ultimately emerge from attosecond research will have its own unique drive.

The approach that Papadogiannis *et al.* use for generating attosecond pulses has been under investigation for some time. They use the short-wavelength harmonics generated when rare gases (such as argon) ionize as a result of irradiation from an intense femtosecond pulse. Harmonics occur at multiples of the frequency of the original femtosecond pulse. Next, the authors select a set of these harmonics, which theory indicates should combine to produce a train of pulses about 100 attoseconds in duration (Fig. 1). Such pulses have probably already been created in many laboratories, but no one has been able to measure them accurately.

Papadogiannis *et al.* may eventually be recognized as the parents of experimental attosecond science because they have actually measured the duration of these pulses. Their measurement process is experimentally simple, but theoretically complex. This is because the production of the attosecond pulses is intrinsically entwined with the measurement. They use a technique influenced by autocorrelation, which is widely used for measuring femtosecond pulses and is a close cousin of the pump–probe technique used in femtochemistry.

For autocorrelation measurements, a femtosecond pulse is split into two at a beam splitter. (A beam-splitter functions like a window at night. In a lighted room you can see your reflection in the window while simultaneously being able to see outside.) The two beams are sent through different paths, and usually recombine within a crystal with nonlinear optical properties. Because the harmonic light produced by the nonlinear crystal is stronger when the two pulses are overlapped, observing the signal strength as a function of the difference in the path length of the two beams gives a measurement of the pulse's duration.

Unfortunately, the short duration and wavelength of attosecond pulses means that neither traditional beam splitters nor nonlinear crystals are suitable. Papadogiannis *et al.*

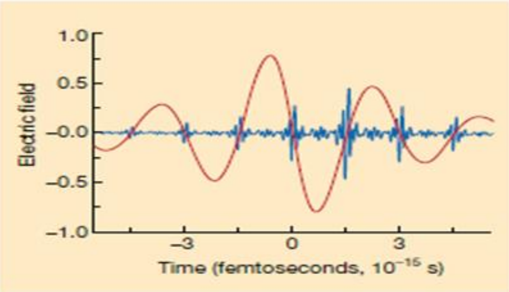

Figure 1 **Train of attosecond pulses similar to that produced by Papadogiannis *et al.* Here, the initial femtosecond pulse (red) is much shorter than the one that they used, and the higher-frequency harmonic radiation (blue) is much more intense than in their experiment. The offset between the peak of the initial pulse and of the harmonic radiation illustrates the delay in the harmonic emission imposed by the laser field oscillation.**

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Physics News Update
The American Institute of Physics Bulletin of Physics News

Number 471 (Story #4), February 17, 2000 by Phillip F. Schewe and Ben Stein

ATTOSECOND LIGHT PULSES. A curtailed wave pulse can be represented mathematically as the weighted sum of a number of wavetrains of various wavelengths. In this way, scientists at the Foundation for Research and Technology-Hellas (FORTH) in Crete have created light pulses less than a femtosecond (10^{-15} seconds) in duration (Papadogiannis et al., *Physical Review Letters*, 22 November 1999). First they split a beam of light (wavelength of 800 nm) into two parts; each of these, when sent through an argon vapor, produces sets of higher-harmonic wavetrains (at wavelengths equal to several fractions of the original 800 nm) which add together in a synchronized way to form the ultrashort wave pulse with a duration estimated to be less than 100 attoseconds. Before this the record short pulse was 4.5 fs in duration. (*Physics World*, Feb 2000.)

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Phys. Rev. Lett. **83** 4289

PhysicsWorld

Physics in Action: February 2000

Back to Volume 13 Issue 2 — Article 5 of 9

Experimental attosecond science makes its debut

For the first few decades after the invention of the laser in 1960, the record for the shortest laser pulse fell by a factor of two every three years or so. Each development provided new insights into the microworld of atoms, molecules and solids. In 1986, however, this trend essentially stopped when the pulse length reached 6 femtoseconds (6×10^{-15} seconds). For visible light this corresponds to just three oscillations of the electromagnetic field in the laser.

Since the mid-1980s there have been many advances in laser science, but the minimum pulse duration has decreased only slightly. To significantly break the current record - a 4.5 femtosecond pulse from a laser with a wavelength of 800 nanometres - a completely different approach is needed. Physicists at the Foundation for Research and Technology-Hellas (FORTH) on Crete have recently demonstrated one such approach (N Papadogiannis *et al.* 1999 *Phys. Rev. Lett.* **83** 4289).

The non-linear optics in soft X-rays

VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Two-Photon Ionization of He through a Superposition of Higher Harmonics

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G. D. Tsakiris, P. Tzallas, and K. Witte
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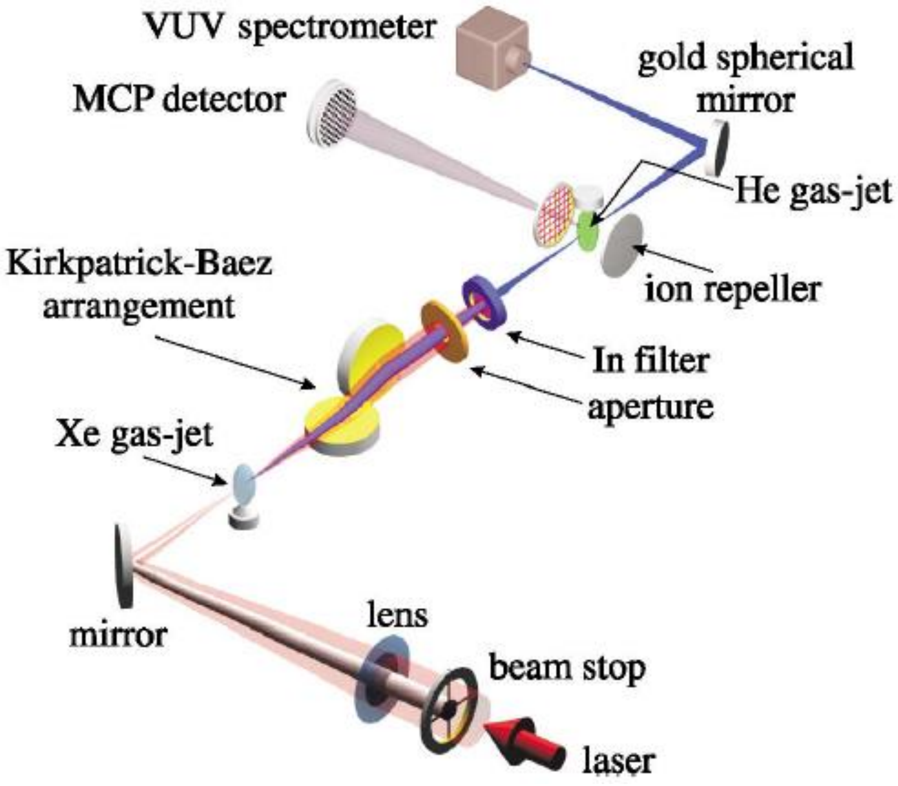
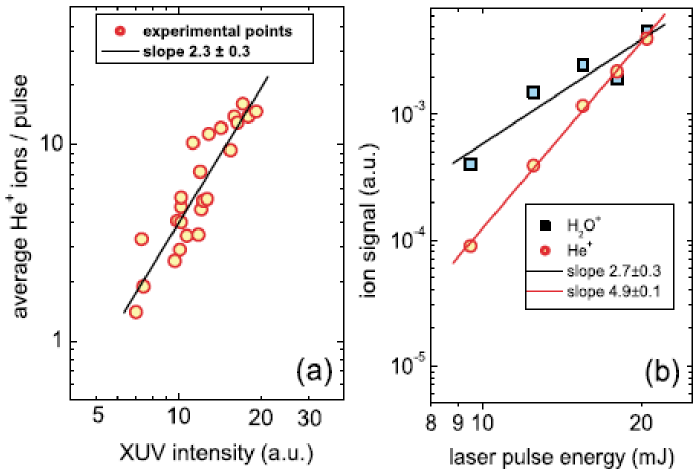
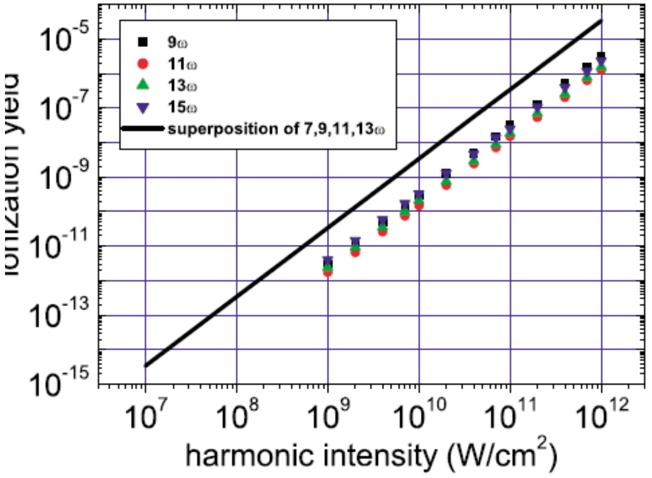
(Received 3 July 2002; published 4 April 2003)

We present experimental results and theoretical analysis of two-photon ionization of He by a superposition of the 7th to the 13th harmonic of a Ti:sapphire laser. Solving the time-dependent Schrödinger equation for He in a coherent polychromatic field, the He^+ yield is calculated. From this yield the number of He^+ ions produced has been estimated and found in reasonable agreement with its measured value. The present results establish the feasibility of a second-order autocorrelation measurement of superposition of harmonics, and thus they represent the precursor towards the direct temporal characterization of attosecond pulse trains.







- The non-linear optics in XUV opens the road of HH pulse duration measurements

The direct measurement of HH duration

Centre for Plasma Physics and Lasers

Direct observation of attosecond light bunching

NATURE | VOL 426 | 20 NOVEMBER 2003 |

P. Tzallas[1], D. Charalambidis[2], N. A. Papadogiannis[2], K. Witte[1] & G. D. Tsakiris[1]

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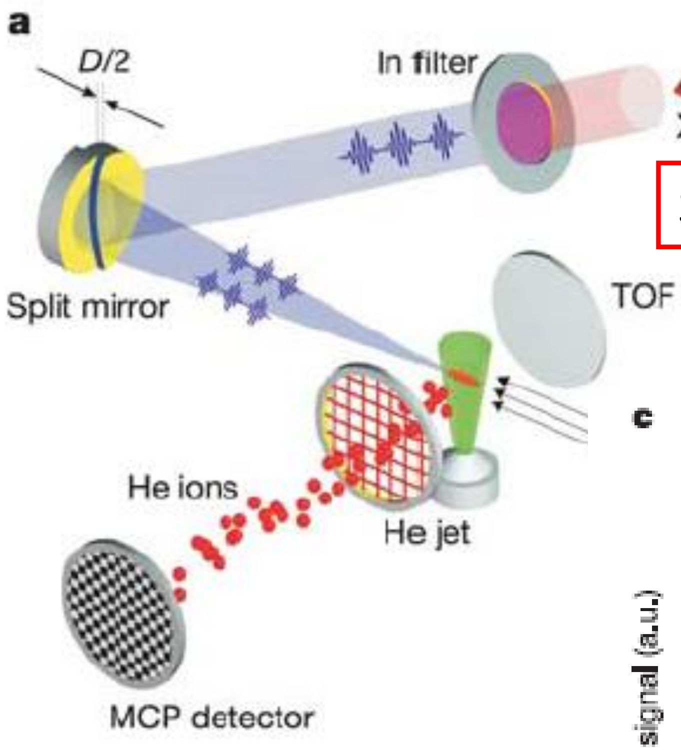
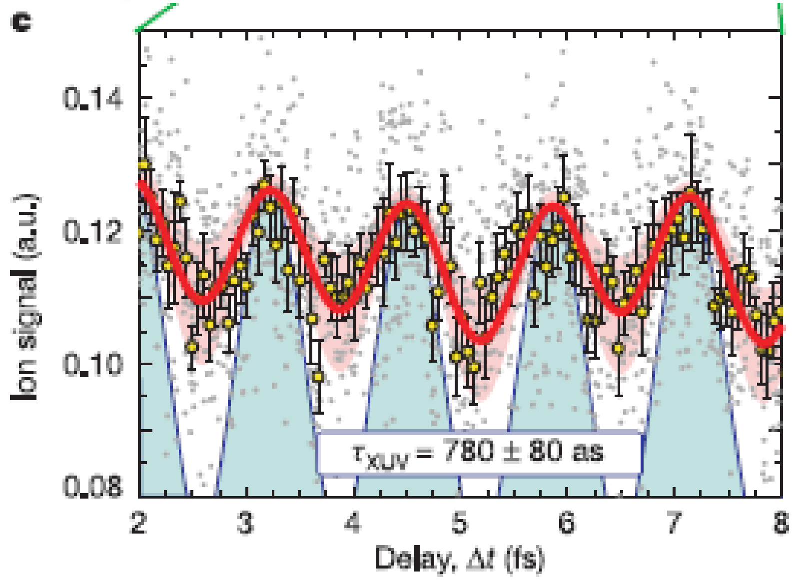
Temporal probing of a number of fundamental dynamical processes requires intense pulses at femtosecond or even attosecond (1 as = 10^{-18} s) timescales. A frequency 'comb' of extreme-ultraviolet odd harmonics can easily be generated in the interaction of subpicosecond laser pulses with rare gases: if the spectral components within this comb possess an appropriate phase relationship to one another, their Fourier synthesis results in an attosecond pulse train[1,2]. Laser pulses spanning many optical cycles have been used for the production of such light bunching[3,4], but in the limit of few-cycle pulses the same process produces isolated attosecond bursts[5,6]. If these bursts are intense enough to induce a nonlinear process in a target system[7–9], they can be used for subfemtosecond pump–probe studies of ultrafast processes. To date, all methods for the quantitative investigation of attosecond light localization[4,6,10] and ultrafast dynamics[11] rely on modelling of the cross-correlation process between the extreme-ultraviolet pulses and the fundamental laser field used in their generation. Here we report the direct determination of the temporal characteristics of pulses in the subfemtosecond regime, by measuring the second-order autocorrelation trace of a train of attosecond pulses. The method exhibits distinct capabilities for the characterization and utilization of attosecond pulses for a host of applications in attoscience.

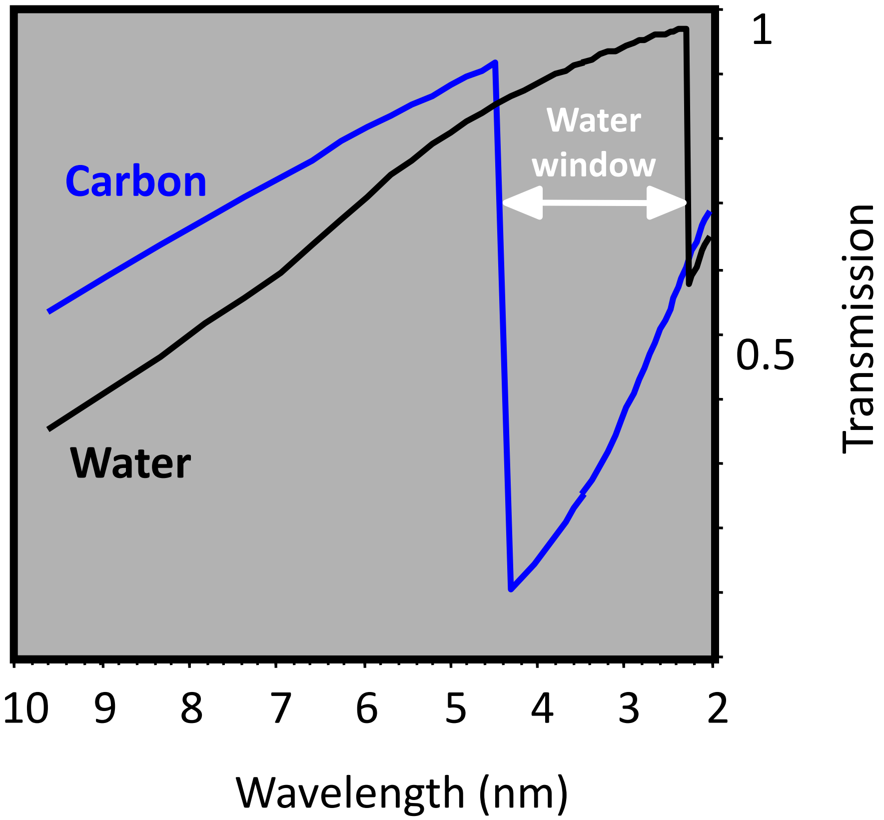


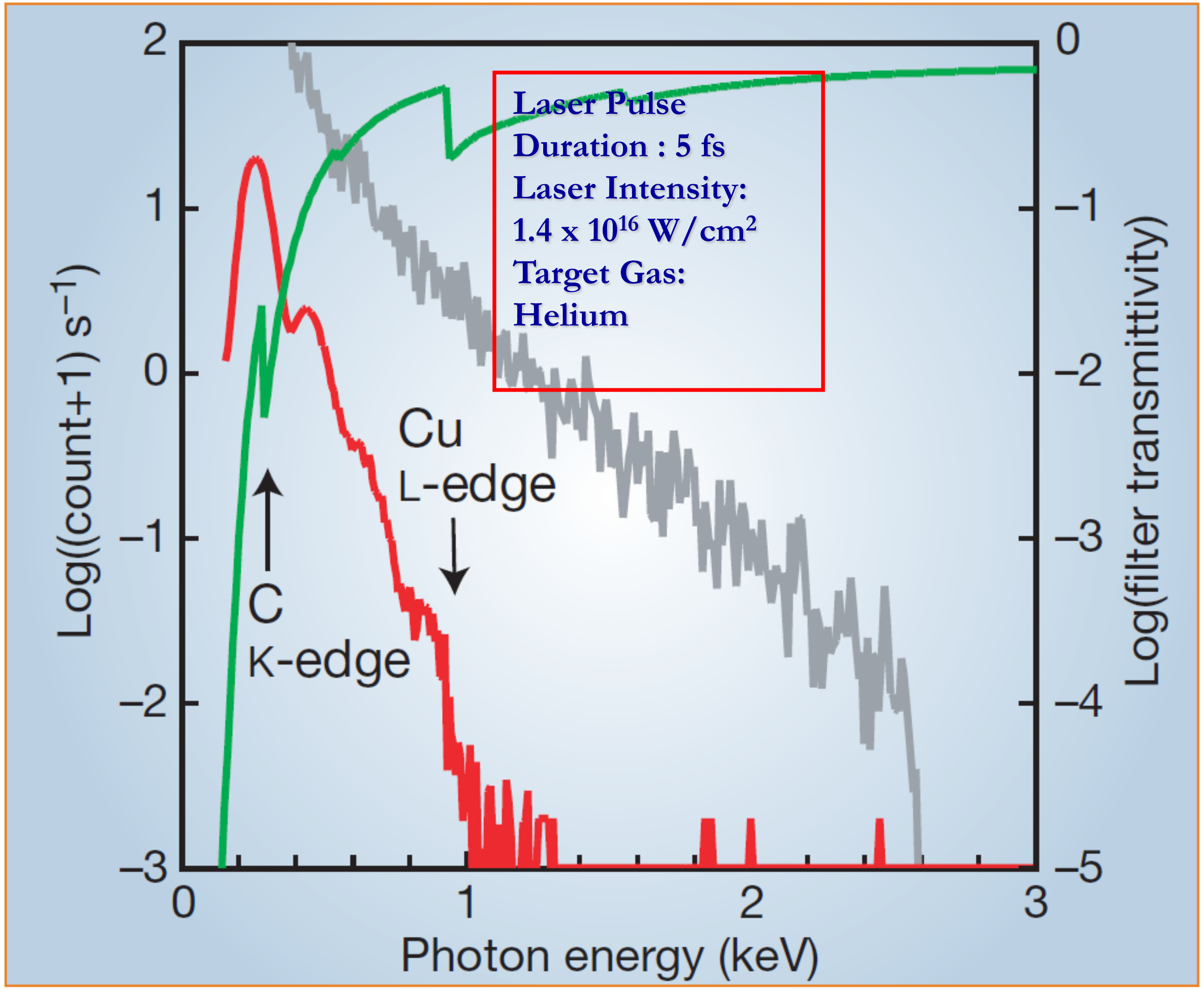
Split-Mirror Volume autocorrelator



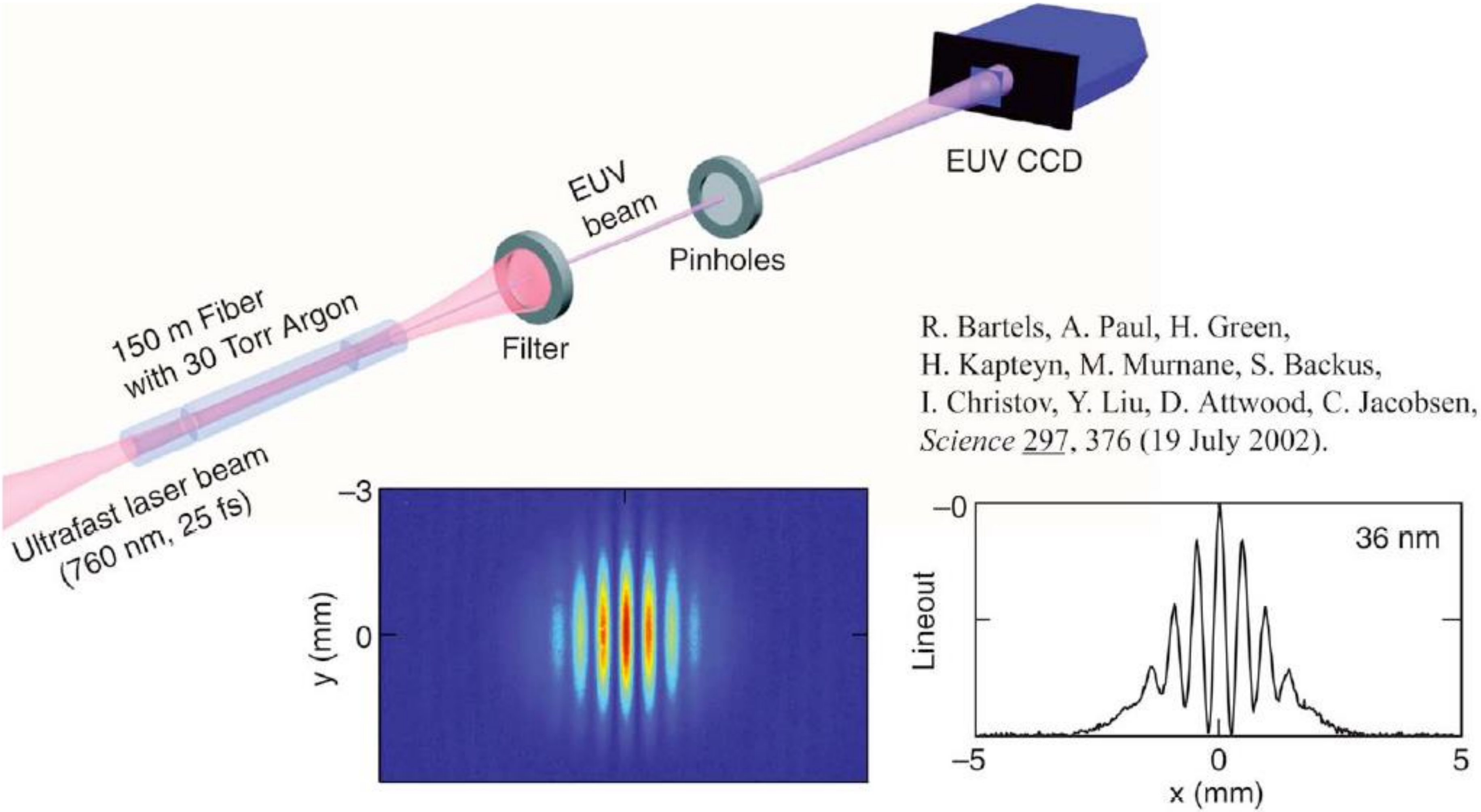
HHG in Hard X-ray Region

Serres et al, Nature 433, 596 (2005)





Coherence of HH



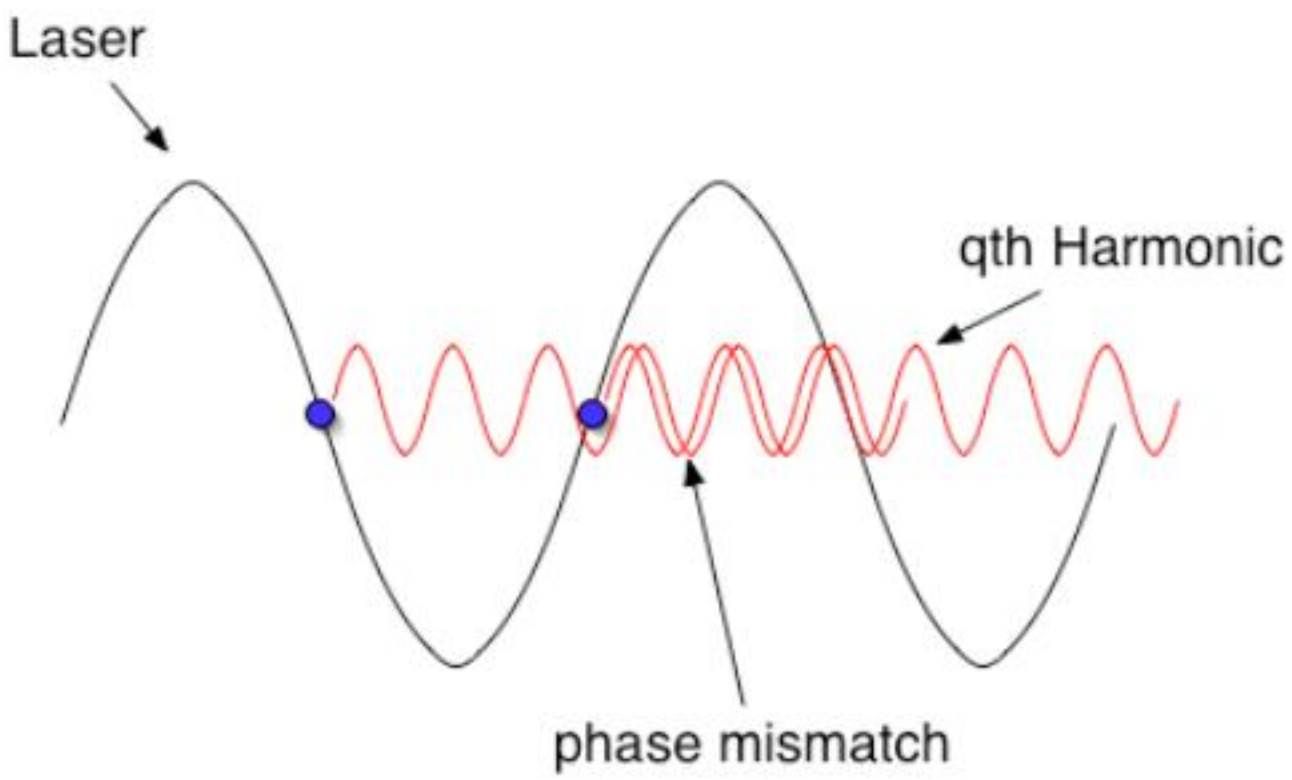
R. Bartels, A. Paul, H. Green,
H. Kapteyn, M. Murnane, S. Backus,
I. Christov, Y. Liu, D. Attwood, C. Jacobsen,
Science 297, 376 (19 July 2002).

$P \simeq 10\ \mu W \rightarrow 2 \times 10^{12}$ ph/sec @ 36 nm (n = 21; 34 eV)

The phase matching problem

Centre for Plasma Physics and Lasers

Constructive interference of harmonics generated in different parts of the non-linear medium



Phase matching condition

k_0= laser wavenumber

k_q= q^{th} harmonic wavenumber

$$\Delta k = qk_o - k_q = 0$$

Quasi Phase Matching in CPPL labs

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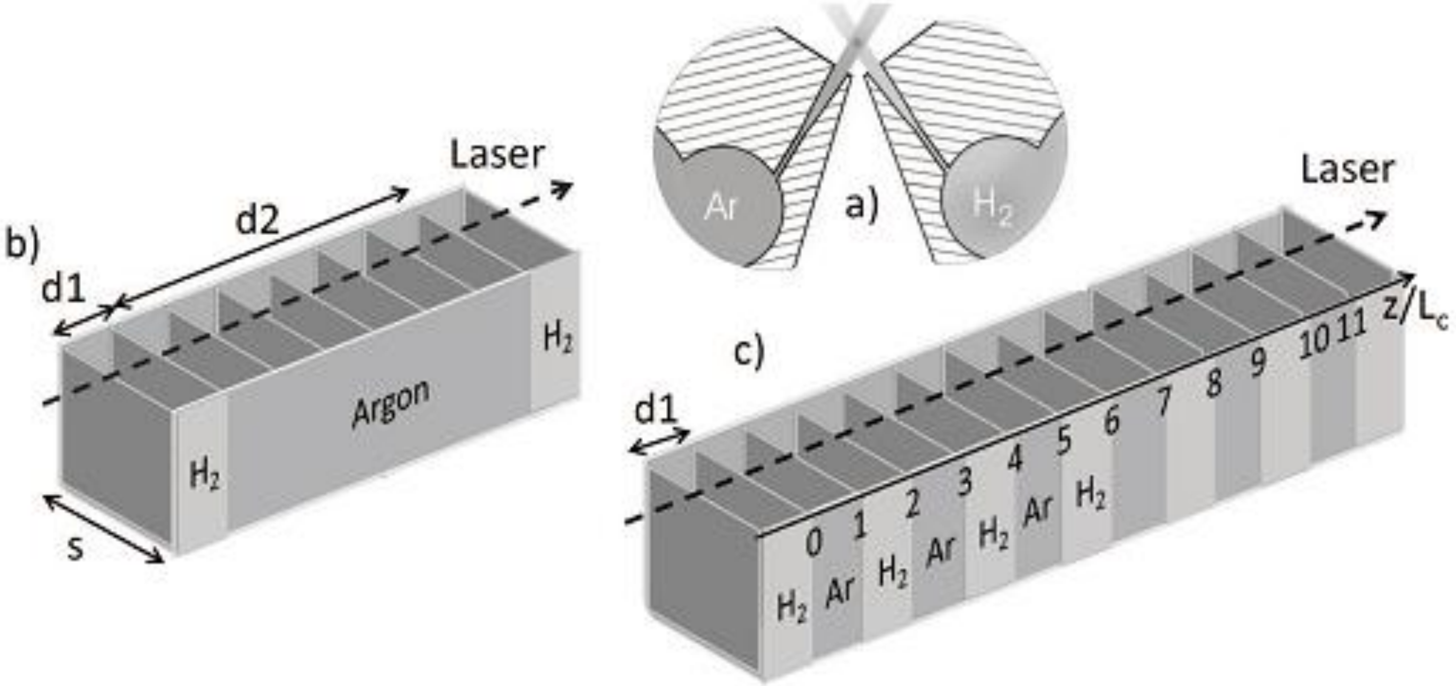
DESY, Queens Univ. Belfast, CPPL/TEI of Crete collaboration



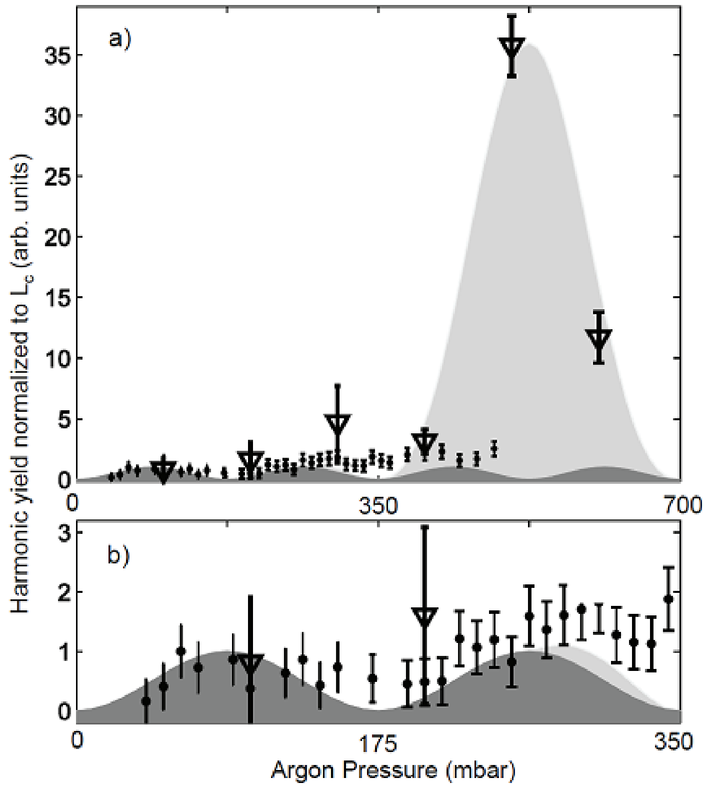
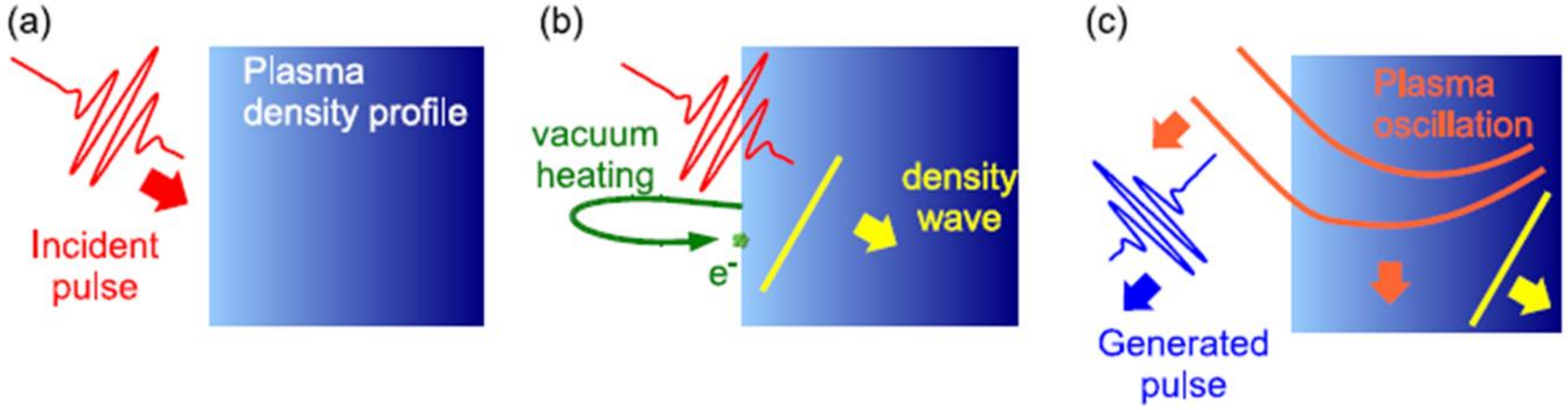


FIG. 4. a) Comparison of the angularly and spectrally integrated harmonic yield for the 27th harmonic using a 700 μm merged argon jet (circles) and a dual-gas 6-sources-jet (triangles) which has 5 hydrogen jets placed between the 6 Argon jets. For comparison the theoretical curves are included for $N_{QPM} = 1$ (dark shaded) and $N_{QPM} = 6$ (light shaded). b) Close-up of the merged-jet oscillations with increasing argon backing pressure.

A. Willner, F. Tavella, M. Yeung, T. Dzelzainis, C. Kamperidis, M. Bakarezos, D. Adams, M. Schulz, R. Riedel, M.C. Hoffmann, W. Hu, J. Rossbach, M. Drescher, V.S. Yakovlev , N.A. Papadogiannis, M. Tatarakis, B. Dromey, M. Zepf
Coherent control of high harmonic generation via dual-gas multijet arrays
Physical Review Letters 107, 175002 (2011)

Coherent wake emission harmonics

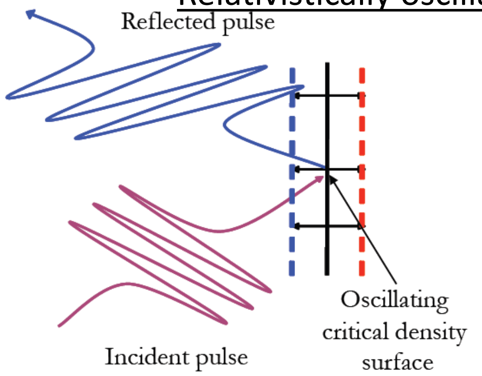


a) The pulse enters the plasma density (created by pre-pulses) under oblique incidence.
b) The E-field of the pulse pulls electrons out from the plasma into vacuum and then drives them back. This way a plasma density wave is generated.
c) Plasma oscillation in the wake of the density wave generates a pulse back into the vacuum with harmonic frequencies!

The new road: Relativistic coherent harmonics

Centre for Plasma Physics and Lasers

Relativistically oscillating plasma mirrors



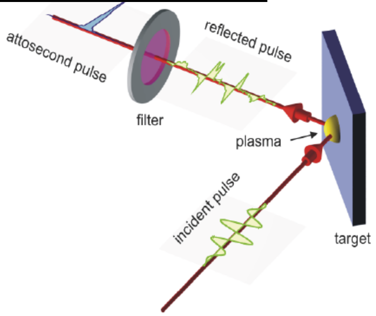


Illustration from George Tsakiris
New Journal Physics 8, 19, 2006

- The target surface is highly ionised by the leading edge of the pulse – becomes rapidly over dense (reflecting to incident radiation)
- The collective electron motion created by the incident E/M wave can be considered as an oscillating mirror

Relativistic spiking

Einstein's Relativistic Doppler effect - $4\gamma^2$

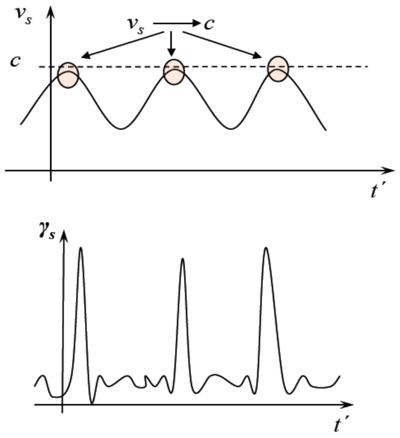
Oscillatory extension to Relativistic Doppler effect

Universal spectrum

$$I_n \propto 1/n^{8/3}$$

Extended Roll-over

$$n_{max} \approx 8^{1/2}\gamma^3$$



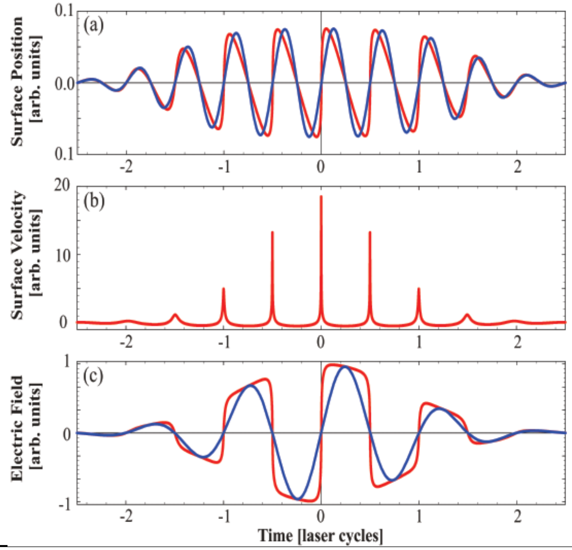
T. Baeva, S. Gordienko, A. Pukhov, *Phys. Rev. E*, **74**, 046404 (2006)

Mechanisms for relativistically oscillating plasma mirrors

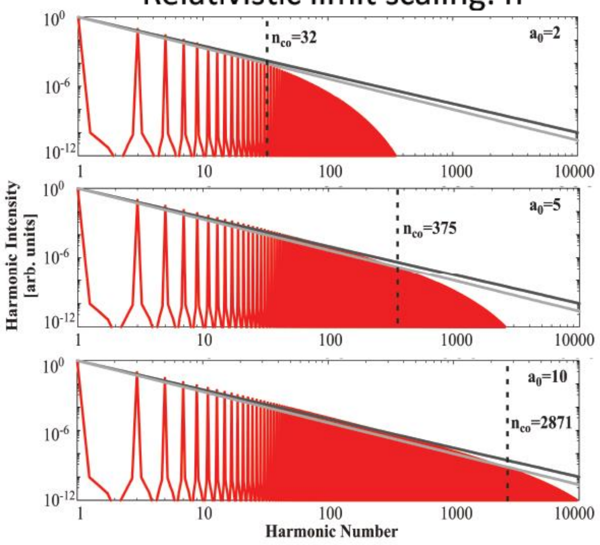
Normalized vector potential $\alpha_0=((I\lambda^2)/(1.37x10^{18}))^{12}$

Intensity *I* in which (Wcm^{-2})
And laser λ in µm

Mirror Motion:

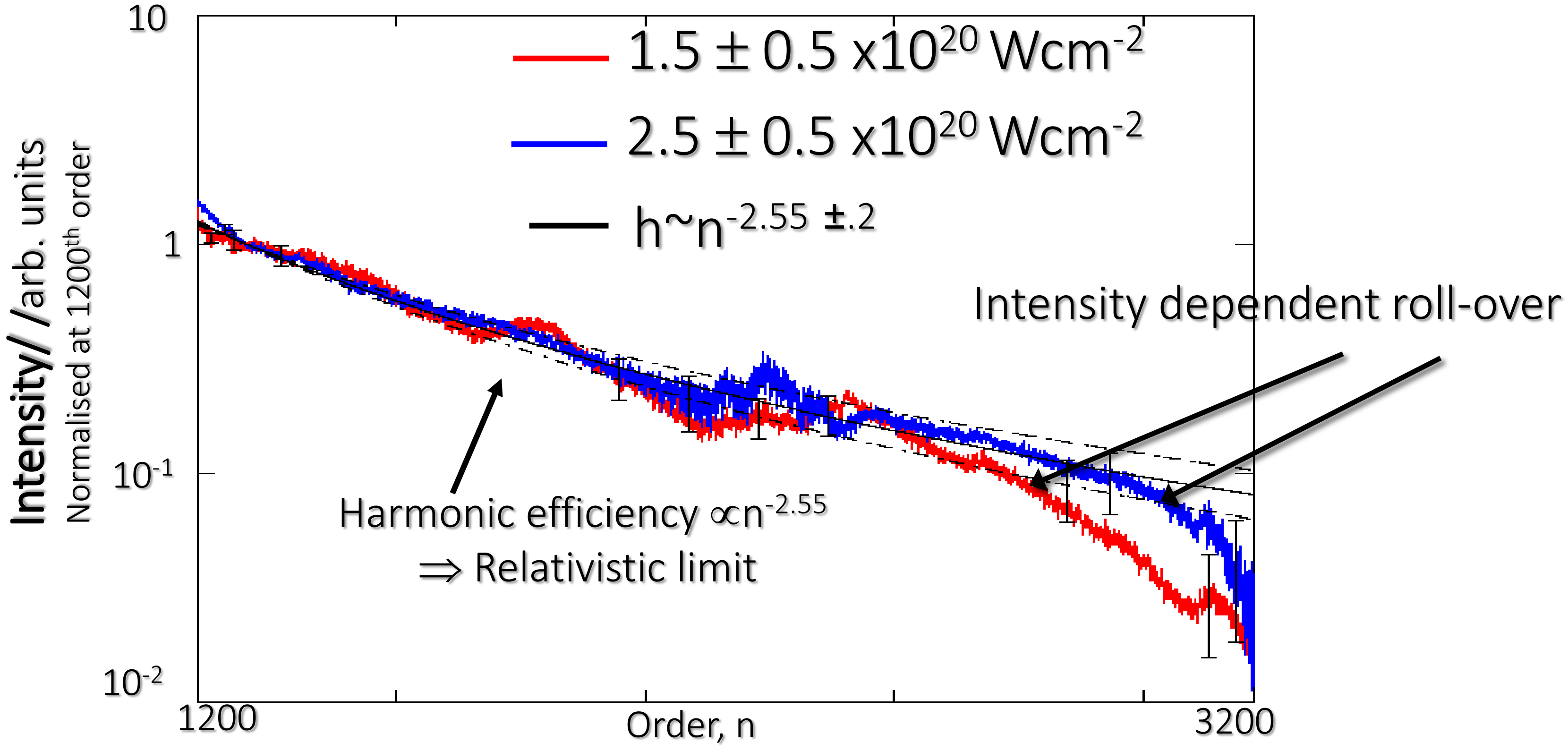


Relativistic limit scaling: $n^{-8/3}$



Relativistic Harmonics (experiment)

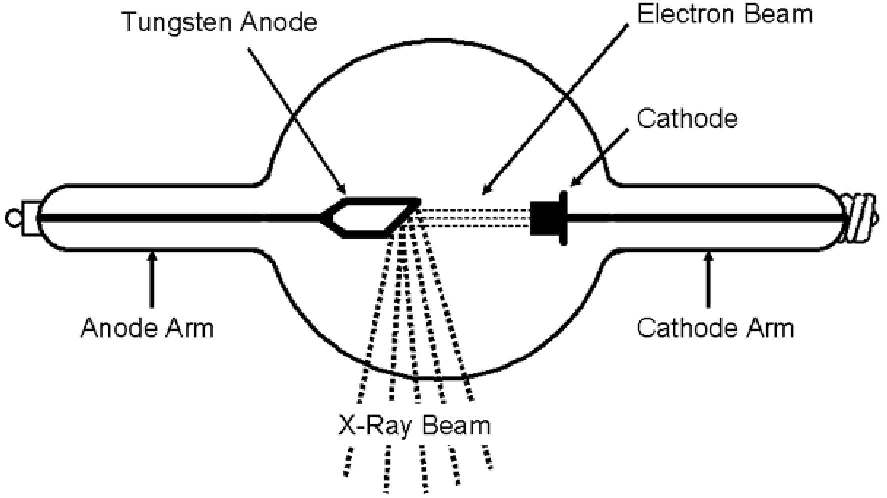
B. Dromey, M. Zepf et. al. (2007)



X-ray tubes vs. Laser High Harmonics

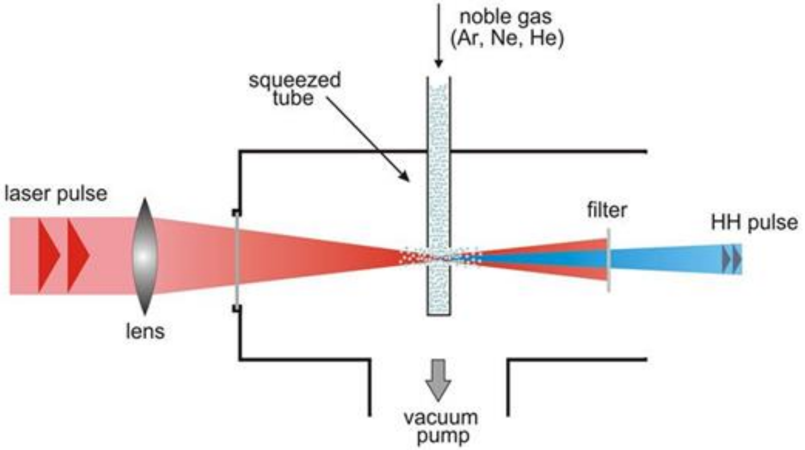
Centre for Plasma Physics and Lasers

X-ray tube



- Electrons are boiled off a filament.
- Then accelerated in an electric field before hitting the anode, where the kinetic energy of the electron is converted into incoherent X-rays.
- These incoherent X-rays are like the incoherent light from a light bulb or flashlight (chaotic light).

Laser HH



- A very intense laser pulse plucks part of the quantum wave function of an electron from an atom.
- Then accelerated and slammed back into the ion, releasing its energy as an X-ray photon.
- Since the laser field controls the motion of the electron, the emitted X-rays can retain the coherence properties of a laser (coherent light).

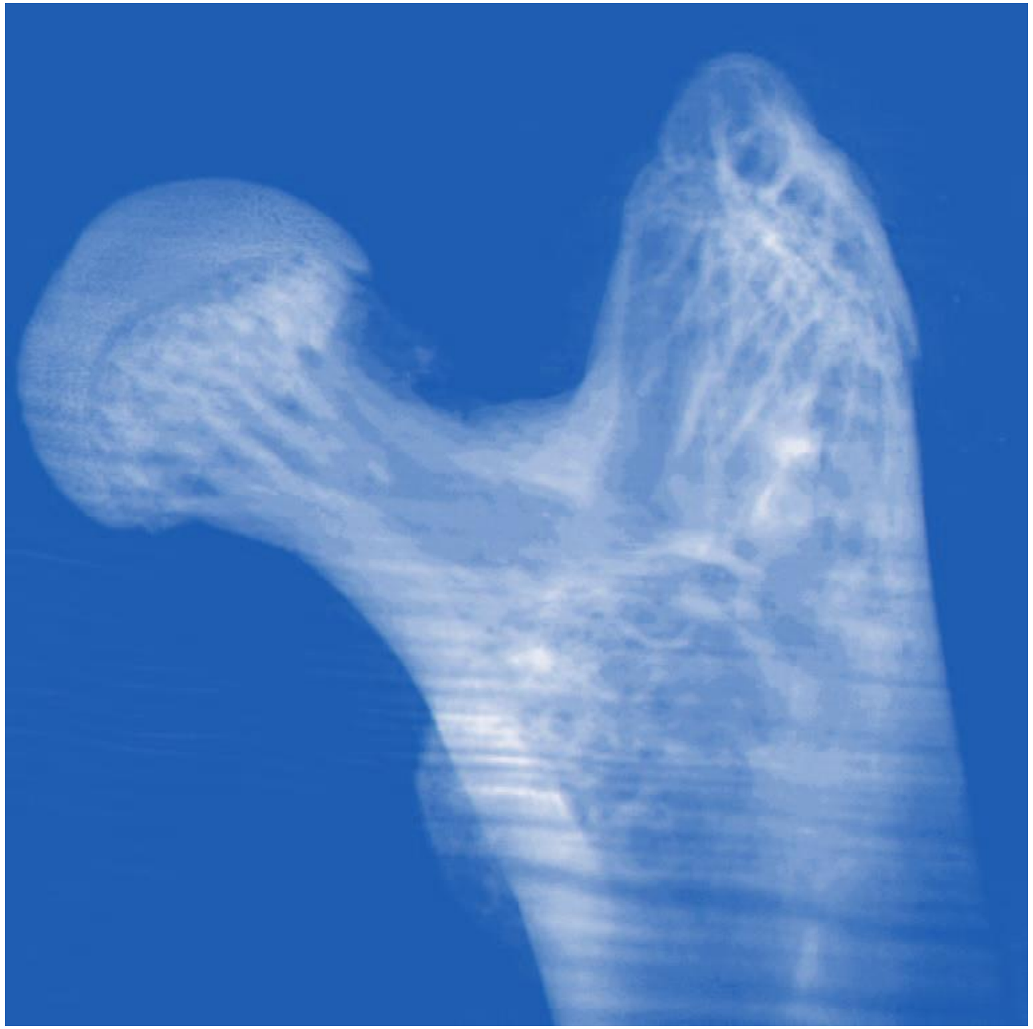
New road with coherent ultrafast X-rays

Centre for Plasma Physics and Lasers

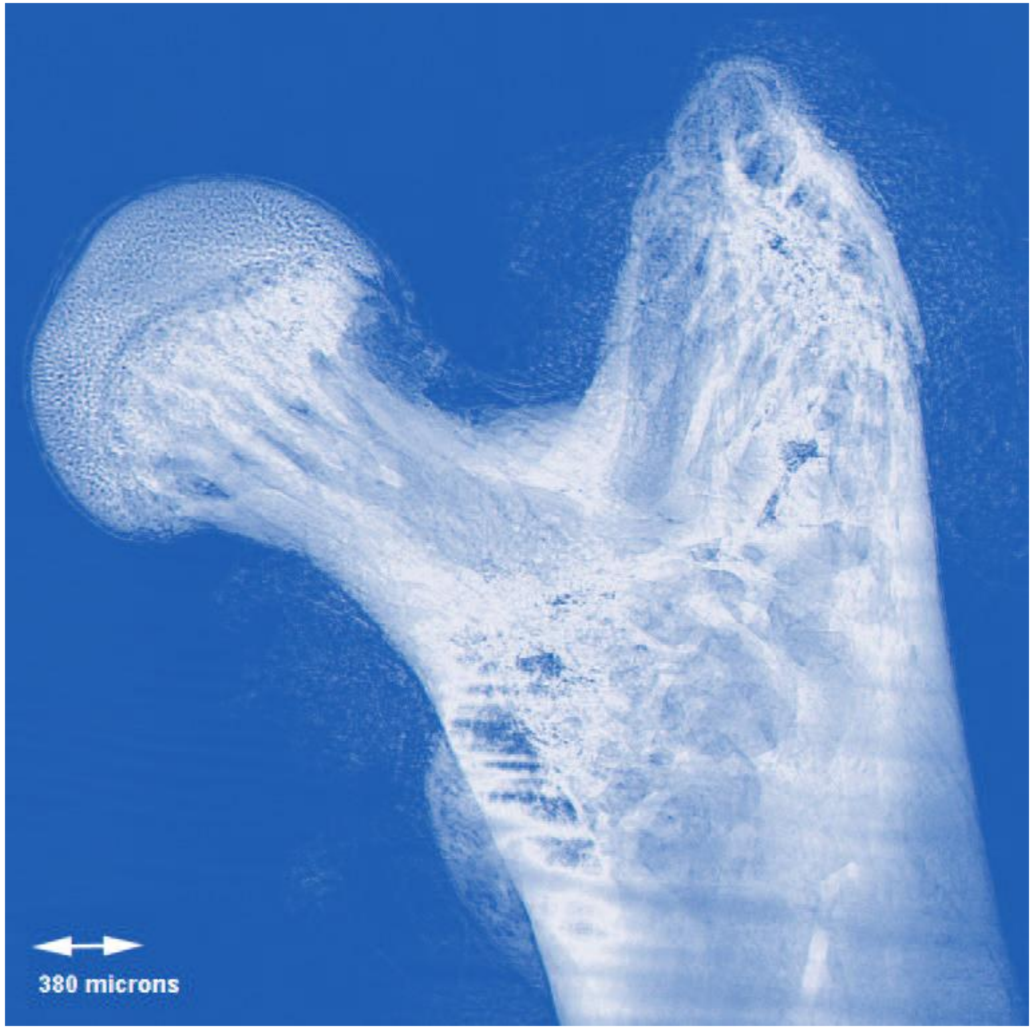
- Phase contrast imaging
- Fresnel and Fraunhofer diffraction
- Speckle interferometry
- Phase retrieval interferometry
- Diffractive imaging
- X-ray photon correlation spectroscopy
- Dynamic imaging

Absorption vs Phase imaging

Incoherent X-rays → only *absorption* contrast

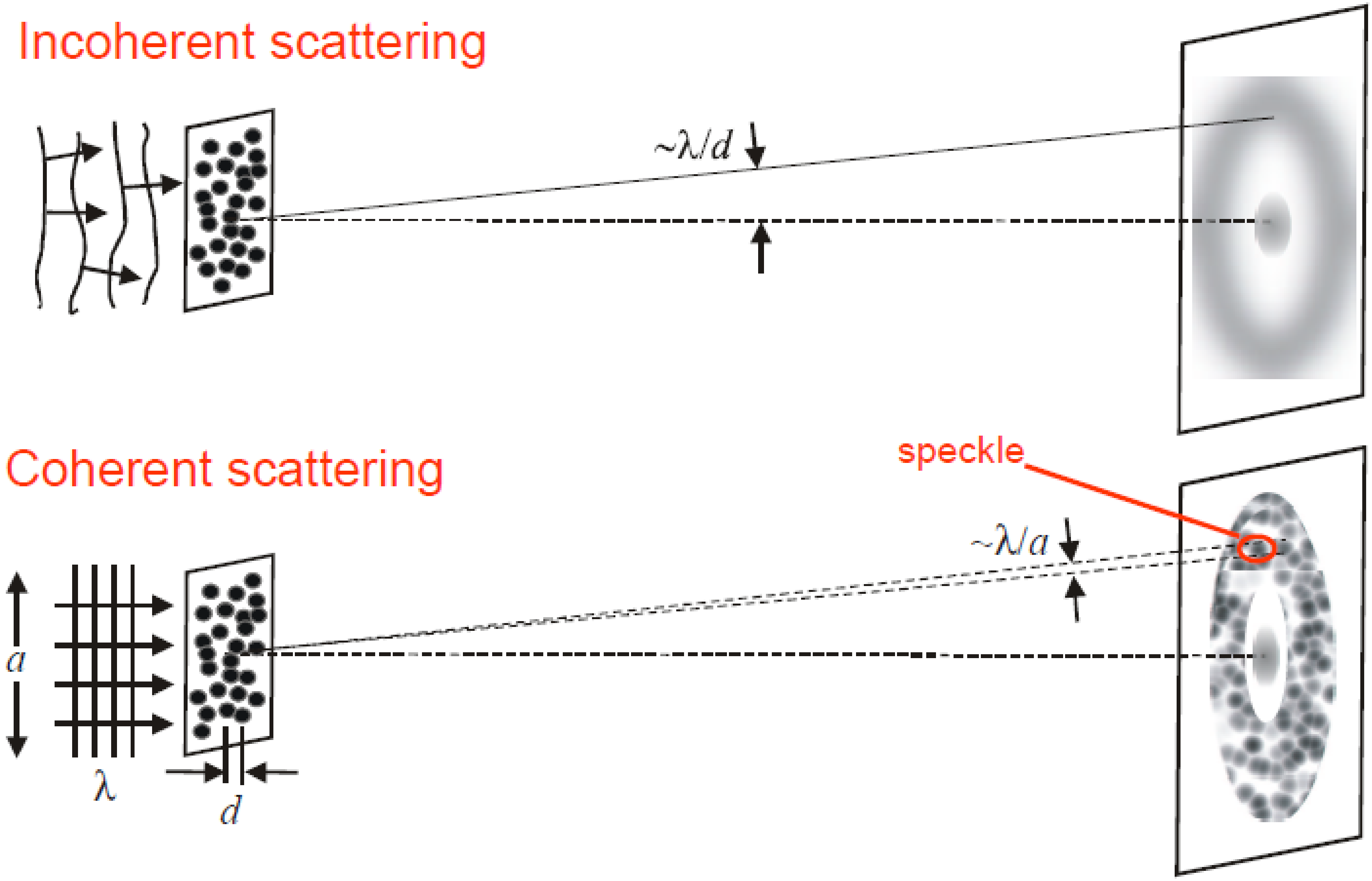


Coherent X-rays → *absorption and phase* contrast

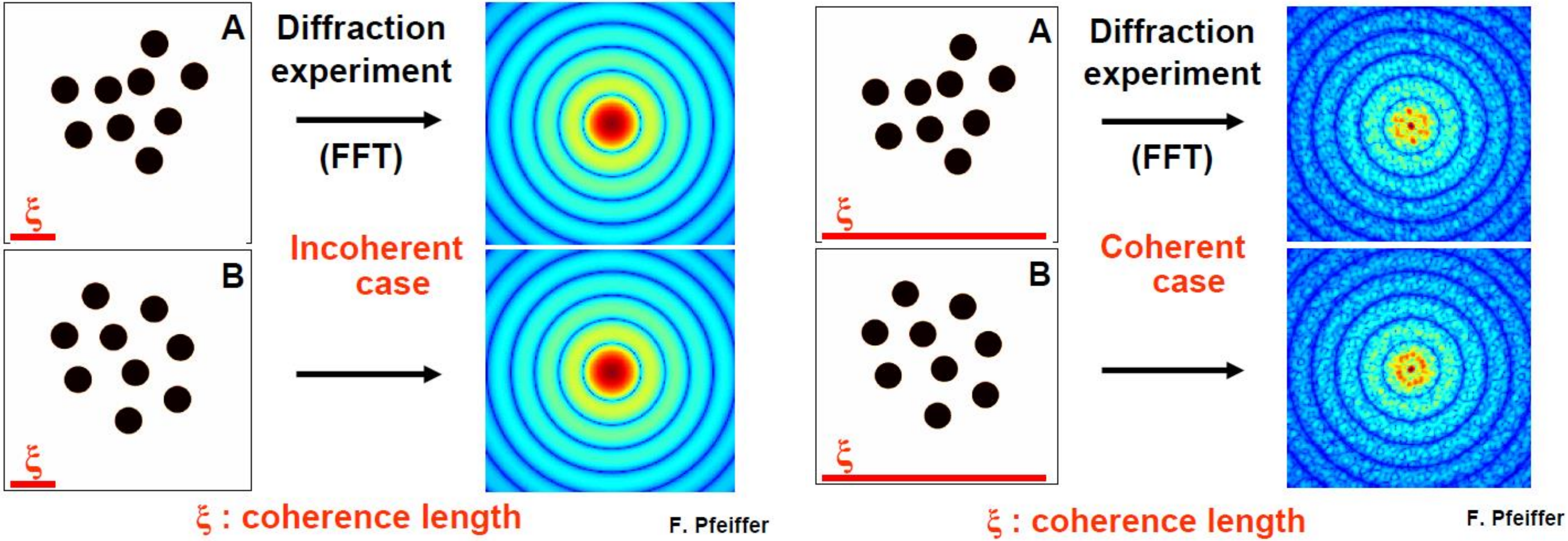


Prof. Dr. Marco Stampanoni Group, Synchrotron Radiation
Paul Scherrer Institut, Switzerland

Speckle Imaging



Diffraction Imaging

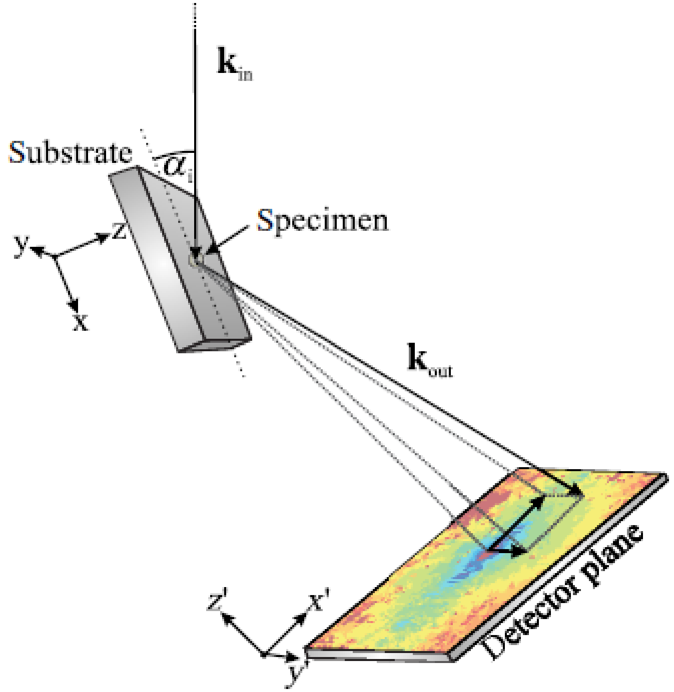


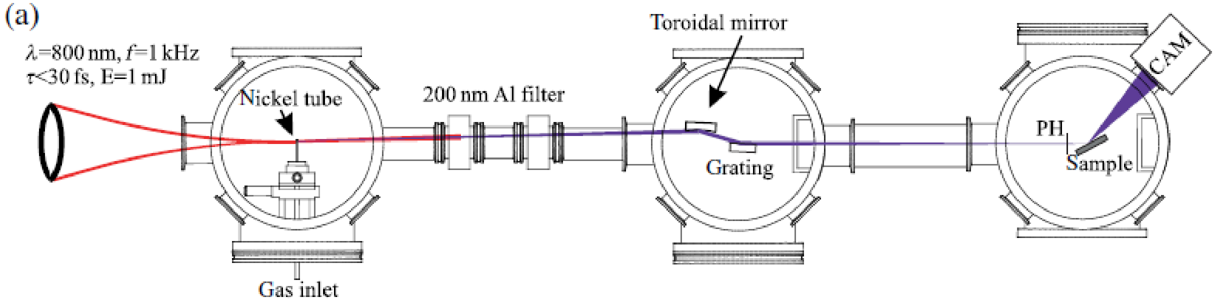
Cancer cell classification with HH

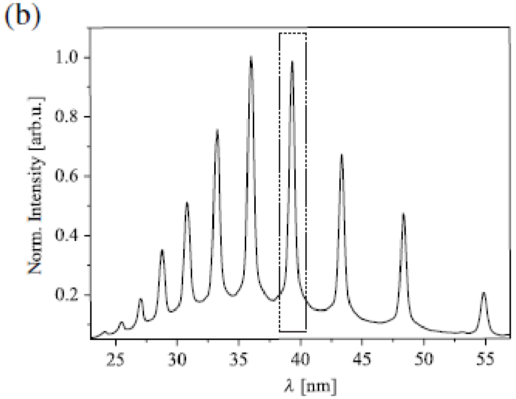
Journal of Medical Imaging 1(3), 031008 (Oct–Dec 2014)

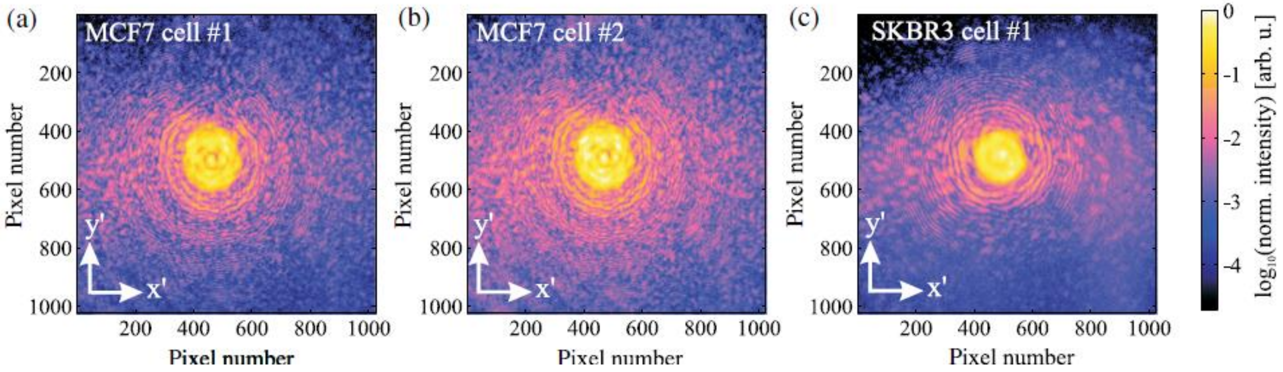
Cancer cell classification with coherent diffraction imaging using an extreme ultraviolet radiation source

Michael Zürch,[a,*] Stefan Foertsch,[b] Mark Matzas,[c] Katharina Pachmann,[d] Rainer Kuth,[b] and Christian Spielmann[a]
[a]Friedrich-Schiller-University Jena, Institute of Optics and Quantum Electronics, Abbe Center of Photonics, Max-Wien-Platz 1, Jena 07743, Germany
[b]Siemens AG, Healthcare Sector Strategy, Hartmann Street 16, Erlangen 91052, Germany
[c]Siemens AG, Corporate Technology, Günther-Scharowsky-Street 1, Erlangen 91058, Germany



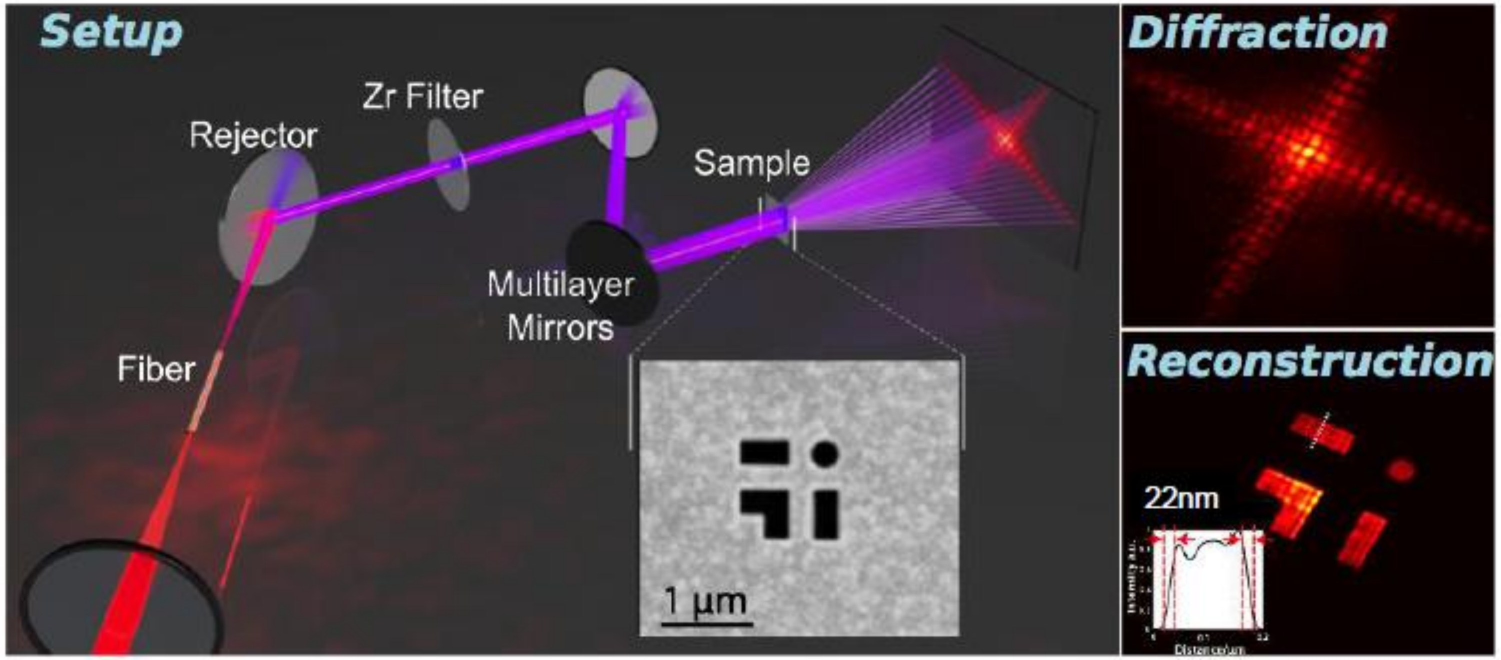




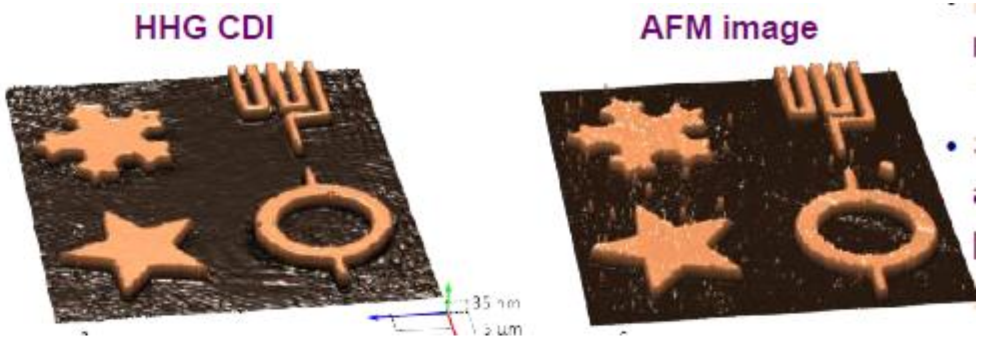


Material microscopy diagnosis with HH

➤ @ JILA Colorado, Murnane/Kapteyn Group



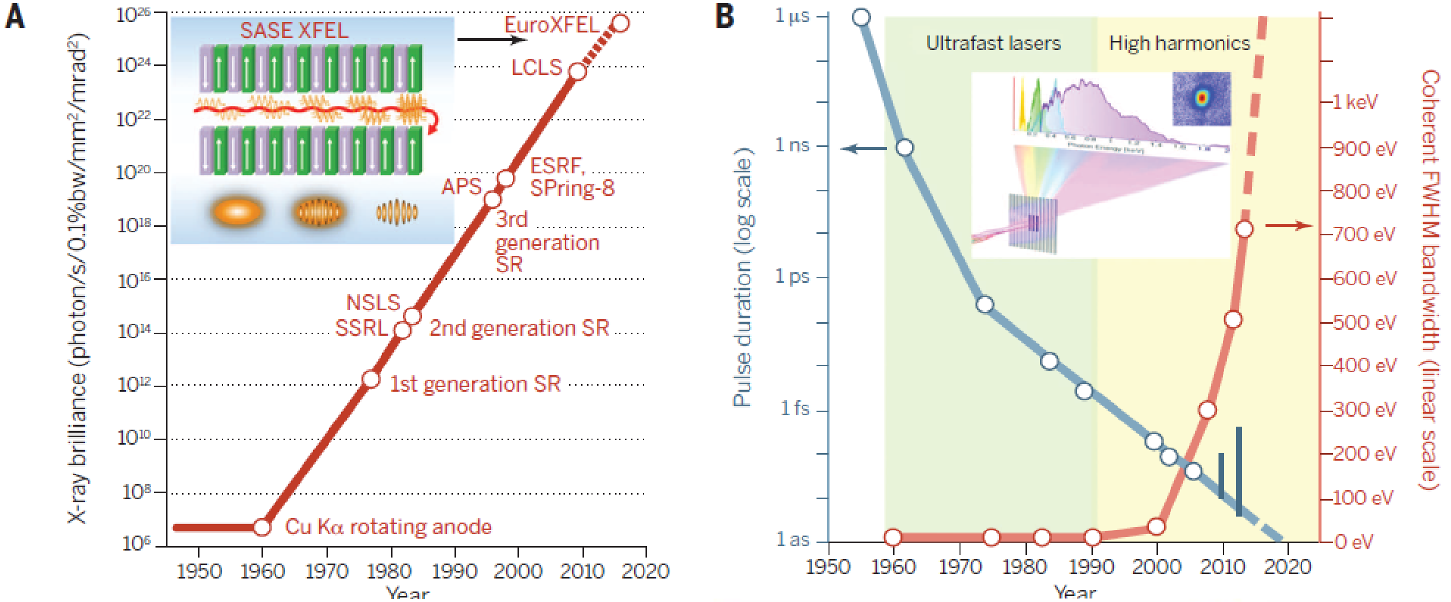
PRL **99**, 098103 (2007); Nature **449**, 553 (2007); PNAS **105**, 24 (2008);
Nature Photon. **2**, 64 (2008); OL **34**, 1618 (2009); Optics Express **19**, 22470 (2011)



- Ptychographic reconstruction recovers 31nm object height (≈ 1nm precision)
- Spatial resolution limited by NA and 30nm wavelength in this preliminary work
- Next steps: increase spatial resolution to 2λ
- Increase spatial resolution to ≈ 30nm using 13nm harmonics

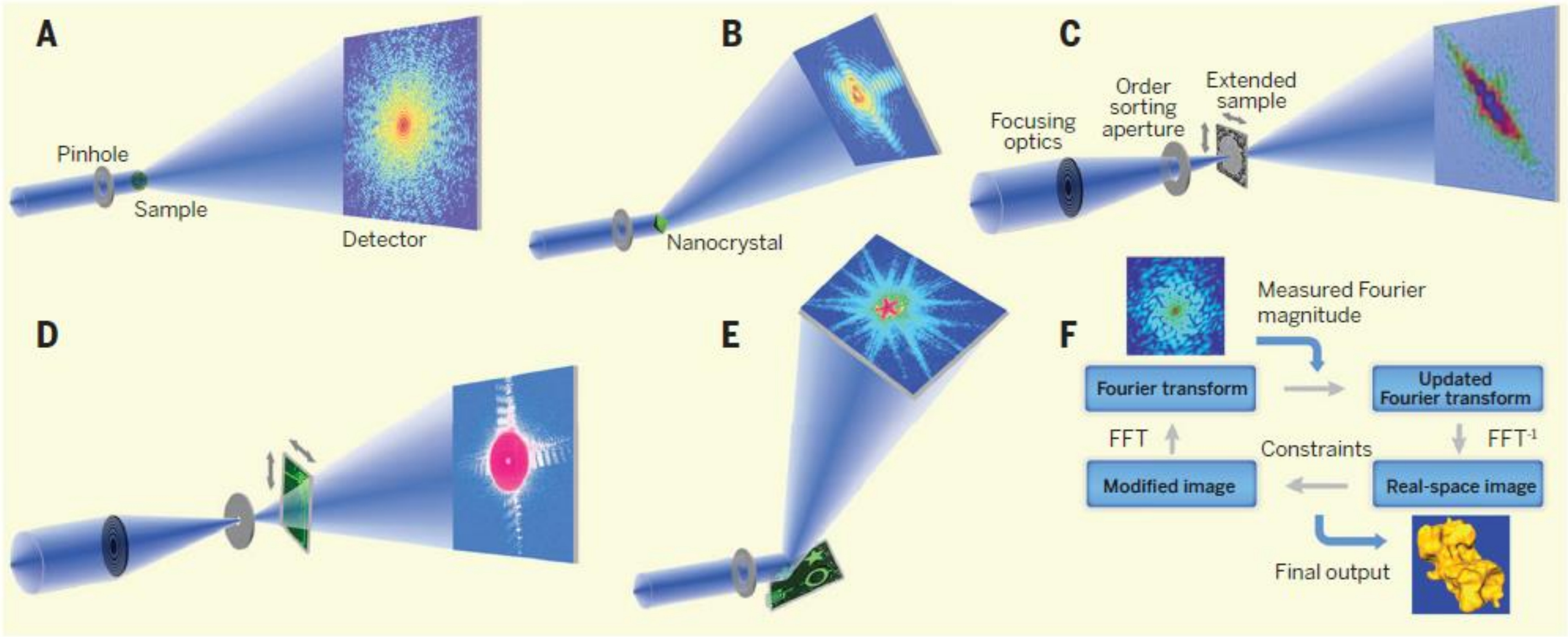
Progress in coherent X-rays and Imaging

Centre for Plasma Physics and Lasers



J. Miao et al, **Science** Review article, 1 May 2015, vol. 348, issue 6234, p.530

(A) Plane-wave CDI
(B) Bragg CDI
(C) Ptychographic CDI (
(D) Fresnel CDI
(E) Reflection CDI
(F) Phase retrieval algorithms

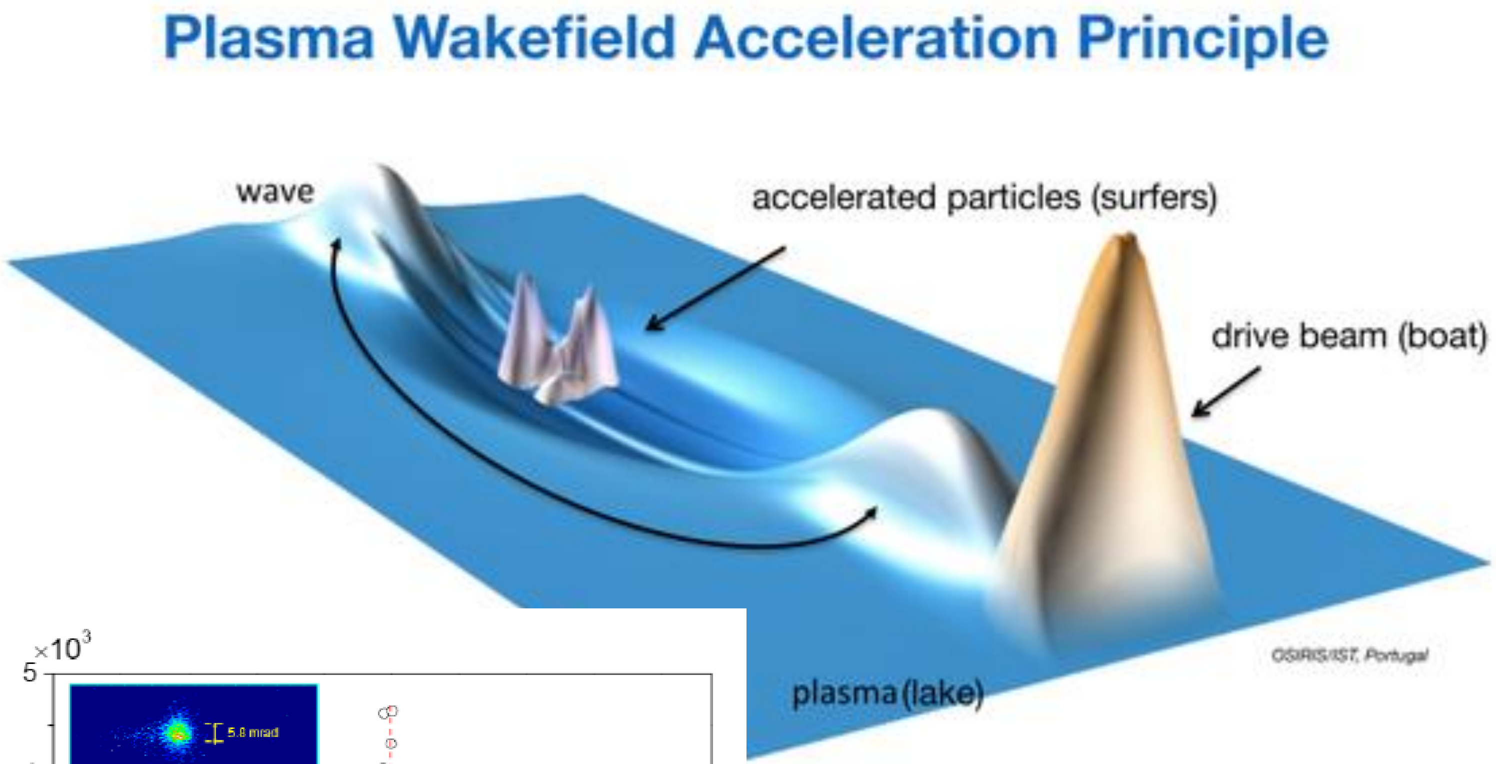


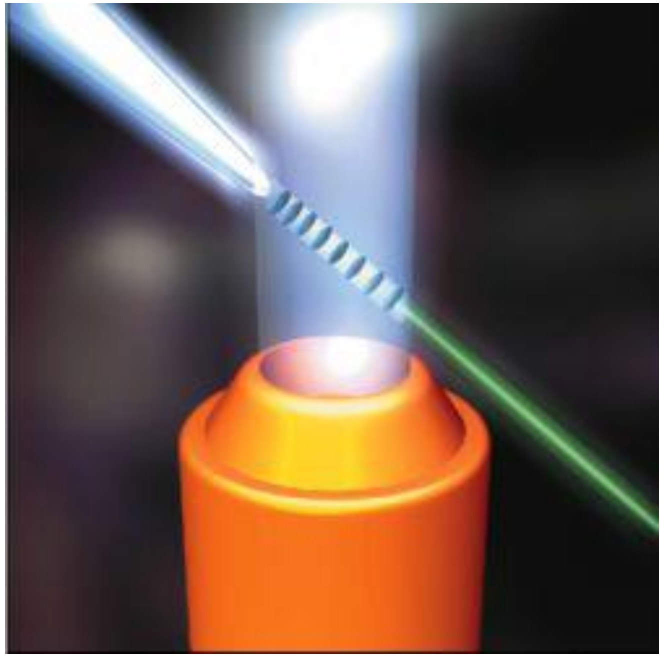
Laser-generated X-ray sources

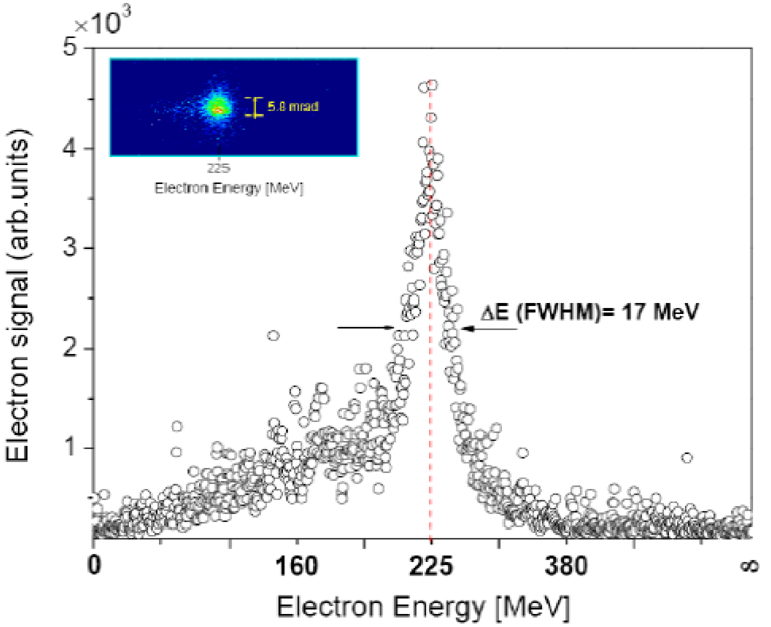
Novel X-ray source	Some distinguishing characteristics of X-ray emissions	Some X-ray applications
MJ-class laser-produced plasmas	Pulses of ns duration, incoherent, high-energy-density (HED) science	Inertial-confinement fusion, nuclear weapons effects and testing
PW-class laser produced plasmas	Pulses of ns duration, incoherent, HED science	Plasma diagnostics: scattering and radiography, fast ignition
X-ray lasers	Coherent; extreme brightness, ultra-short pulses, low divergence	Structure of single biomolecules; femtochemistry
Laser-wake techniques	GeV/cm acceleration gradients	Applications needing high-rep-rate bright and short X-ray pulses
Inverse Compton sources	Tunable, incoherent hard X-rays (<1 Å); ultra-short pulses, 2% bandwidth	Bright and compact source for bioimaging and dynamics
High-harmonic generation (HHG) sources	Coherent soft X-rays; ultrafast pulse durations; strong-field science	Spatially and temporally resolved studies of quantum phenomena

Laser relativistic electrons generate betatron type X-rays

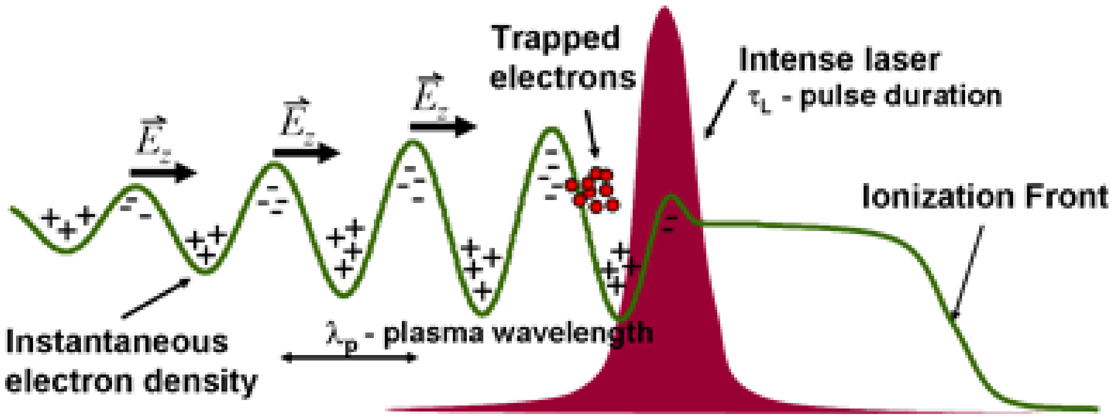
Laser-plasma electron acceleration





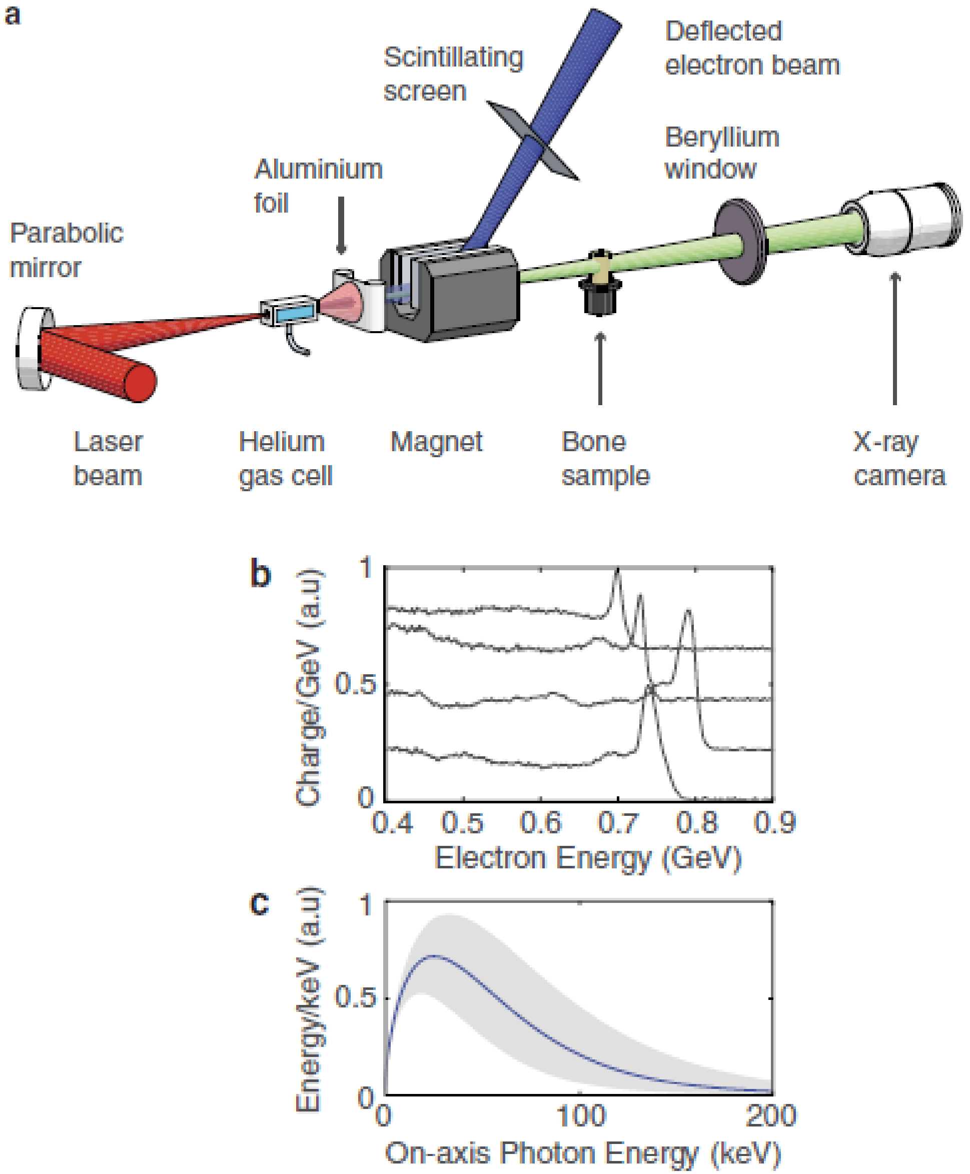


Quasi-monoenergetic 225 MeV electron beam with a width of 17 MeV generated in a 4mm long gas jet when irradiated with a 27 TW laser pulse (N.Hafz *et al 2009)*



Betatron type radiation (LWFA)

SCIENTIFIC REPORTS | 5:13244 | DOI: 10.1038/srep13244



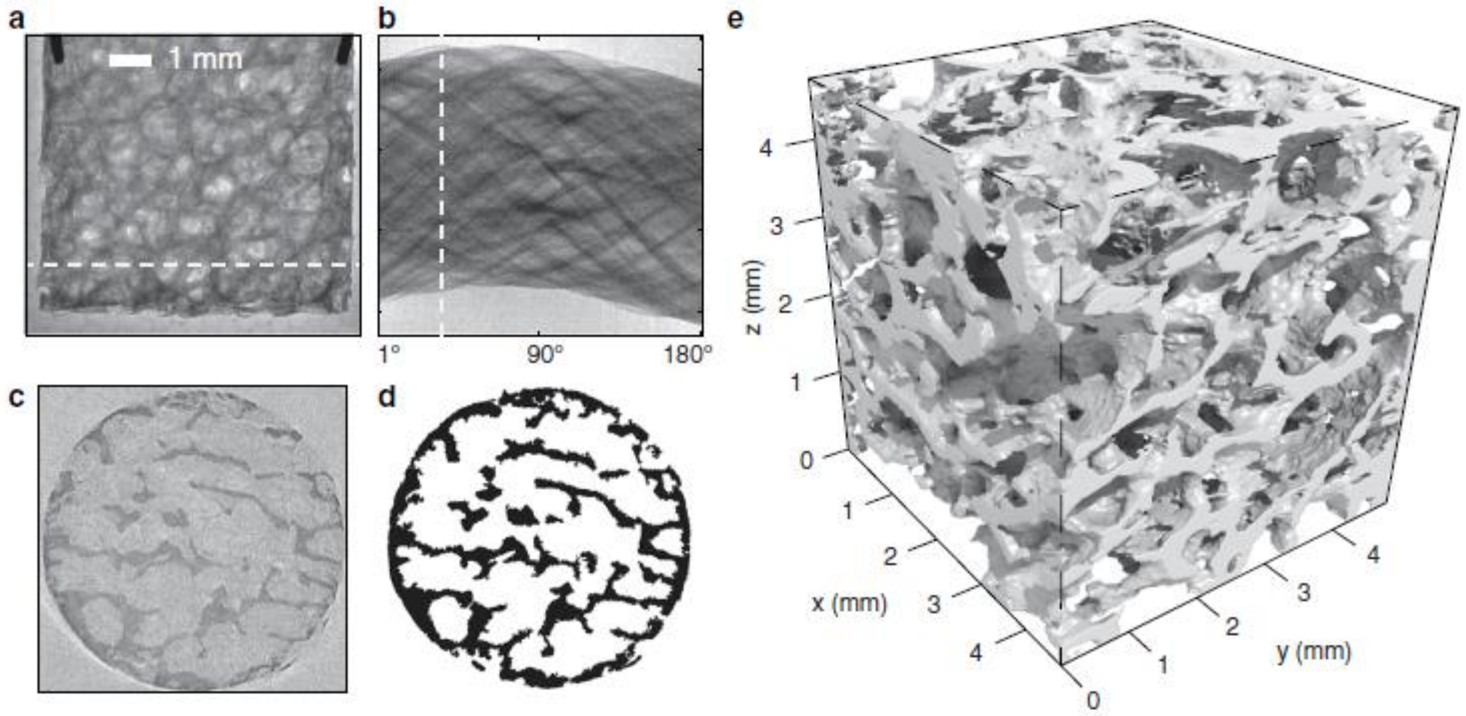


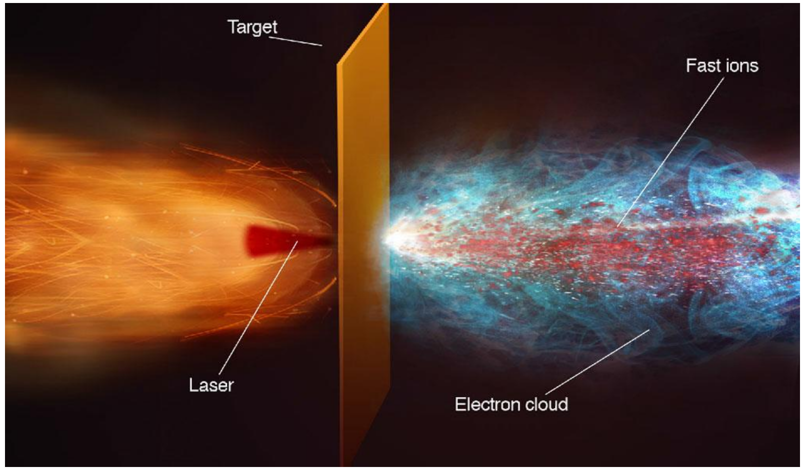
Figure 2. Tomographic reconstruction of trabecular bone sample: (**a**) A raw image of the bone sample recorded on the x-ray camera. (**b**) A sinogram of a particular row in the image, generated by stitching together 180 images of the same row taken at 1° intervals. (**c**) Application of the inverse Radon transform to the sinogram in (**b**) generates a 2D reconstruction of a one-pixel high horizontal slice of the sample. (**d**) Pixels are classified as bone (black) or vacuum (white) if their gray values are below or above the local mean. (**e**) Stacking together 1300 such slices generates a 3D voxel map of the bone sample. An isosurface marking the detailed structure of the bone surface is constructed, rendered using a ray-tracing method.

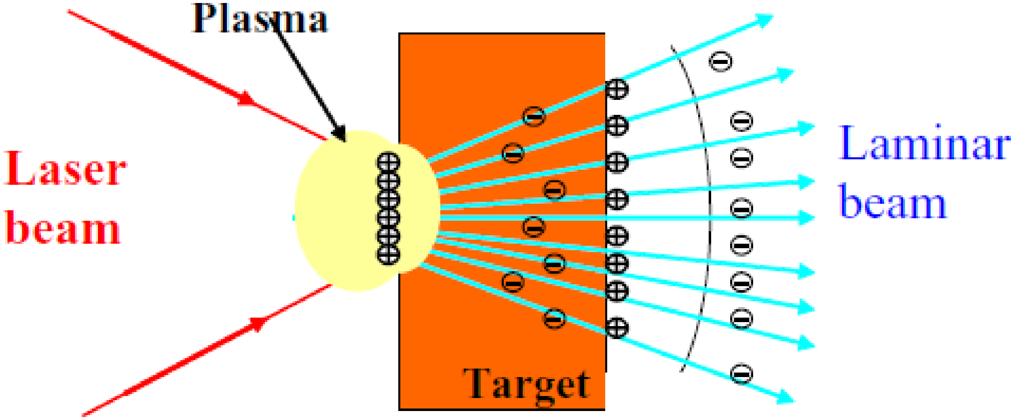
Laser relativistic ion acceleration

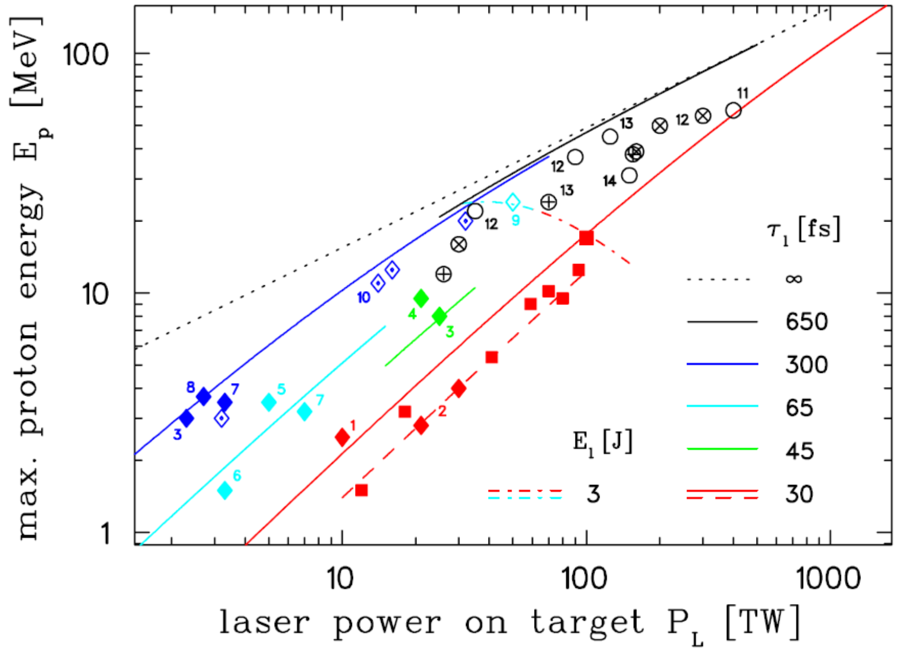
Laser Plasma Proton Acceleration (TNSA)

Centre for Plasma Physics and Lasers

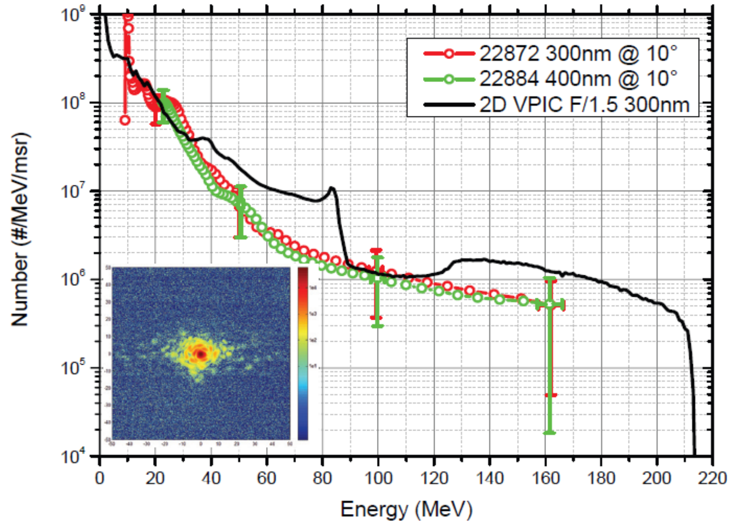
Target Normal Sheath Acceleration (TNSA) scheme







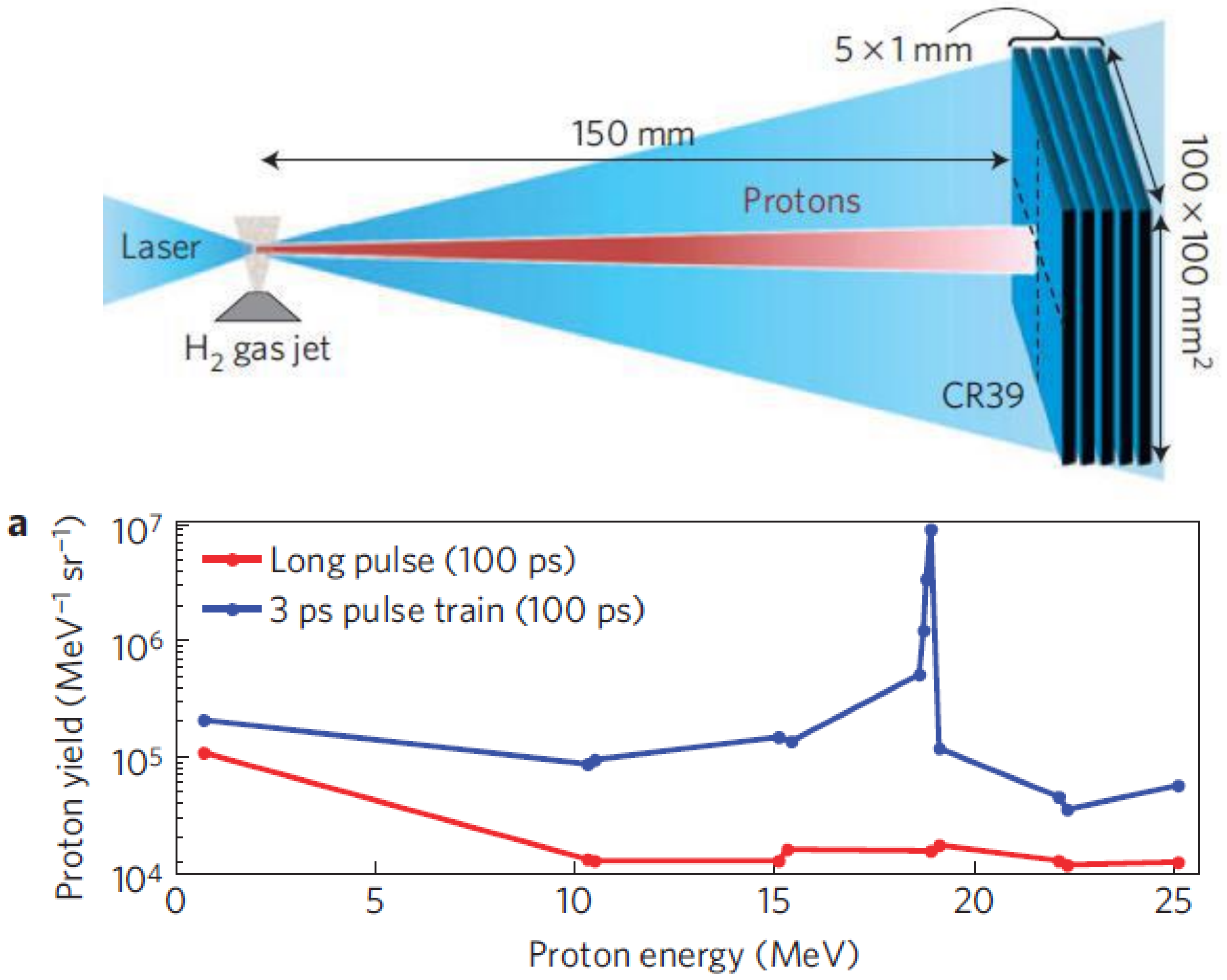
K.W.D. Ledingham et al Review Article "**Towards Laser Driven Hadron Cancer Radiotherapy: A Review of Progress** "



Proton spectra from the LANL Trident laser with 80J, 600fs pulses, r < 2μ spot size, target thickness 300, 400nm with CH2 targets

Laser Plasma Proton Acceleration (CO_2 laser)

Centre for Plasma Physics and Lasers



- Haberberger *et al* and Palmer *et al* used an infrared CO_2 laser with a 10μ wavelength to investigate the collisionless shock-wave acceleration mechanism in a hydrogen plasma.
- A 60 J macropulse (which included a number of 3 ps micropulses) produced almost monoenergetic 20 MeV proton bunches (~ 1 % energy spread) with very low emittance.
- Simulations indicate that ~200 MeV protons could be produced with the current CO_2 laser technology!

Laser Plasma Hardon acceleration future

Centre for Plasma Physics and Lasers

- Accurate delivery and easy optics
  - Protons – and other heavier ions such as carbon – show great promise for radiation therapy because when fired into living tissue, they deposit most of their energy at a very specific depth that depends on their initial energy. This is unlike X-rays and electrons, which tend to deposit energy over much larger regions of tissue.
  - The basic idea is to fire short, intense laser pulses at a thin target, which liberates protons or other ions and accelerates them over distances as small as a few microns.
  - The laser can be drive exactly at the point of interaction and there produces and accelerates the ions (versatile system)

- Biological effectiveness of ultrafast proton pulses
  - Scientists must compare the effectiveness of ultrashort-pulsed ion beams with that of continuous beams from conventional accelerators.

- Ultrafast studies

CPPL selected publication on the field of laser secondary sources for imaging (last 5 years)

Centre for Plasma Physics and Lasers

- S. M. Hassan, E.L. Clark, C. Petridis, G. C. Androulakis, J. Chatzakis, P. Lee, N. A. Papadogiannis, M. Tatarakis
  Filamentary structure of current sheath in miniature plasma focus
  IEEE Transactions on Plasma Science 39, 2432 (2011)
- A. Willner, F. Tavella, M. Yeung, T. Dzelzainis, C. Kamperidis, M. Bakarezos, D. Adams, R. Riedel, M. Schulz, M.C. Hoffmann, W. Hu, J. Rossbach, M. Drescher, V.S. Yakovlev , N.A. Papadogiannis, M. Tatarakis, B. Dromey, M. Zepf
  Efficient control of quantum paths via dual-gas high harmonic generation
  New Journal of Physics 13, 113001 (2011)
- A. Willner, F. Tavella, M. Yeung, T. Dzelzainis, C. Kamperidis, M. Bakarezos, D. Adams, M. Schulz, R. Riedel, M.C. Hoffmann, W. Hu, J. Rossbach, M. Drescher, V.S. Yakovlev , N.A. Papadogiannis, M. Tatarakis, B. Dromey, M. Zepf
  Coherent control of high harmonic generation via dual-gas multijet arrays
  Physical Review Letters 107, 175002 (2011)
- Y. Orphanos, V. Dimitriou, E. Kaselouris, E. Bakarezos, N. Vainos, M. Tatarakis, and N.A. Papadogiannis
  An integrated method for material properties characterization based on pulsed laser generated surface acoustic waves
  Microelectronic Engineering 112, 249 (2013)
- V. Dimitriou, E. Kaselouris, Y. Orphanos, M. Bakarezos, N. Vainos, M. Tatarakis, and N.A. Papadogiannis
  Three dimensional transient behavior of thin films surface under pulsed laser excitation
  Applied Physics Letters 103, 114104 (2013)
- V. Dimitriou, E. Kaselouris, Y. Orphanos, M. Bakarezos, N. Vainos, I.K. Nikolos, M. Tatarakis, and N.A. Papadogiannis
  The thermo-mechanical behavior of thin metal films under nanosecond laser pulse excitation above the thermoelastic regime
  Applied Physics A: Materials Science & Processing 118, 739 (2015)
- E. Tzianaki, M. Bakarezos, G.D. Tsibidis, Y. Orphanos, P.A. Loukakos, C. Kosmidis, P. Patsalas, M. Tatarakis, and N.A. Papadogiannis
  High acoustic strains in Si through ultrafast laser excitation of Ti thin-film transducers
  Optics Express 23, 17191 (2015)
- E. Tzianaki, M. Bakarezos, G. D. Tsibidis, S. Petrakis, P. A. Loukakos, C. Kosmidis, M. Tatarakis and N. A. Papadogiannis
  Controlling nanoscale acoustic strains in silicon using chirped femtosecond laser pulses
  Applied Physics Letters 108, 254102 (2016)

The CPPL/TEI of Crete

cppl

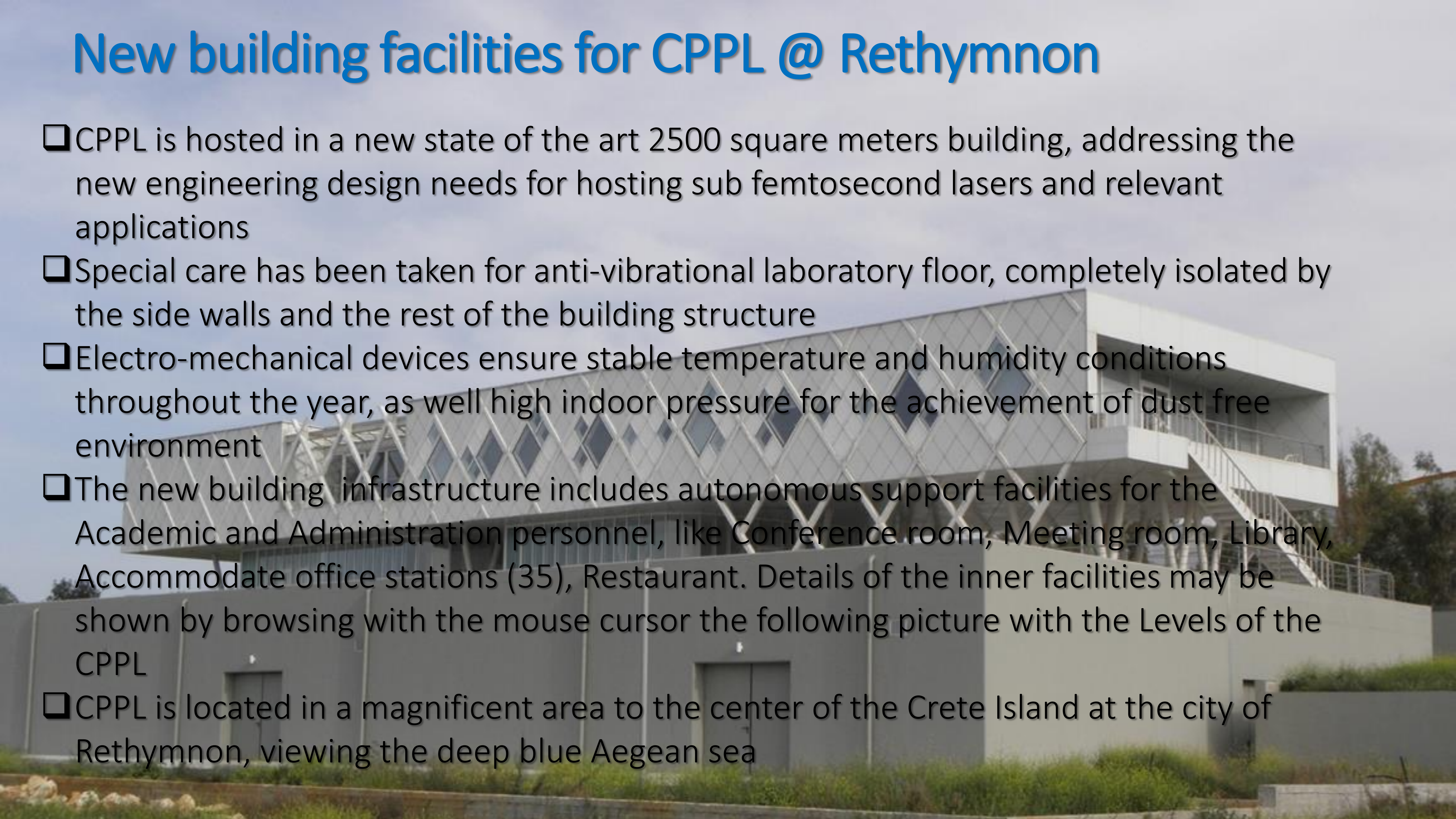
Centre for Plasma Physics and Lasers

CPPL profile

Centre for Plasma Physics and Lasers

CPPL is an internationally renowned centre pursuing cutting edge research on:

- *High Intensity Laser Plasma Interactions Physics and Technology of Ultrashort Laser Generated Secondary Sources*
- *Development and Applications of State of the Art Pulsed Plasma Power Devices*
- *Laser Based Diagnostics Development for Plasmas and Materials*
- *Medical Application of Laser Secondary Sources*



New building facilities for CPPL @ Rethymnon

- CPPL is hosted in a new state of the art 2500 square meters building, addressing the new engineering design needs for hosting sub femtosecond lasers and relevant applications
- Special care has been taken for anti-vibrational laboratory floor, completely isolated by the side walls and the rest of the building structure
- Electro-mechanical devices ensure stable temperature and humidity conditions throughout the year, as well high indoor pressure for the achievement of dust free environment
- The new building infrastructure includes autonomous support facilities for the Academic and Administration personnel, like Conference room, Meeting room, Library, Accommodate office stations (35), Restaurant. Details of the inner facilities may be shown by browsing with the mouse cursor the following picture with the Levels of the CPPL
- CPPL is located in a magnificent area to the center of the Crete Island at the city of Rethymnon, viewing the deep blue Aegean sea

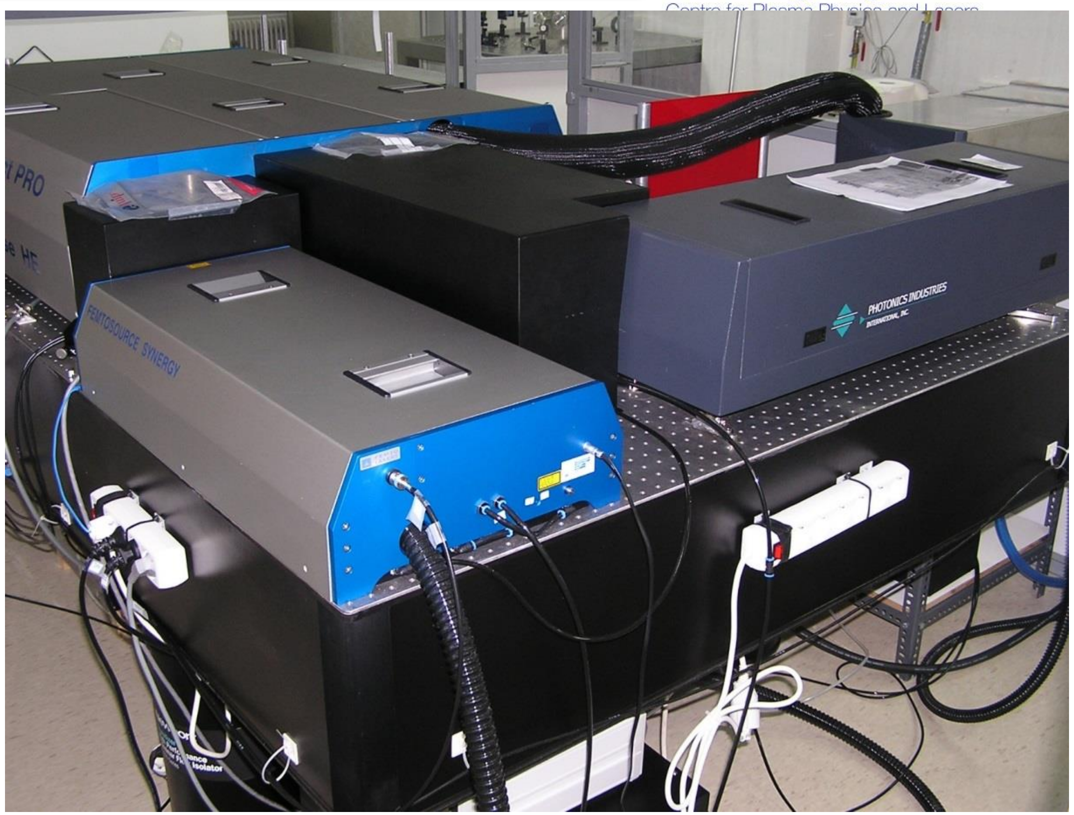
Several high power ultrafast sources

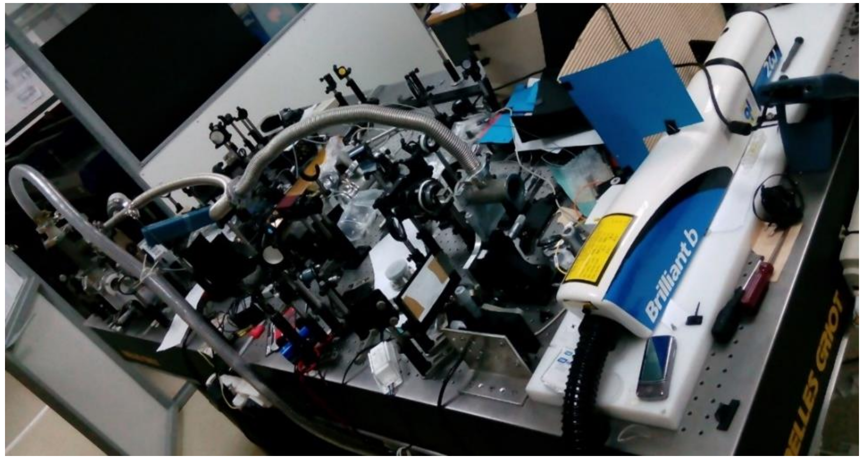
Main Laser Systems

- 45TW Ti:Sapph-based, 25fs, 1J, up to 10Hz (& 15mJ, 25fs probe)
- 2mJ, 7fs, Ti:Sapph-based, 1kHz **C**arrier-**E**nvelope-**P**hase (**CEP**) stabilised
- 4 harmonics Nd:YAG, 150ps, 250mJ, up to 10Hz
- 2 harmonics single longitudinal mode Nd:YAG, 6ns, 800 mJ, up to 10Hz

Laser Sources

cppl





1.5 m interaction chamber

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CPPL peripherals

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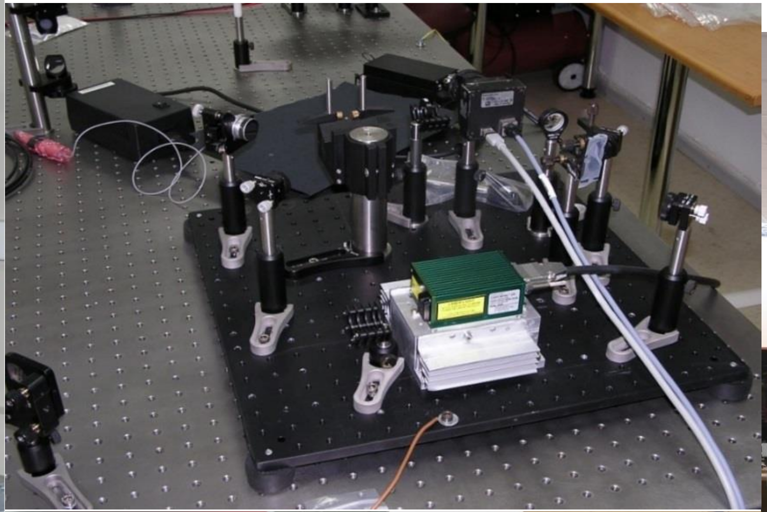
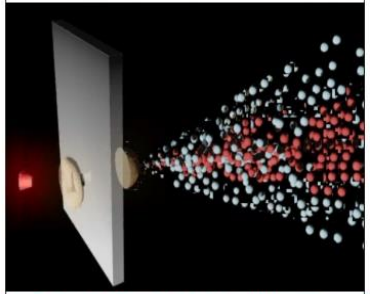


International Master studies @ CPPL

CPPL Centre for Plasma Physics and Lasers

PLAPA
Plasma Physics & Applications

Master of Science in
Plasma Physics & Applications



TEI of Crete - School of Applied Sciences
CPPL Centre for Plasma Physics & Lasers

The course is offered by School of Applied Sciences and Centre for Plasma Physics & Lasers of TEI of Crete in collaboration with leading European Universities and Institutes.

Objective

The main objective of the two years training program is to prepare high quality scientists & engineers in the field of laser produced plasmas, laser physics and laser fusion. Courses focus at professional training for plasma research in the academic or the private sector: plasma industry, optoelectronics, microelectronics, material processing, fusion engineering and relevant leading edge laser innovations.

Prospective Students

PLAPA Master of Science is an international course targeted to graduate students with a bachelor or equivalent degree in Science or Engineering. Good knowledge of English language is required.

Curriculum - Outline

- Total of four semesters
- 120 European Credit Transfer System (ECTS) credits equally distributed in four semesters
- Two semesters of compulsory modules followed by a semester of five elective modules chosen from three main directions:
  - i) Plasma Science - **PS**
  - ii) Laser Physics - **LP**
  - iii) Inertial Fusion - **IF**
- MSc Thesis project at fourth semester
- Possibility of MSc project conduction in leading European laboratories
- Close relation between fundamental science and modern technology
- Student and teacher mobility across Europe and Greece

Students are encouraged to take advantage of the ERASMUS+ mobility programme to attend classes and/or to carry out part/whole of their Thesis in the collaborative Universities and Research Centers

Curriculum modules

1st Semester
- Introduction to Plasma Physics
- Electrodynamics
- Principles of Scientific Computing Research Methodologies
- Introduction to Quantum Mechanics

2nd Semester
- Laser Physics & Technology
- Atomic Processes in Plasma
- Plasma Diagnostics & Photon Transport
- Plasma Kinetics
- Short Pedagogical Project

3rd Semester

IF
- Principles of Laser Fusion
- Laser Matter Interaction
- Plasma Diagnostics & Particle Beam Transport in Matter
- Target & Reactor Technology
- Modeling & Numerical Methods for Plasma Physics

LP
- Principles of Laser Fusion
- Laser Matter Interaction
- Radiation & Laser Safety
- Non Linear Optics
- High Power Lasers & Diagnostics

PS
- Laser Matter Interaction
- Non Linear Optics
- Dense Plasmas
- Non Linear Dynamics & Instabilities in Plasma
- Modeling & Numerical Methods for Plasma Physics

4th Semester
Msc Thesis

Facilities

During the course of their studies, the students will have the opportunity to benefit from State of the Art research facilities.

- Ultrafast and ultraintense laser sources
- Advanced pulsed power plasma devices
- Advanced optical systems for spatiotemporal characterization of plasmas and materials
- Modern Computational and Modeling-Simulation systems
- State of the art new building facilities for education and research

The challenge of studying Plasma & Lasers

- **Laser plasmas and diagnostics** provide links between fundamental science and current technologies in materials, opto- and micro-electronics.
- **Laser fusion plasma** is an attractive method to potentially provide unlimited energy without the problem of long lived radioactive waste.
- **Ultrafast and intense lasers** and their secondary sources have novel applications in medical imaging and therapy, material testing and safety.

Information

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CPPL Funding I

- ***National research infrastructure for HiPER (MIS 376841)***

2012 – 2015, Funding through the European Regional Development Fund (ERDF) and National Funds through the Operational Programme "Competitiveness and Entrepreneurship".

Total budget: €2.281.000

- ***Innovative optoacoustic arrangement for the three-dimensional spatiotemporal micro-characterisation of composite materials based on ultrafast laser pulses (Sub-action 19)***

2012 – 2015, "Archimedes III – Strengthening the Research Groups of the T.E.I. of Crete" (MIS 380353).

Total budget: €80.000

- ***Design and development of a neutron source for the detection of explosive materials (Sub-action 16)***

2012 – 2015, "Archimedes III – Strengthening the Research Groups of the T.E.I. of Crete" (MIS 380353).

Total budget: €80.000

- ***Building research infrastructure for CPPL – TEI of Crete***

2009 – 2015, Funding through the Hellenic Structural Funds.

Total budget: €4.000.000

- ***Multilateral Erasmus programmes (HIPOLIN, APPEPLA, OLA)***

2006 – 2015, Funding through the European Union under the Erasmus Lifelong learning.

Total budget: €530.000

CPPL Funding II

Centre for Plasma Physics and Lasers

❖ ***HiPER – European HIgh Power laser Energy Research facility – preparatory phase study***

2010 – 2011, Funding through the European Union.

Total budget: €400.000

❖ ***HiPER-GR – Hellenic Network for the European Research Infrastructure HiPER (MIS 303839)***

2010 – 2011, Funding through the European Regional Development Fund (ERDF) and National.

Total budget: €110.000

❖ ***DAIX – Development of An Innovative X-ray source (FP6-014423)***

2005 – 2009, ***Centre of excellence***, Funded by the "Marie Curie ToK".

Total budget: €940.000

❖ ***Acoustic microscopy using ultra-high frequency, laser-generated ultrasounds (Sub-action 4)***

2005 – 2007, "Archimedes II – Strengthening the Research Groups of the T.E.I. of Crete" (MIS 99954).

Total budget: €70.000

❖ ***Quality control of traditional musical instruments using laser interferometric techniques (Sub-action 13)***

2004 – 2006, "Archimedes II – Strengthening the Research Groups of the T.E.I. of Crete" (MIS 86384).

Total budget: €80.000

CPPL group member + collaborators

Faculty Members

- Prof. Michael Tatarakis, Laser Plasma Physics (Director)
- Prof. Nektarios Papadogiannis, Ultrafast laser Physics (Vice-Director)
- Prof. Makis Bakarezos, Non-linear Optics
- Prof. John Chatzakis, Electronic Engineering
- Prof. Vasilios Dimitriou, Models and Simulations
- Dr. Yannis Orphanos, Mechanical and Optical Engineering
- Mr Stylianos Piotogiannakis, Electronic Engineering

Researchers and Postgraduate Students

- Dr. Eugene Clark, Senior Researcher
- Dr John Fytilis, Senior Researcher
- Dr Kiki Kosma, Post Doc
- Dr. Evagelos Kaselouris, Post Doc
- Dr Irene Tzianaki
- Mr Stelios Petrakis, MSc, PhD candidate
- Mr George Koundourakis MSc, PhD candidate
- Mr Alexandros Skoulakis, BEng
- Mr Theodore Papadoulis, BEng
- Mr Anastasios Grigoriadis, BSc
- Mr George Tazes, BSc

+ 11 Postgraduate Students

Collaborators

- Prof. J. Collier, Rutherford Appleton Laboratory, UK
- Prof. Z. Najmundin, Imperial College, London, UK
- Prof. M. Zepf, Queen's University Belfast, UK
- Prof. D. Batani, University of Bordeaux, France
- Prof. V. Tikhonchuk, University of Bordeaux, France
- Prof. L. Volpe, University of Salamanca, Spain
- Prof. F. Beg, University of Californnia, San Diego, USA
- Prof. A. Rivera, Technical University Madrid, Spain
- Prof. M. Kalal, Technical Univ. Prague, Czech Republic
- Prof. N. Vainos, University of Patras, Greece
- Prof. K. Kosmidis, University of Ioannina, Greece
- Prof. I. Nikolos, Technical University of Crete, Greece
- Prof. E. Benis, University of Ioannina, Greece
- Prof. P. Patsalas, Aristotelian Univ. Thessaloniki, Greece
- Dr. P. A. Loukakos, IESL FoRTH, Heraklion, Greece
- Dr. G. Tsimbidis, IESL FoRTH, Heraklion, Greece

CPPL collaborators

cppl
Centre for Plasma Physics and Lasers

University of Crete

FORTH
Foundation for Research & Technology - Hellas

Imperial College London

Queen's University Belfast

University of Oxford

CLPU
Centro de Láseres Pulsados Ultracortos Ultraintensos

University of Ioannina

ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ ΠΑΝΕΠΙΣΤΗΜΙΟΝ ΑΘΗΝΩΝ

université de BORDEAUX

l'X ÉCOLE POLYTECHNIQUE
UNIVERSITÉ PARIS-SACLAY

Εθνικό Μετσόβιο Πολυτεχνείο (ΕΜΠ)

University of Cyprus

Dublin City University
Ollscoil Chathair Bhaile Átha Cliath

University of St Andrews

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ
UNIVERSITY OF PATRAS

Πολυτεχνείο Κρήτης

DESY

Czech Technical University in Prague

Amplitude Technologies
Nothing but ultrafast.

CLASS5 Photonics

FEMTO LASERS

OPTRONICS TECHNOLOGIES S.A.

VECTOR TECHNOLOGIES

The End