Extreme Physics -
Ultra-fast and *Ultra-intense* Lasers

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www.physics.dcu.ie/~jtc

NCPST

sfi
science foundation ireland

Magh Ene College
Bundoran - January 25, 2016

inspire
Integrated NanoScience Platform for Ireland

DCU

DCU Laser Plasma-AMO Physics Group

Laser Plasma/AMO Physics @ NCPST - 6 laboratory areas focussed on pulsed laser matter interactions (spectroscopy/ imagingIparticles)

Principal Investigators (6): John T. Costello, Eugene T. Kennedy (Emeritus), Lampros Nikolopoulos (Theory), Jean-Paul Mosnier & Paddy Hayden (SFI SIRG PI)

Current Postdocs (3): Dr. Pramod Pandey, Dr. Colm Fallon & Dr. Mossy Kelly

Current PhD students (9 + (1)): Nichola Walsh, Brian Sheehy, Ben Delaney, Stephen Davitt, Hu Lu, Getasew Wubetu, Sri. Inguva, William Hanks, Muhammed Alli & Sadaf Syedah (Lazaros Varvarezos)

Recent Interns (2012-14): K. Nishant/R. Tejaswi, (LNMIIT, Jaipur), C Hand, (NUIM), S Reddy/R Namboodiri/A Neettiyath (IIT Madras), R Singh/S Gupta (IIT Kanpur), S Howard (Notre Dame), I-M Carrasco Garcia (Malaga), Robert Black (Notre Dame)

Recent PhD Grads (2009-2014): Padraig Hough, Conor McLoughlin, Rick O'Haire, Vincent Richardson, Dave Smith, Tommy Walsh, Jack Connolly, Jiang Xi, Leanne Doughty, Eanna MacCarthy, Colm Fallon, Mossy Kelly, D Middleton & Cathal O'Broin

Recent Past Postdocs (2012-2014): Satheesh Krishnamurthy (Open Univ. UK), Pat Yeates (Elekta Oncology UK) & Subhash Singh (U. Allahabad).

Outline of the Talk

Part I - How does a LASER work ?

Part II - What is an ultrafast laser ?

Part III - What do the biggest lasers in the world look like ?

How does a LASER work ?

Some Notes.

LASER **-** Light Amplification via the Stimulated Emission of Radiation - *it's a Light Amplifier…*

Einstein worked out the basic mathematical and theoretical principles in the 1920s !!

The laser was invented 40 years later in 1960 in the Bell Laboratories in the USA.

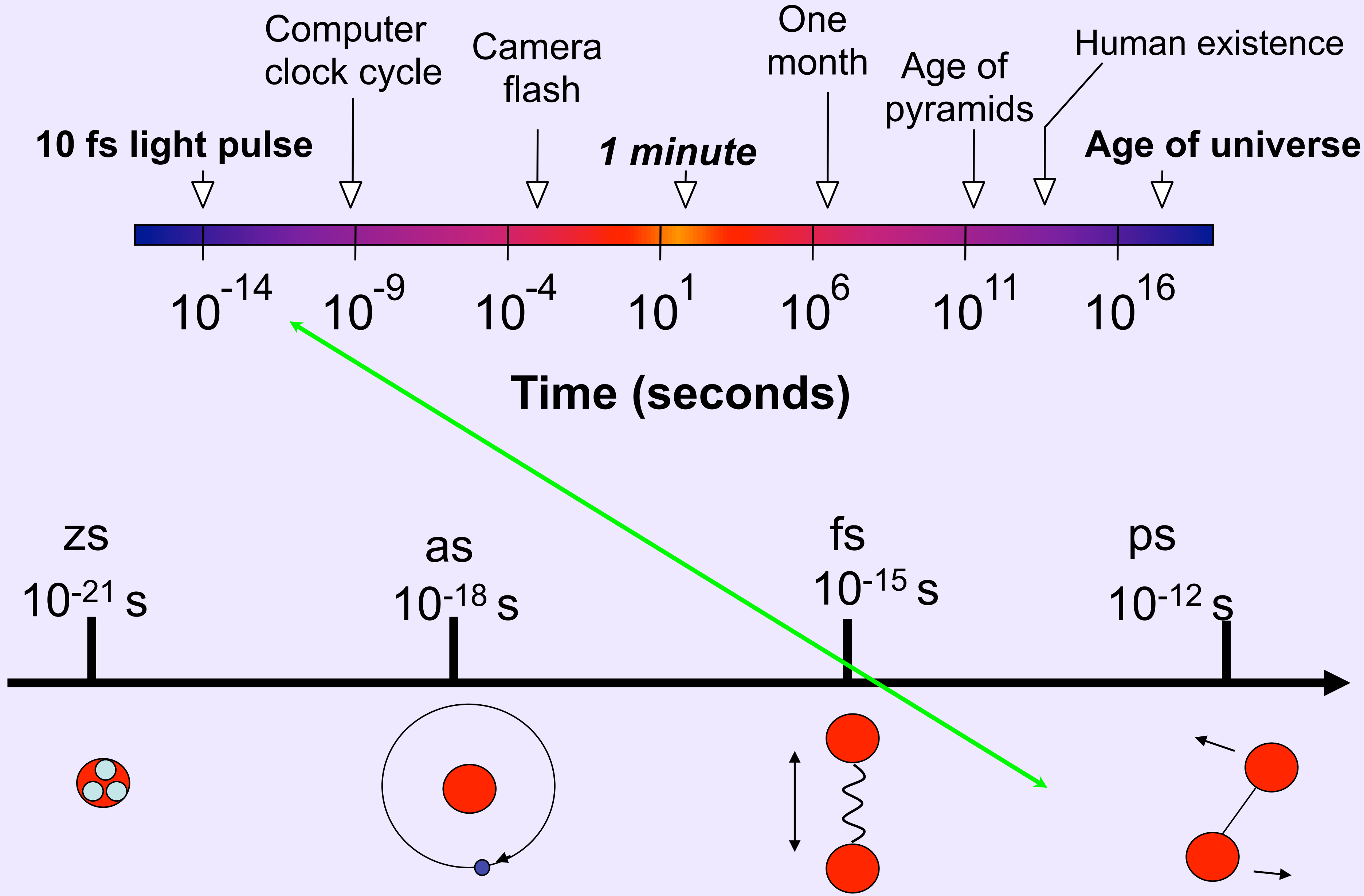
SCALES - ORIENTATION
The Metric System - Prefixes

Small		Big	
Milli (m)	(1/1,000) 10^{-3}	Kilo (k)	(1,000) 10^{+3}
Micro (μ)	10^{-6}	Mega (M)	10^{+6}
Nano (n)	10^{-9}	Giga (G)	10^{+9}
Pico (p)	10^{-12}	Tera (T)	10^{+12}
Femto (f)	10^{-15}	Peta (P)	10^{+15}
Atto (a)	***10^{-18}***	Exa (E)	10^{+18}
Zepto (z)	10^{-21}	Zetta (Z)	10^{+21}

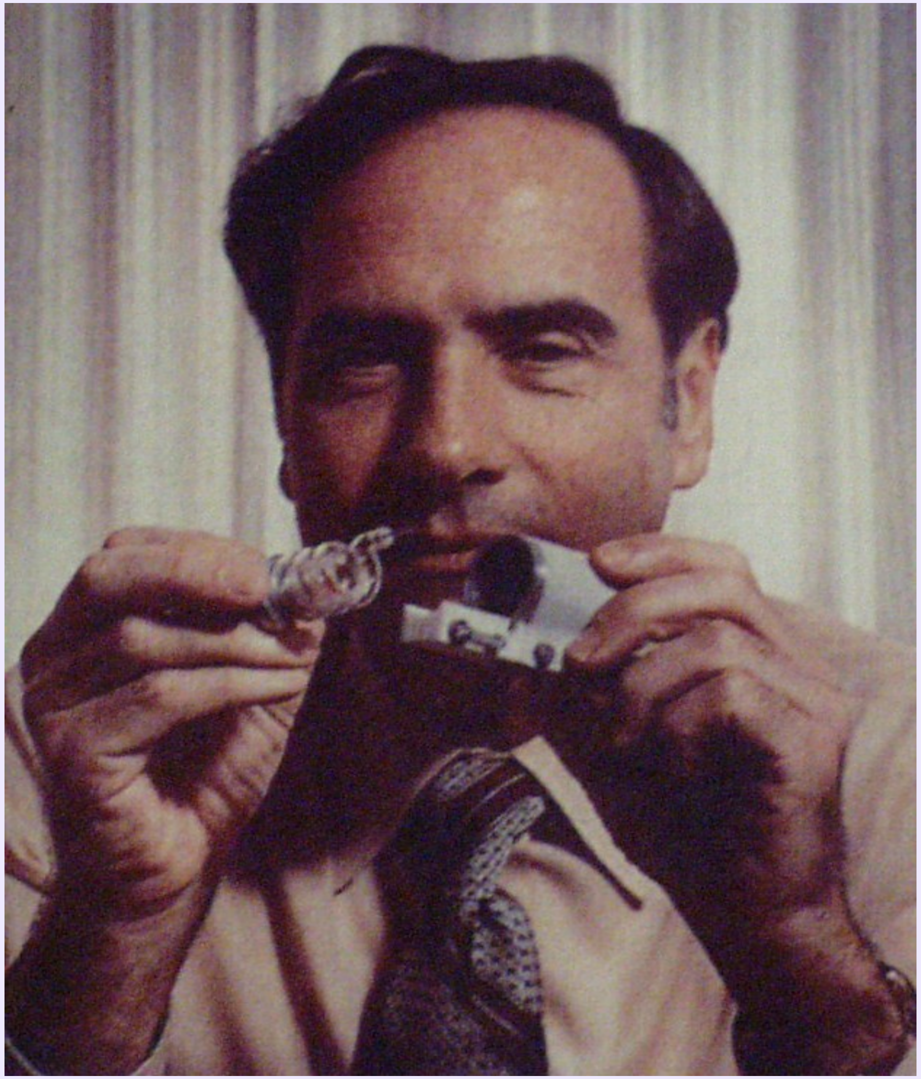
Attosecond = 0.000000000000000001 seconds

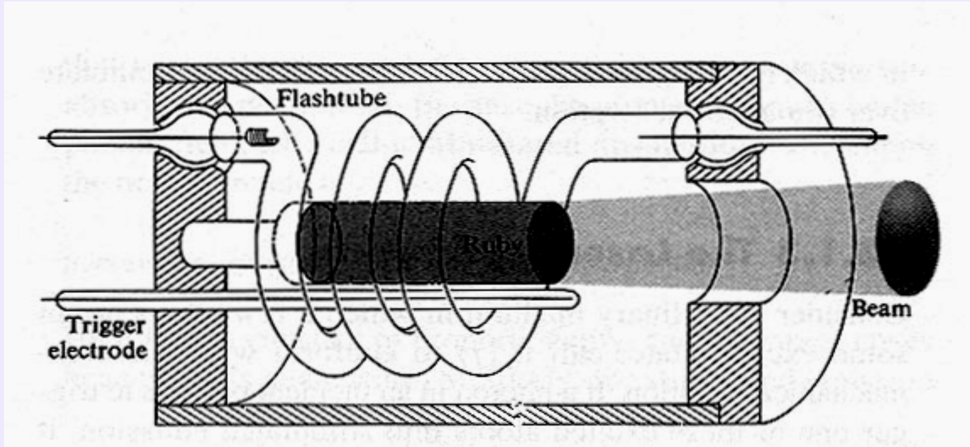
TIMESCALES - HOW FAST IS FAST ?

TIMESCALES - HOW FAST IS FAST ?



How does a LASER work ?





Theodore Maiman-1960

Inventor of the LASER

But first !

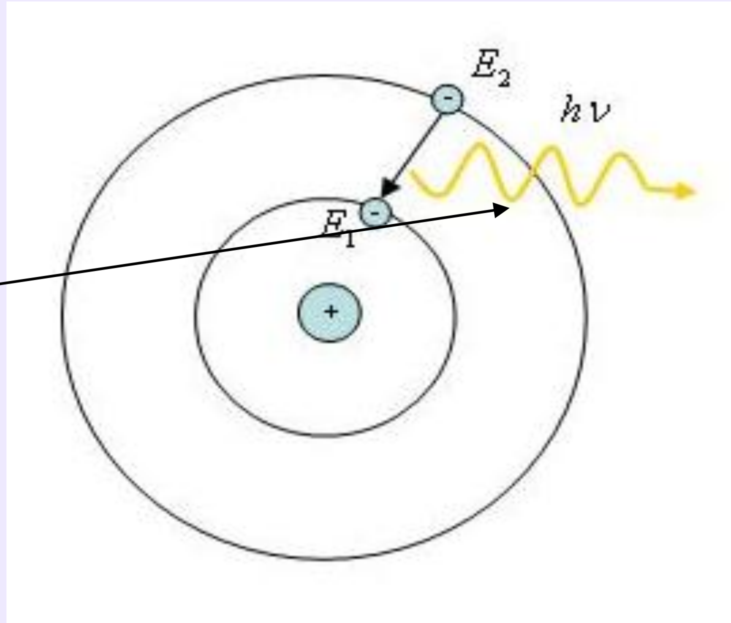
Question: What is the origin of light ?
Answer: When matter (solid, liquid or gas) is heated up to high temperature it emits radiation in the form of light. In fact it is the individual atoms that make up the matter that emit light…..

For example - when you light a fire the it is the carbon atoms in the coal that emit bright light……

However - we must look to see how an atom emits light:
Spontaneous versus Stimulated Emission

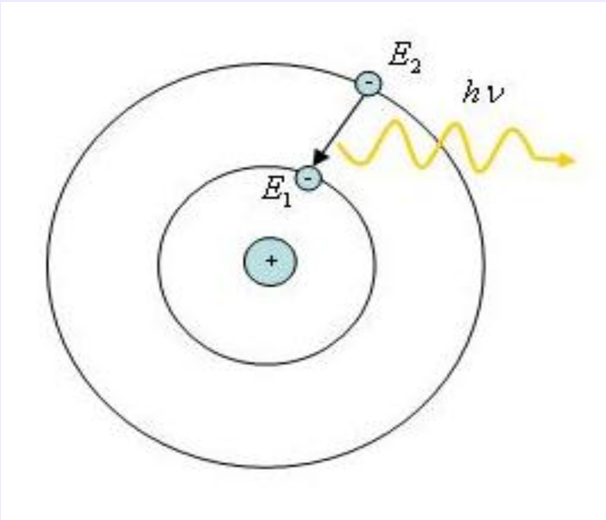
How does a LASER work ?

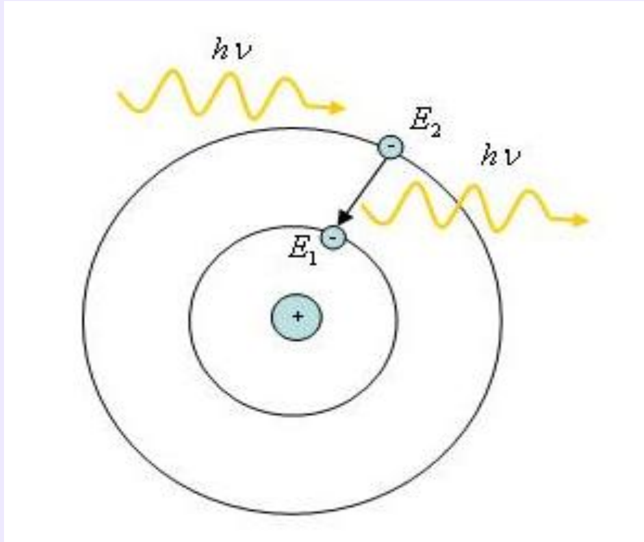
1. Every atoms is composed of a 'positively charged' nucleus at its centre surrounded by electrons which 'orbit' the nucleus - like a mini-solar system.
2. The size of the orbit depending on how much energy the electron has, i.e., the most energetic electrons are furthest from the nucleus.
3. If an electron loses energy it drops down from a higher to a lower orbit and 'emit' the energy lost as a packet of light known as a 'Photon'
4. This is the basic process by which atoms radiate light and is called 'spontaneous emission'.



How does a LASER work ?

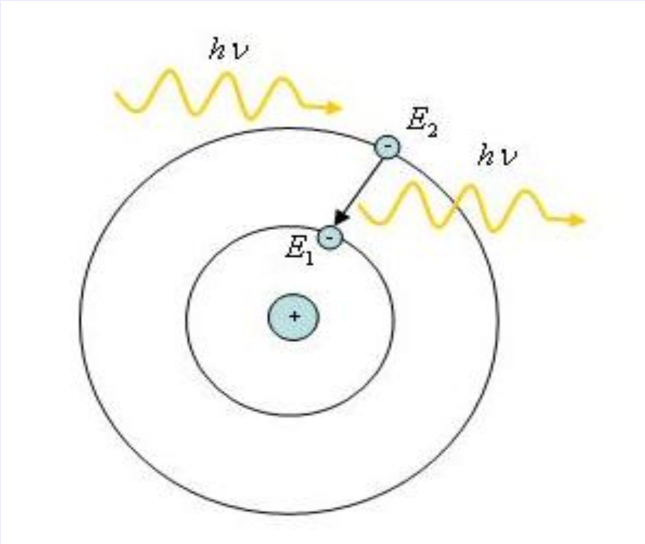
Now look at the picture below on the right hand side and compare with the original on the left hand side…



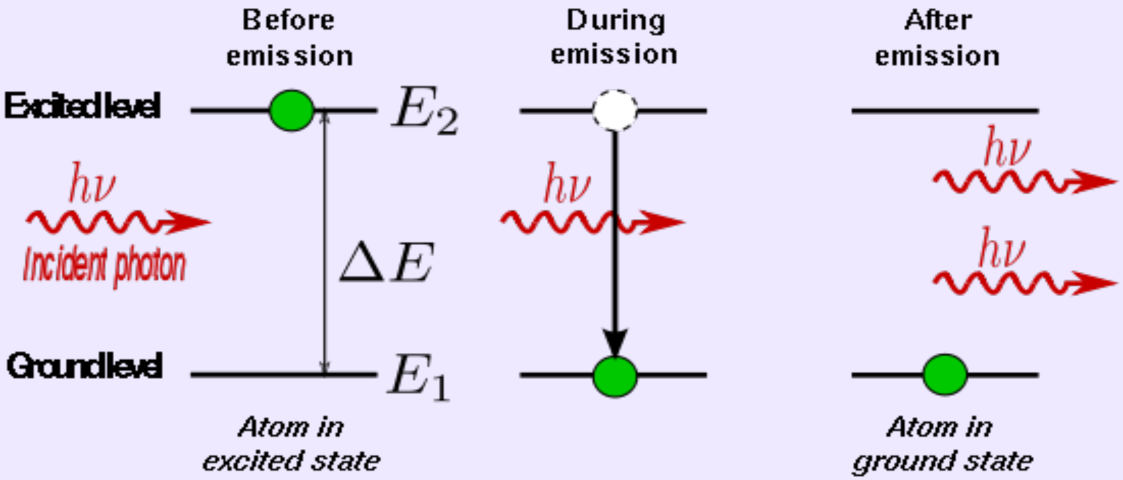


On the right hand side, a photon emitted from another atom (e.g., the one on the left hand side) causes the atom on the right hand side to emit a another photon - *this process is known as 'stimulated emission' and the result is 'Light Amplification'….*

How does a LASER work ?



If an atom has an electron orbiting around the nucleus with an energy E_2 and it slows down so that its energy becomes E_1, then it will emit a 'photon' of energy E_2 - E_1. The wavelength of the light emitted can be calculated from:



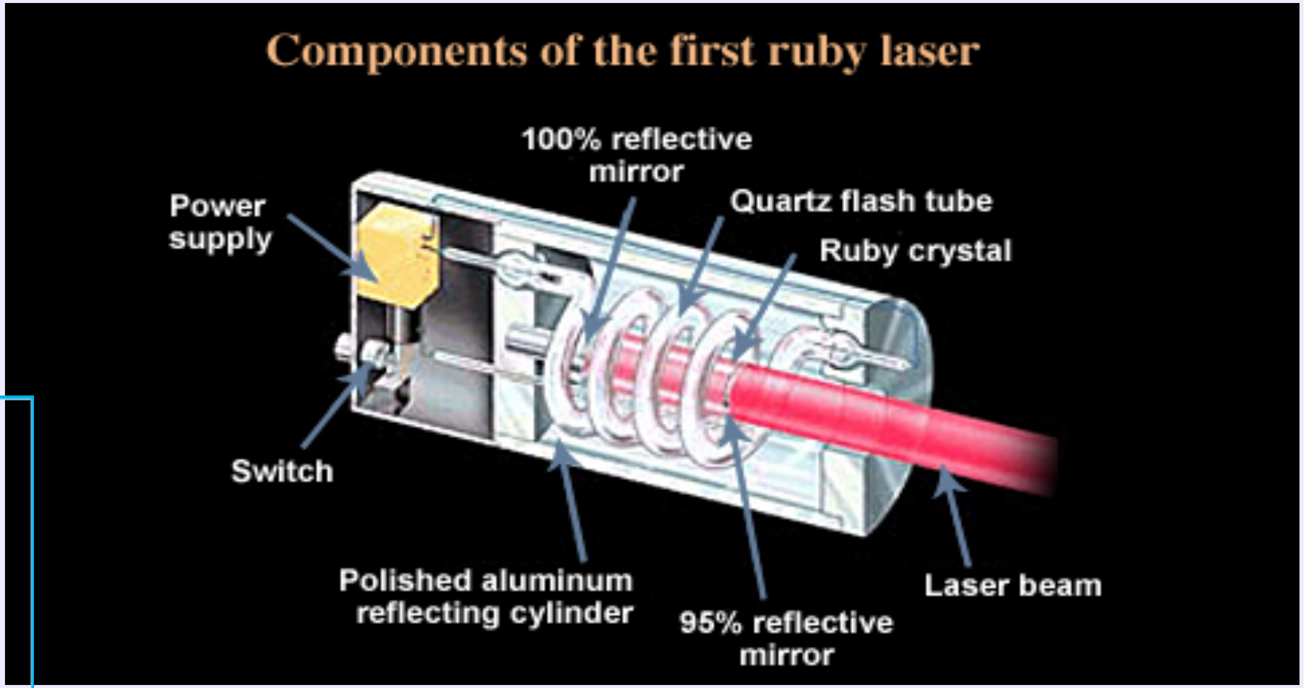
$$E_2 - E_1 = \Delta E = h\nu$$

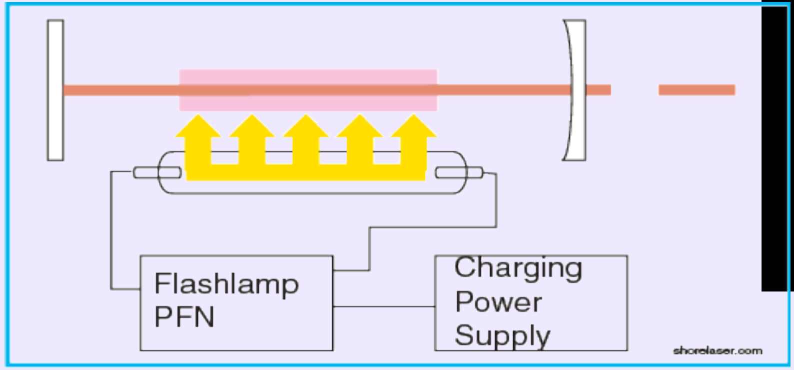
$$h\nu = \frac{hc}{\lambda} = E_2 - E_1$$

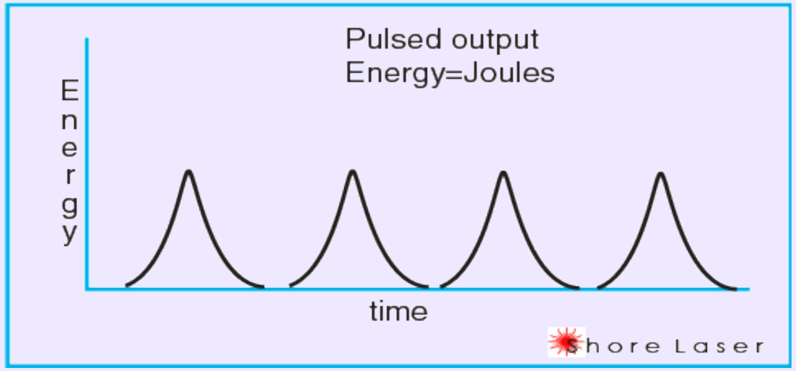
ν = frequency

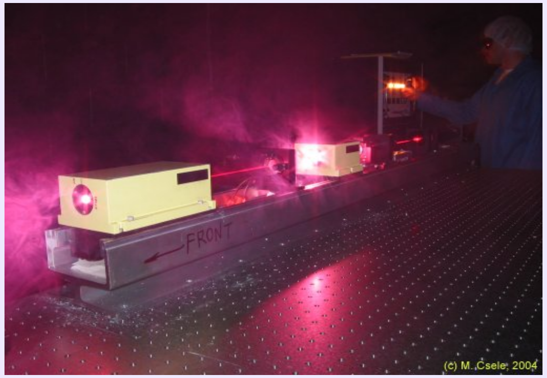
λ =wavelength

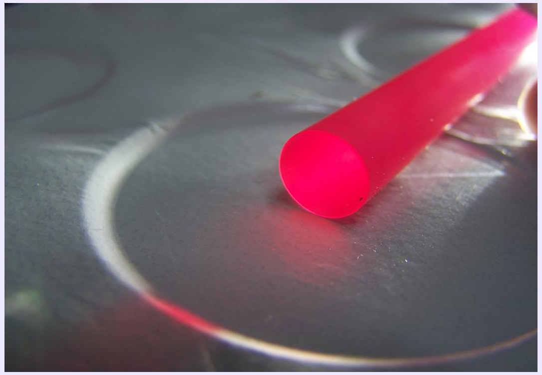
How does a LASER work ?







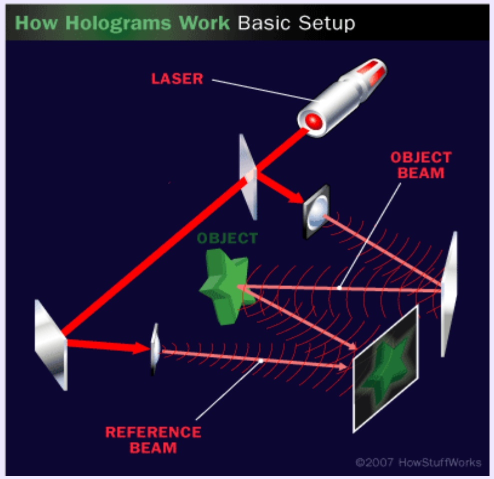


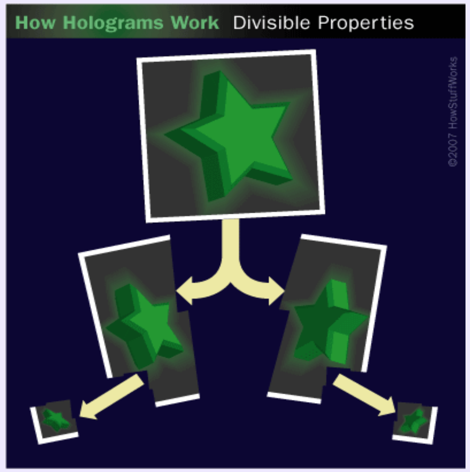


How does a LASER work ?

How is laser light different to ordinary light from an ordinary bulb ?

1. It is collimated (it forms a parallel beam)
2. It is monochromatic (single colour)
3. It is coherent (so that you can make holograms)





Part II - Ultrafast Lasers (Strobe Lights)

What is an ultrafast laser ?

Put simply it is a laser where the pulse duration is a few picoseconds or less…………….

Ultrafast lasers have applications ranging from cancer (photodynamic) therapy, to freezing the motion of molecules to study chemical reactions, to making the most accurate clocks in the world (atomic clocks) and making 'fusion energy plasmas'……

Ultrafast Lasers (Strobe Lights)

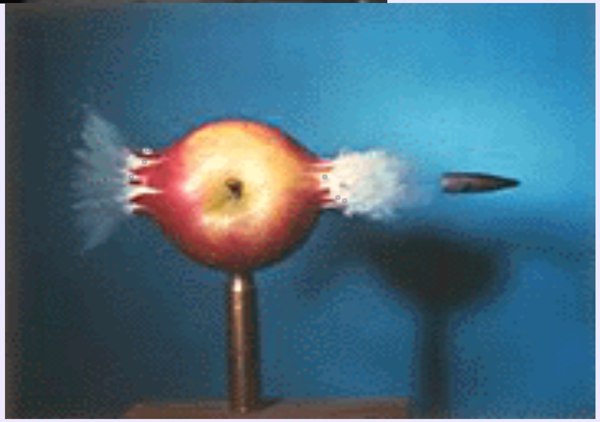
Harold Edgerton - Ultrafast Pioneer

Using a Pulsed Strobe Light

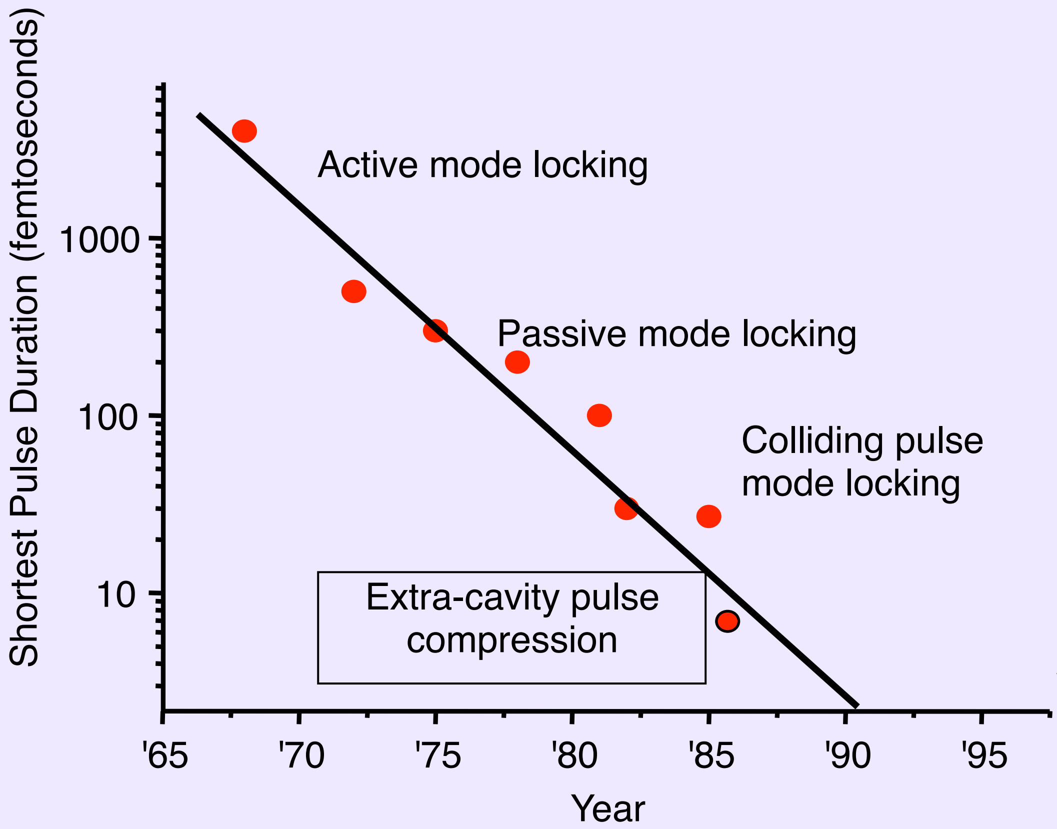
Harold Edgerton MIT, 1942

Time Resolution: a few microseconds

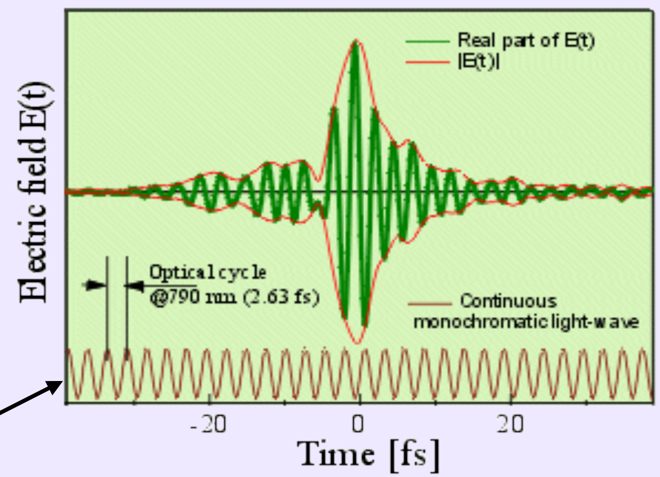
“How to Make Tomato Ketchup and Apple Sauce at MIT” 1964



How short in time can you make the pulses ?



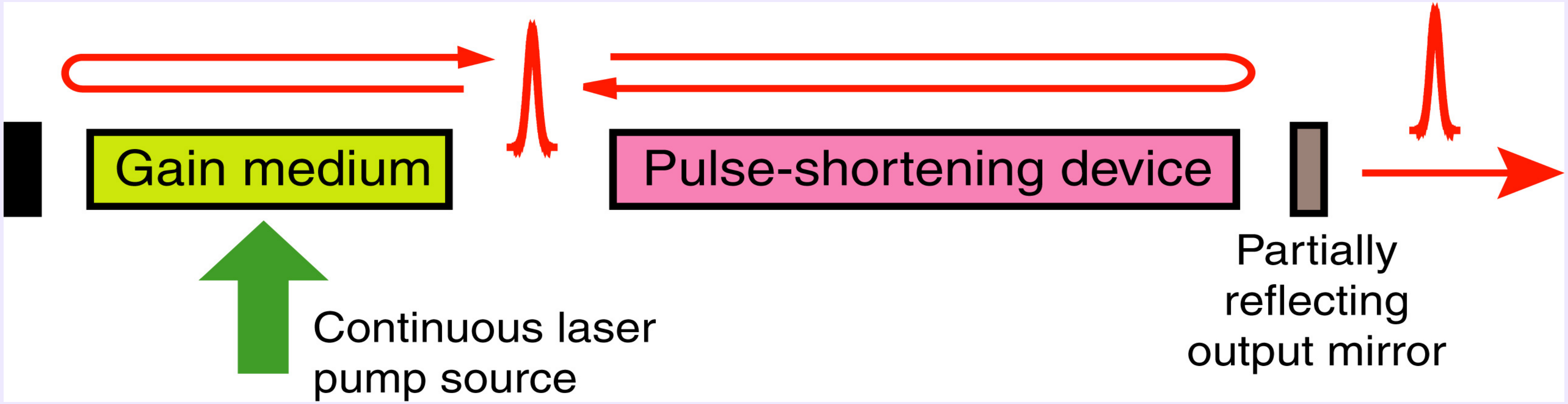
A 4.5-fs pulse…



Current record:
4.0 femtoseconds -

1fs = 10^{-15} seconds !

Part II – How do you do that ?

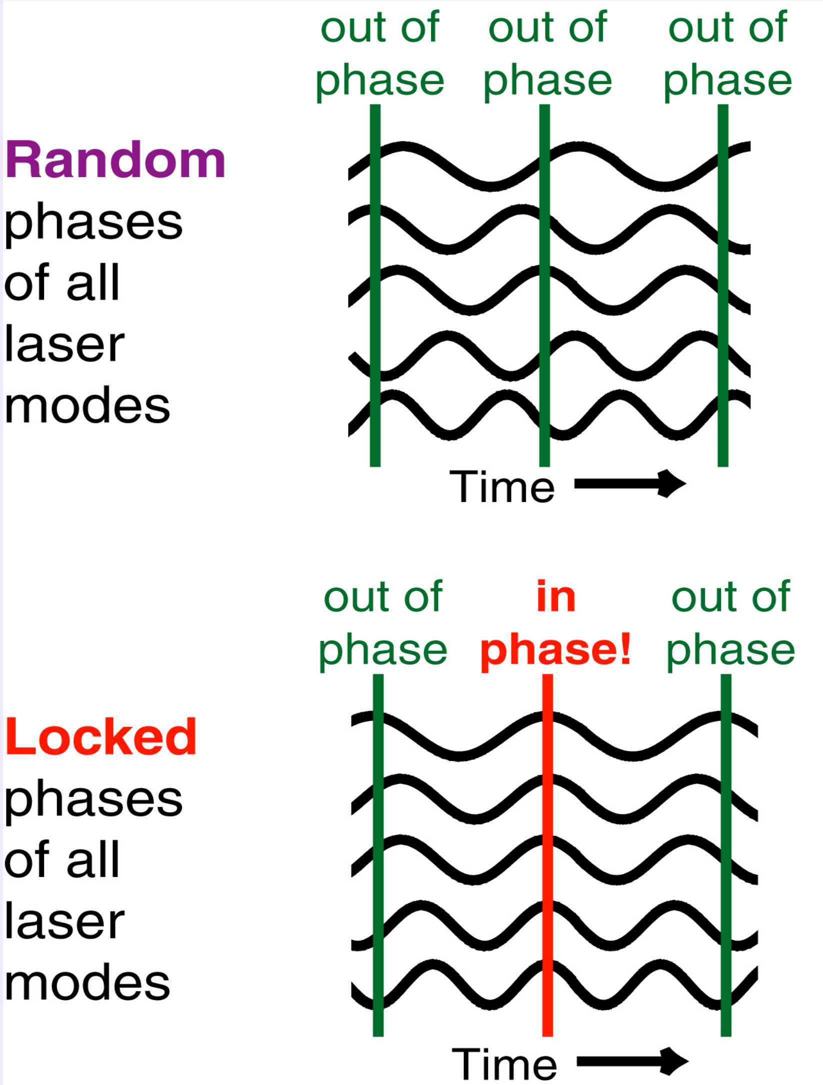


FASTER LASERS =>
HIGHER INTENSITY

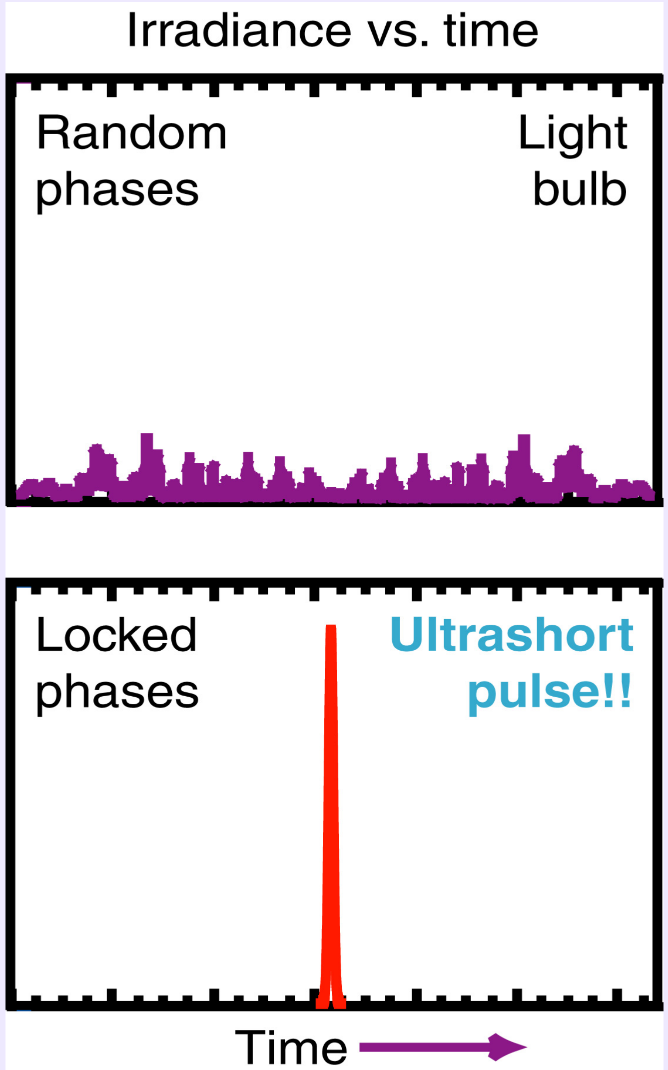
Into the nanosecond regime
Q-switching (10 - 100 ns pulses)
P = 1J/10 ns = 100 MW

Into the picosecond regime
Mode-Locking (100 - 1000 ps pulses)
P = 1J/100 ps = 10 GW

Modelocking to make really short pulses



Add up the (Harmonic) sinusoidal electric fields (Modes)

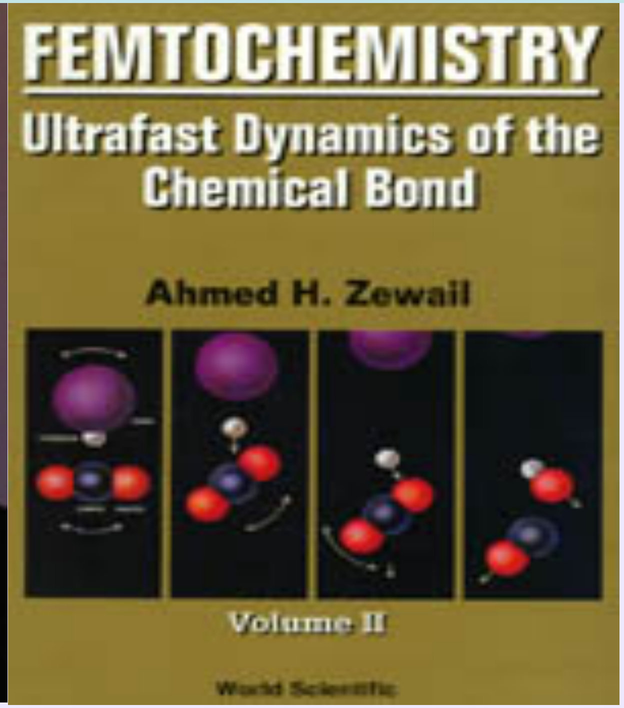


FEMTO-PHYSICS - NOBEL PRIZE

The **2005 Nobel Prize** was awarded to Ted Haensch for his work on ultrfast lasers (frequency comb) for precise optical metrology and spectroscopy

FEMTO CHEMISTRY - NOBEL PRIZE

The 1999 Nobel Prize in Chemistry went to Professor Ahmed Zewail of Caltech for ultrafast spectroscopy.



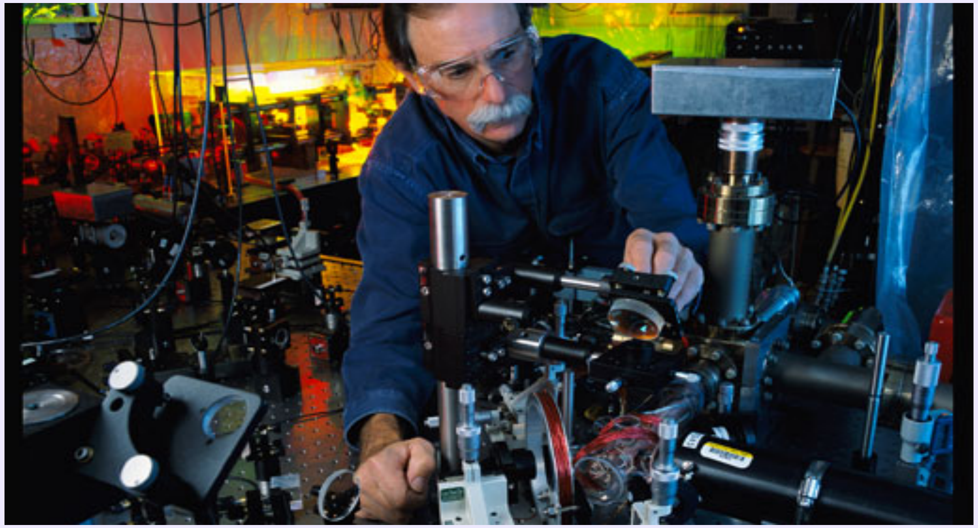
Zewail used ultrafast-laser techniques to study how atoms in a molecule move during chemical reactions.

NOBEL PRIZE PHYSICS – 2012

The 2012 Nobel Prize in Physics went to Dr Serge Haroche and Dr David Wineland for fundamental laser experiments…

Serge Haroche

David Wineland



Part III - Into the future
Lasers, Plasmas &
Even More Extreme Physics

Faster ? Attosecond (as) 10^{-18}s

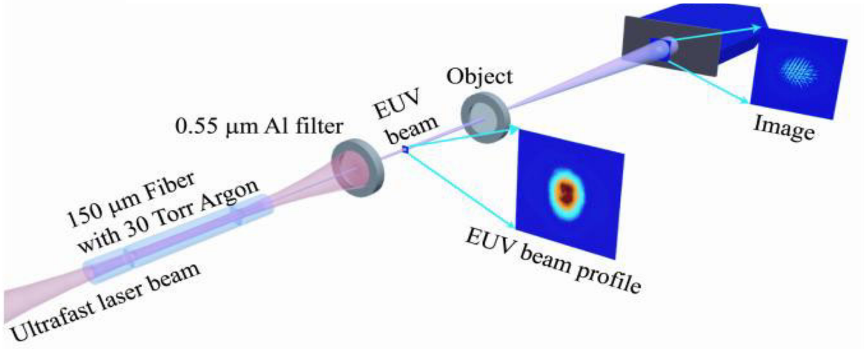
Brighter ? Petawatt (PW) 10^{15}W

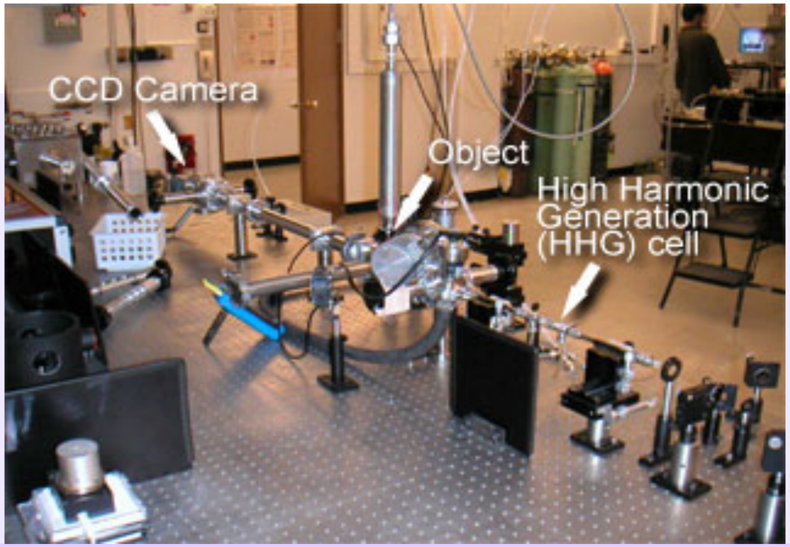
Even Shorter

Wavelength ? *X-ray (0.1 nm)*

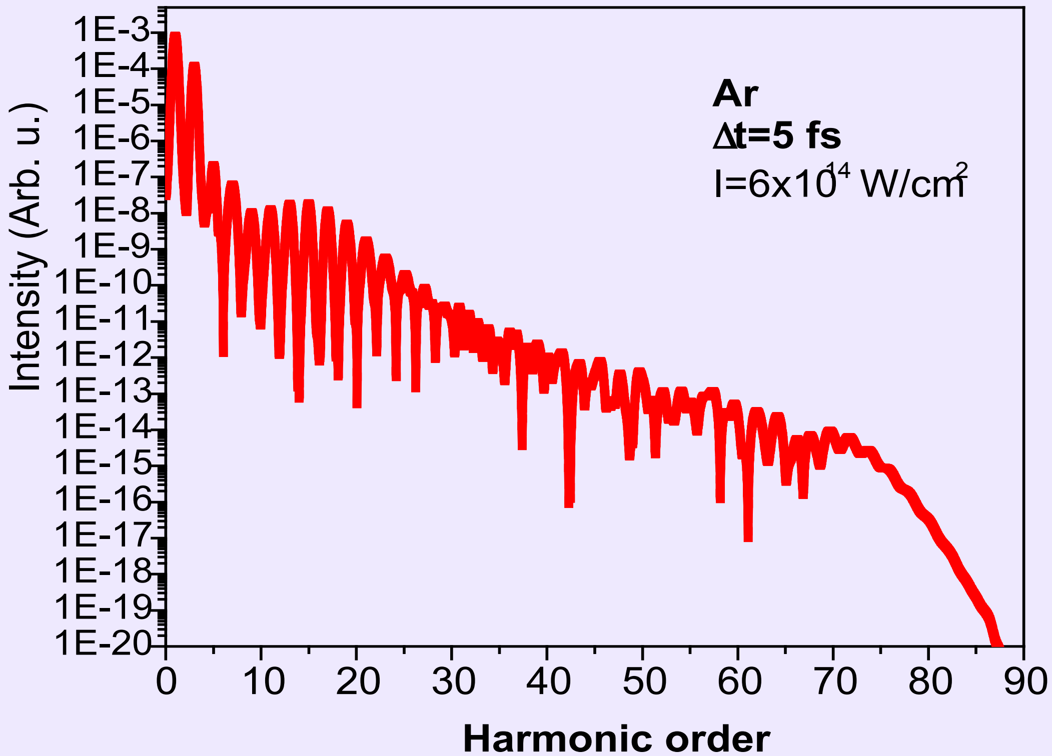
FASTER - Attosecond (10^{-18}s) Pulses

If you focus a fs laser into a gas you generate a series of Harmonics of the laser frequency just like the Modes in a laser cavity
If you adjust the shape and phase of the fs pulse correctly you can Modelock these harmonics - the summed harmonics = a spike of attosecond duration



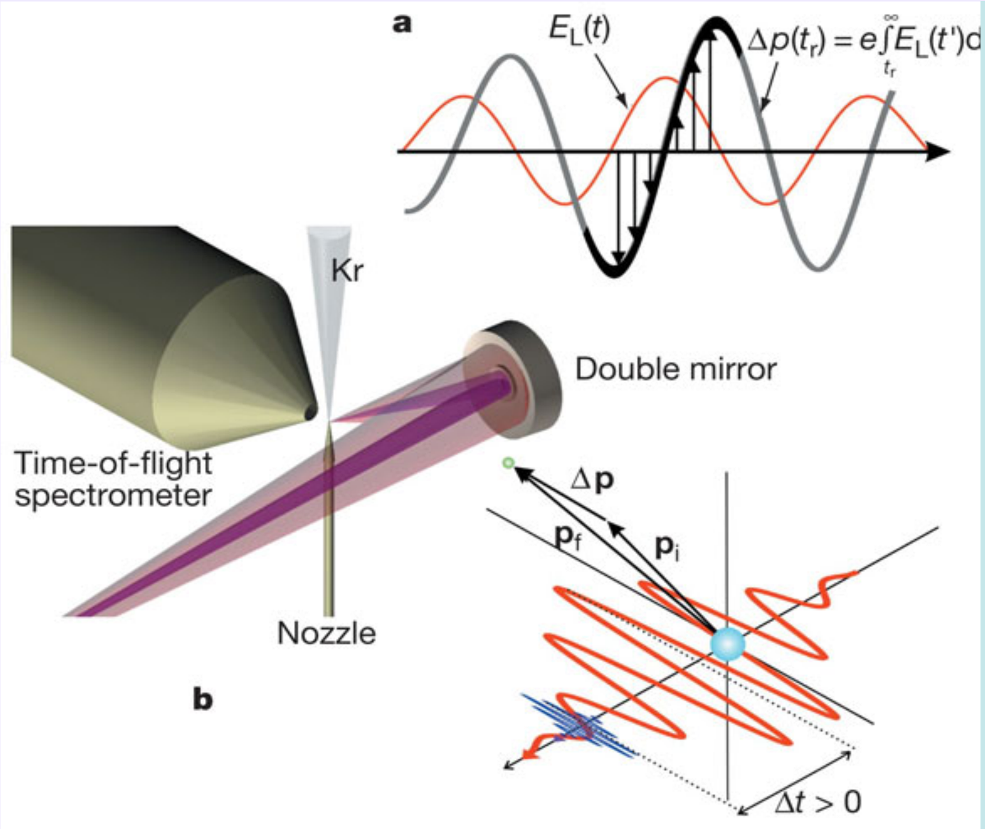


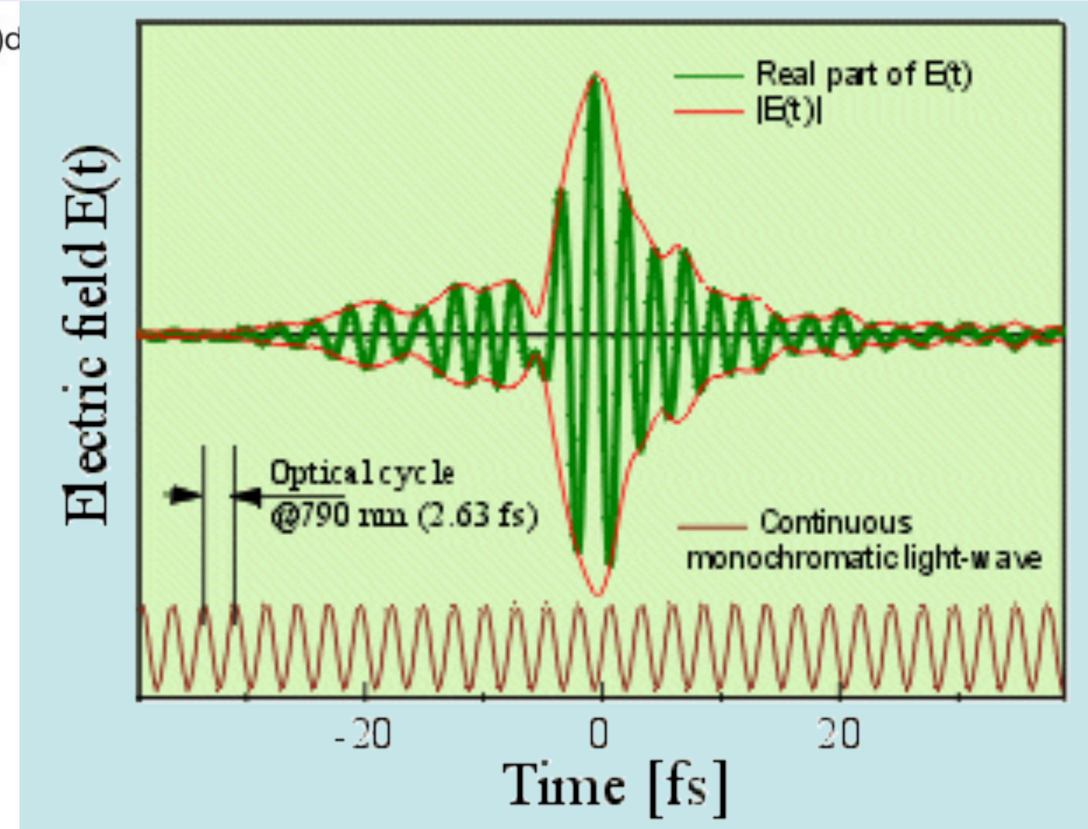
Murnane & Kapteyn - Colorado



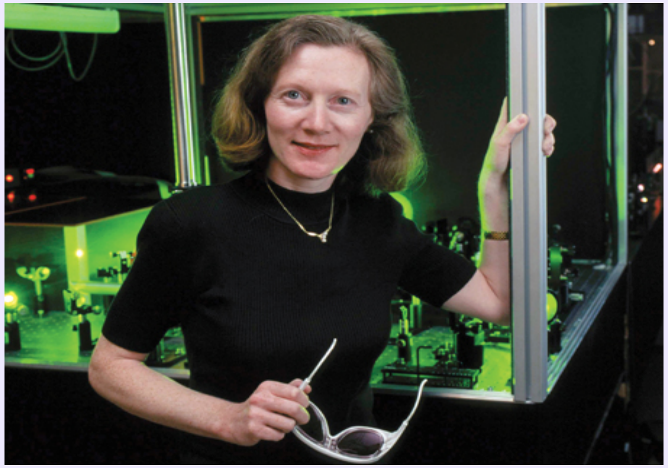
An attosecond framing camera - Seeing the electric field of a fs pulse !

Krausz et al. MPI, Garching, 2004





Who are the Attosecond Pioneers ?



Margaret
Murnane
JILA/ Univ. Boulder
Colorado,
USA

Paul
Corkum
Natl Res Council
Ottawa
Canada

Ferenc
Krausz
Max-Planck Institute
Garching,
Germany

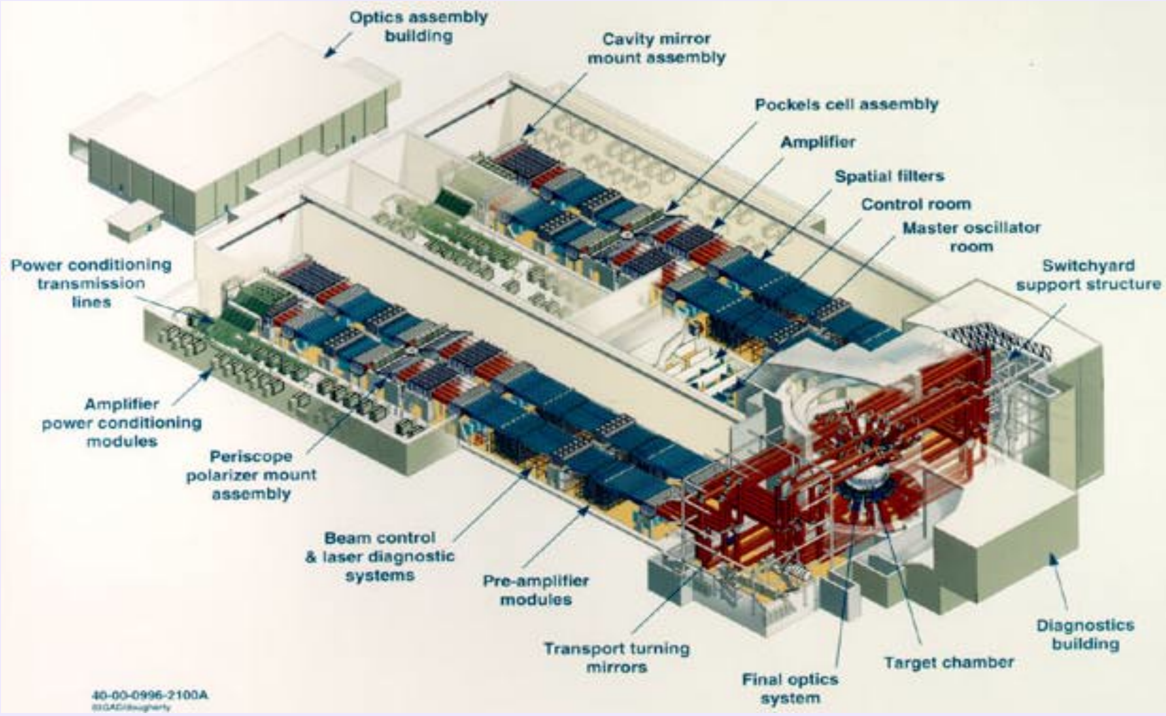
BRIGHTER - ‘PETAWATT’ LASERS

NIF - USA

OTHERS LMJ & ELI-Nuclear

All designed to create Fusion Energy Plasmas

NIF (USA) Even Higher Intensities!

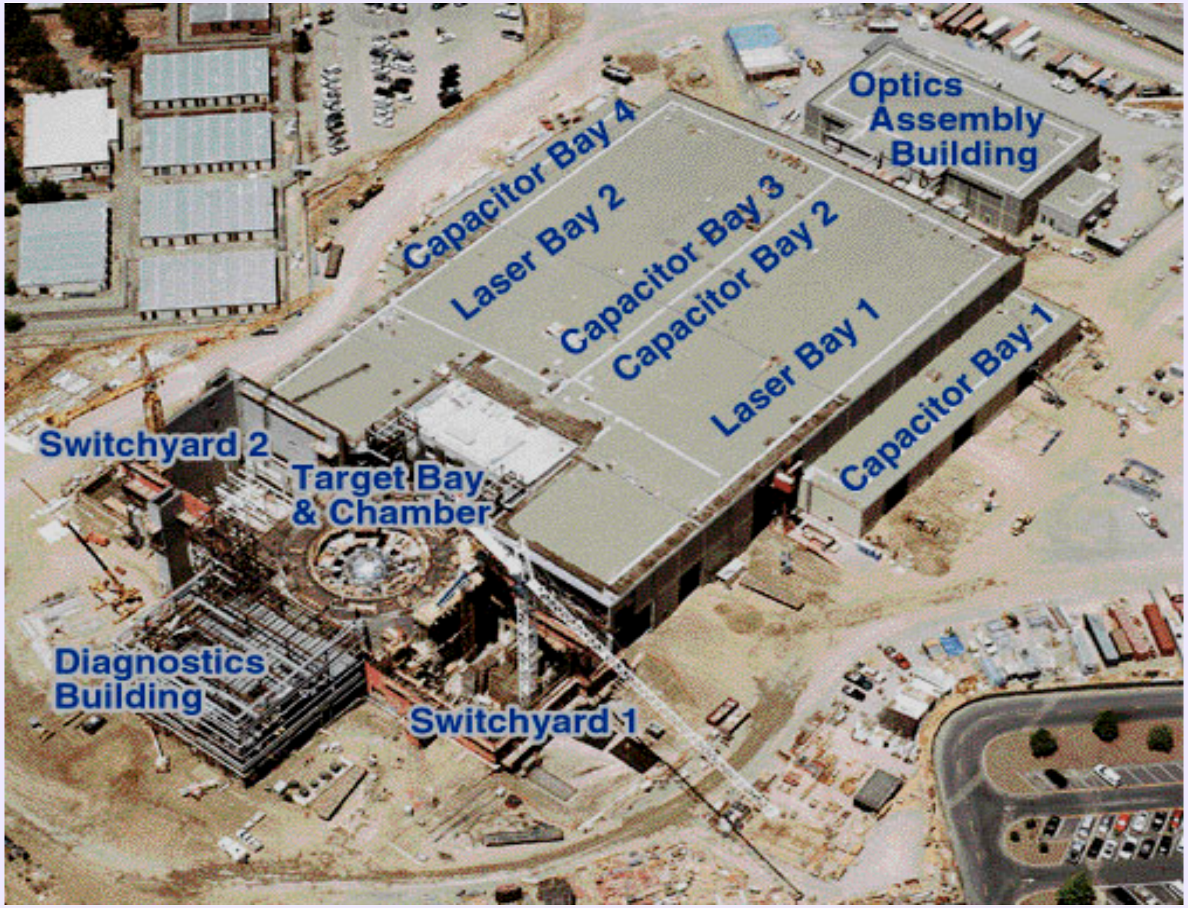


National Ignition Facility

NIF achieves plasma temperatures and densities ten times greater than those in the sun's core and pressures far in excess of those at the core of Jupiter.

192 shaped pulses - 4 Mega Joules in 1 ns = 4 Petawatts peak power !!!

NIF (USA) Even Higher Intensities!



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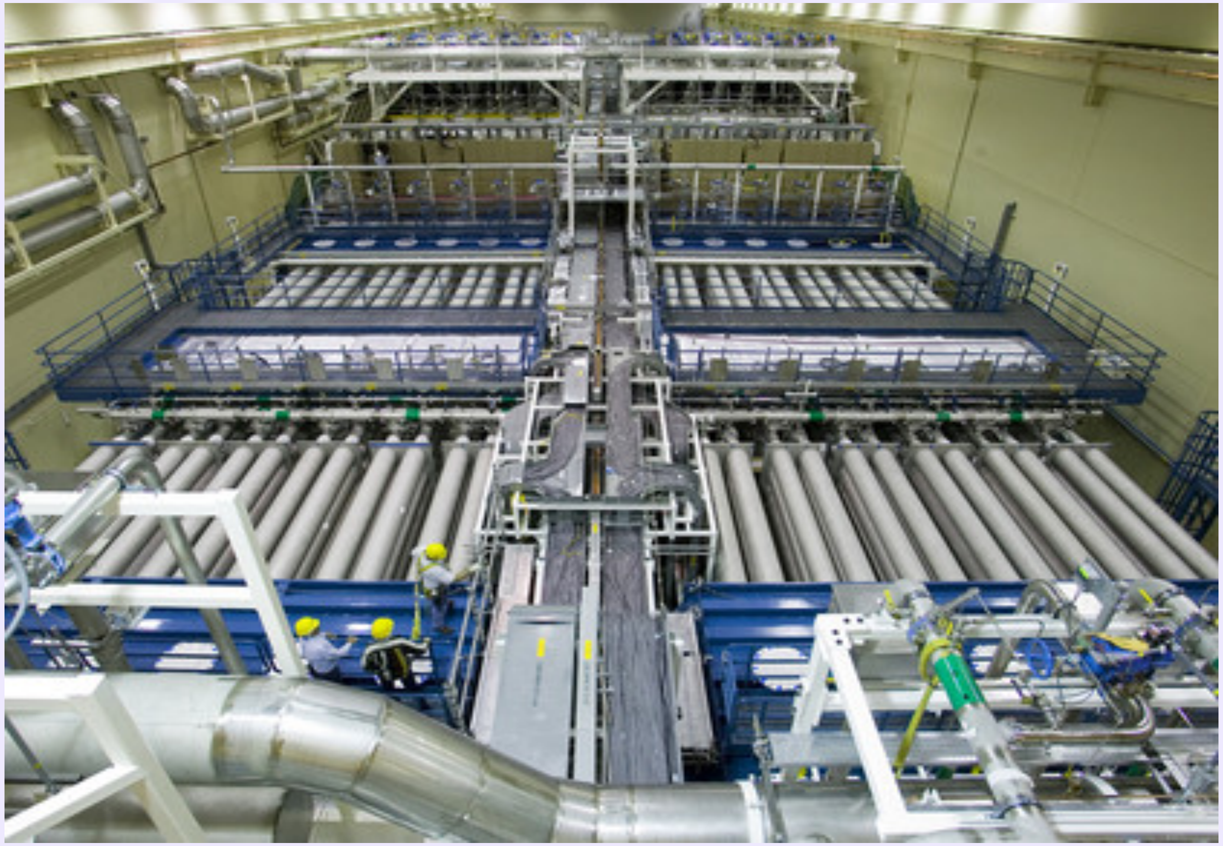

National Ignition Facility

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What is a Plasma ?

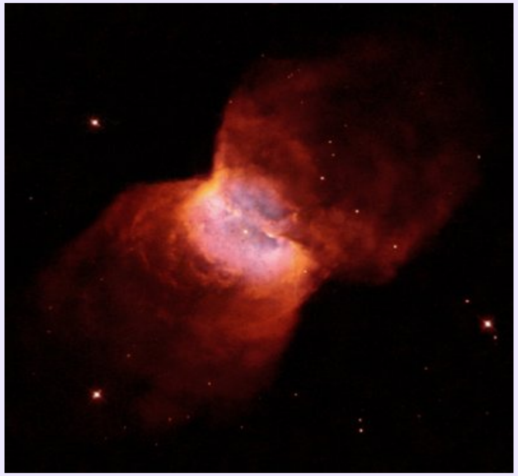
At such power densities solid matter is instantly turned into plasma !!

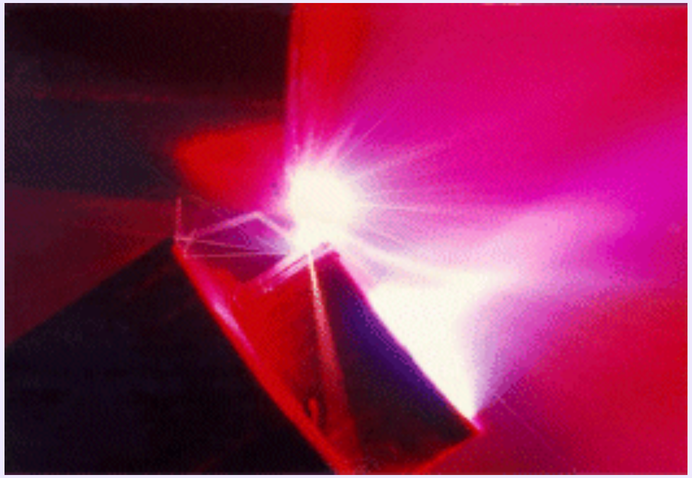
Greek Philosophers	***Physicists***
Earth	Solid
Water	Liquid
Wind	Gas
Fire	**Plasma**

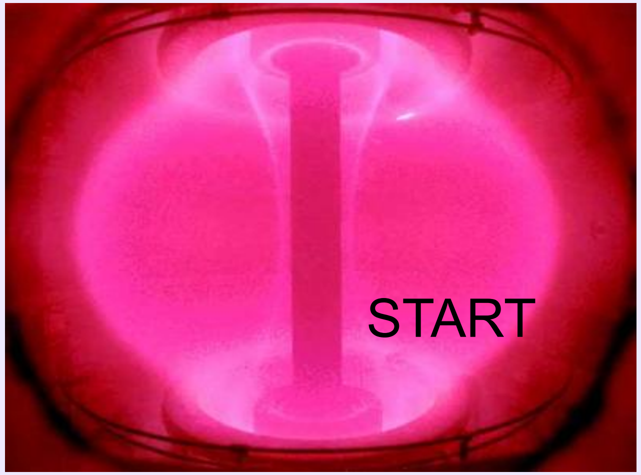
Plasma: Fluid (gas) of electrons and ions

WHY STUDY PLASMAS ?

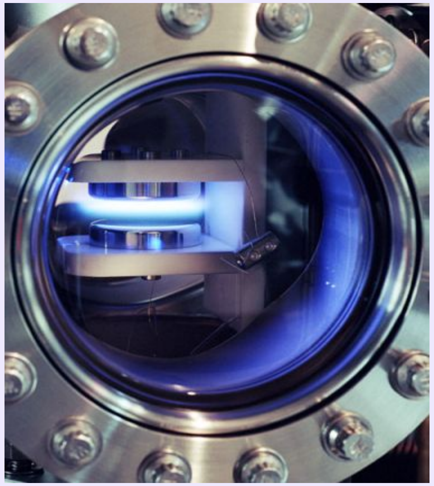
NGC
2346



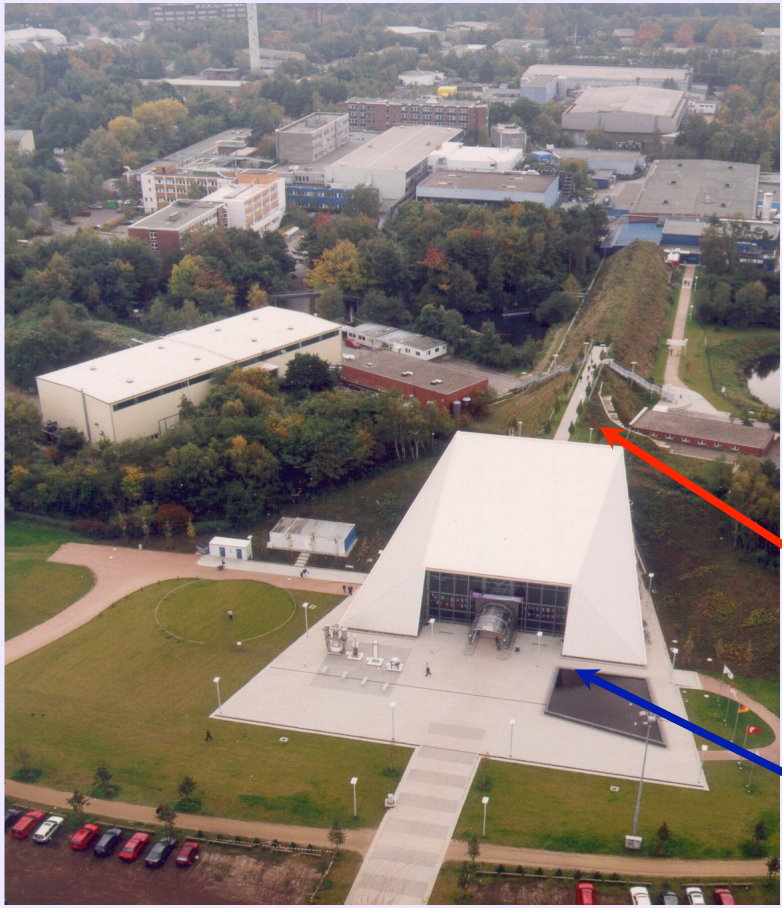


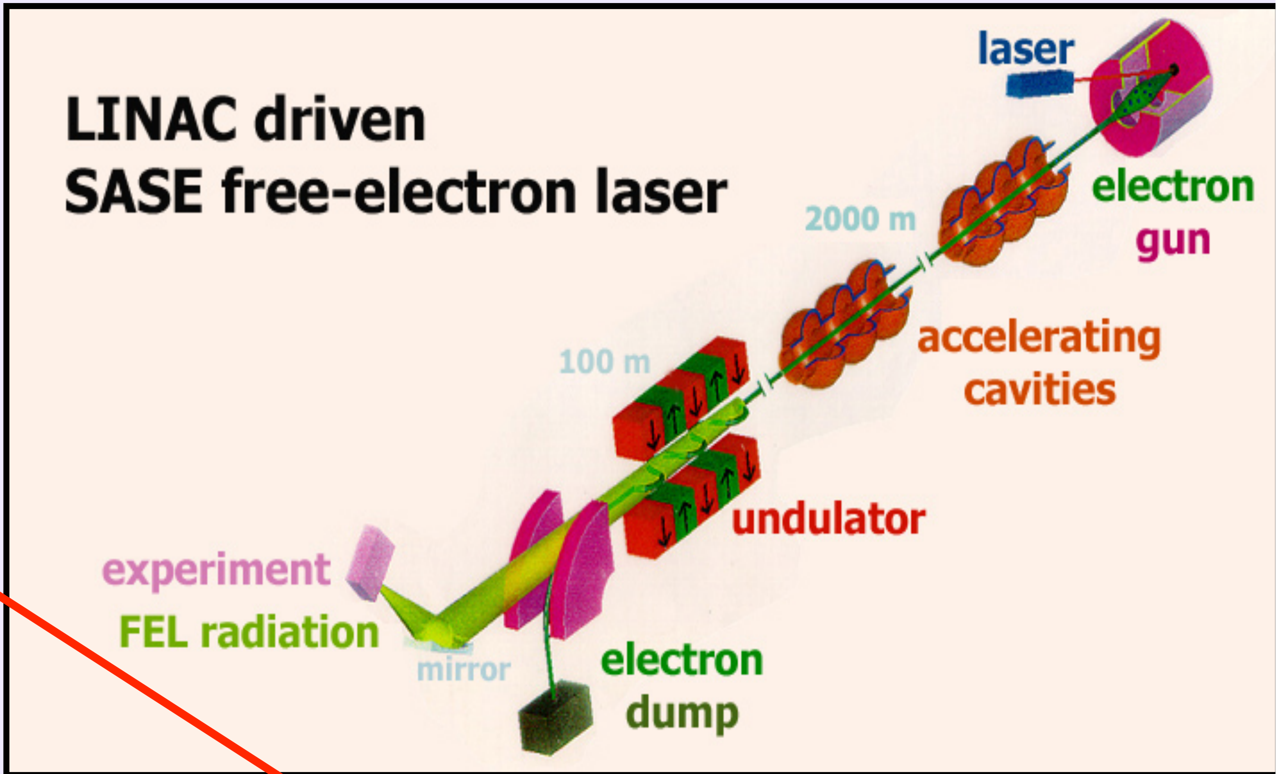


Plasma Process
Chamber at DCU
Research for
INTEL in Lexilip



Deeper - Free Electron Lasers (FELs) in the VUV, EUV and X-ray

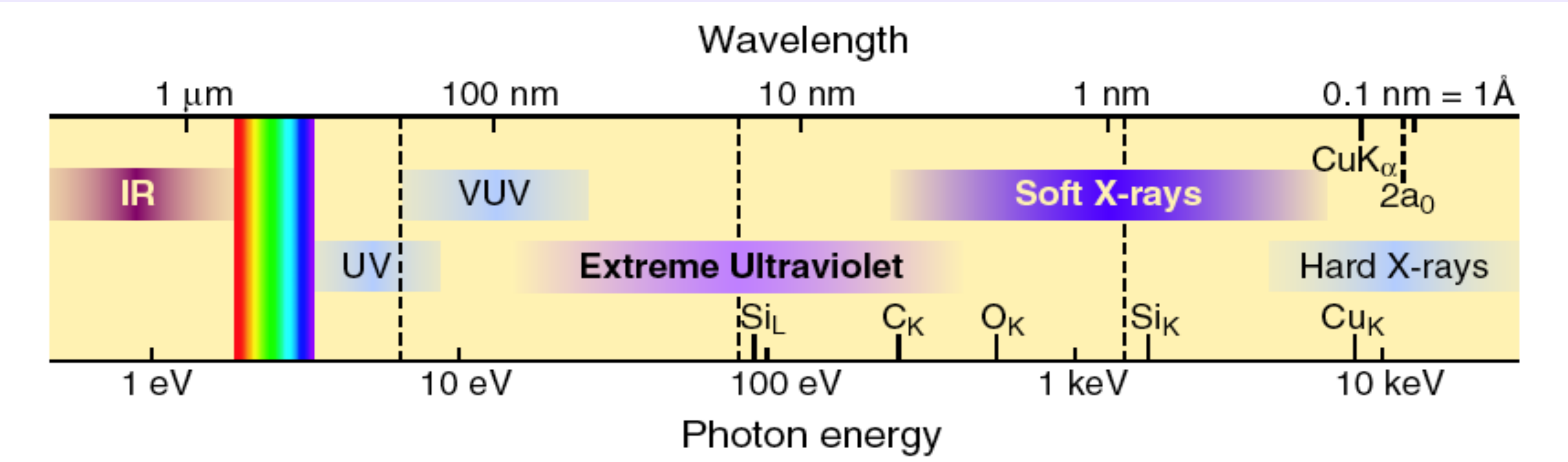




Hamburg FEL
Tunnel &
Experimental Hall

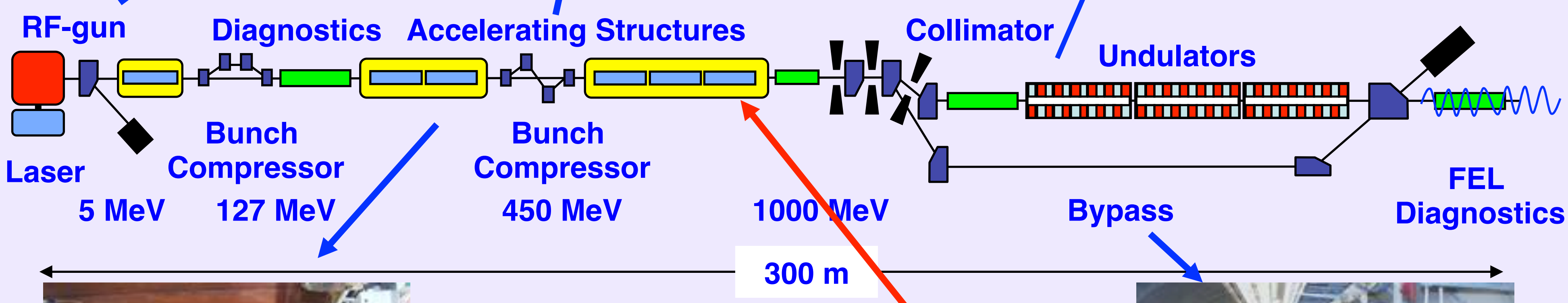
VUV, EUV and X-ray - Free Electron Lasers (FELs)

'Laser-like' radiation in the Extreme-UV
(From ~0.1 to 60 nm)



FLASH FEL - Operation/Physical Layout

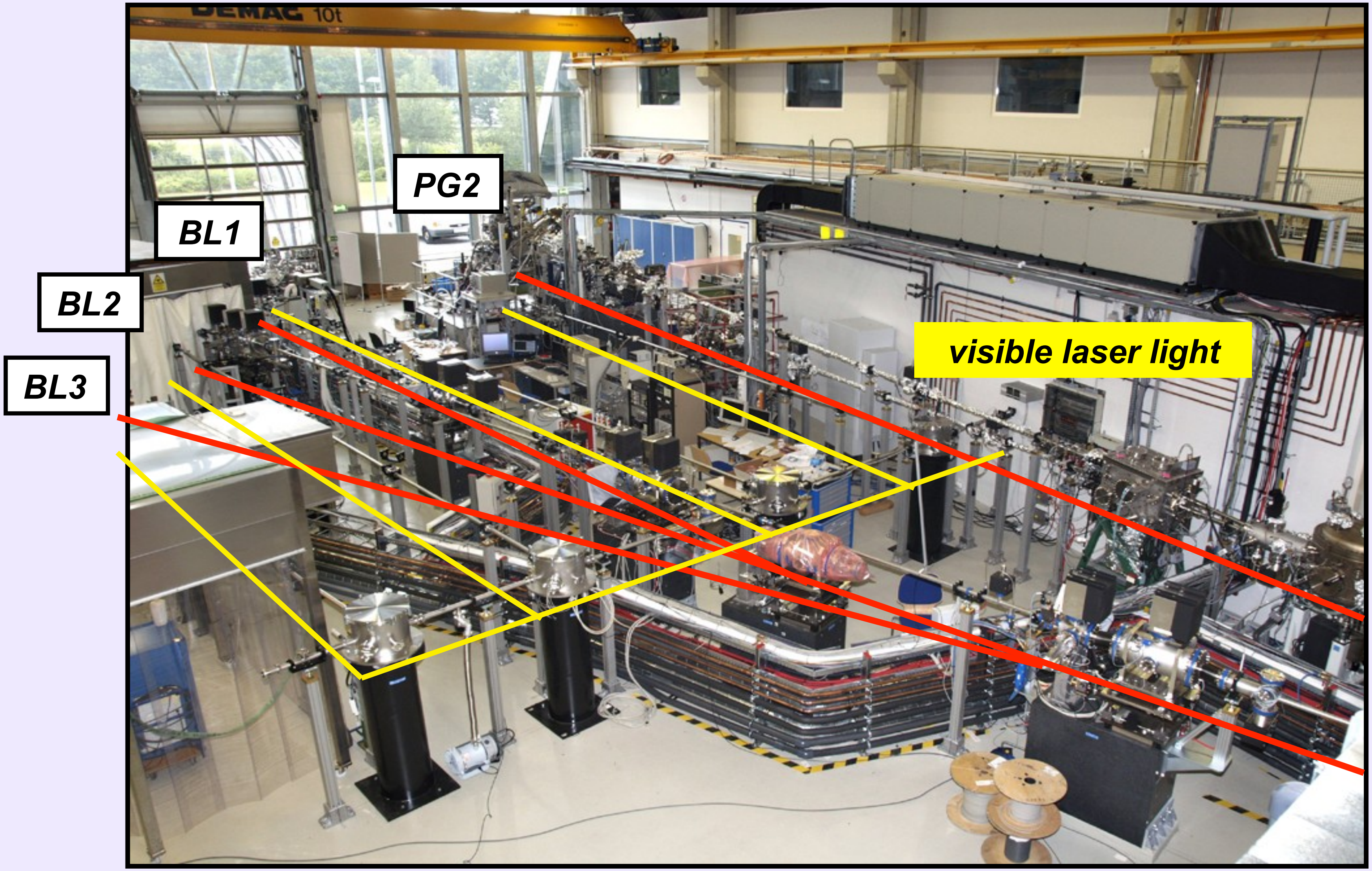


LINAC Energy : ~ 1 GeV

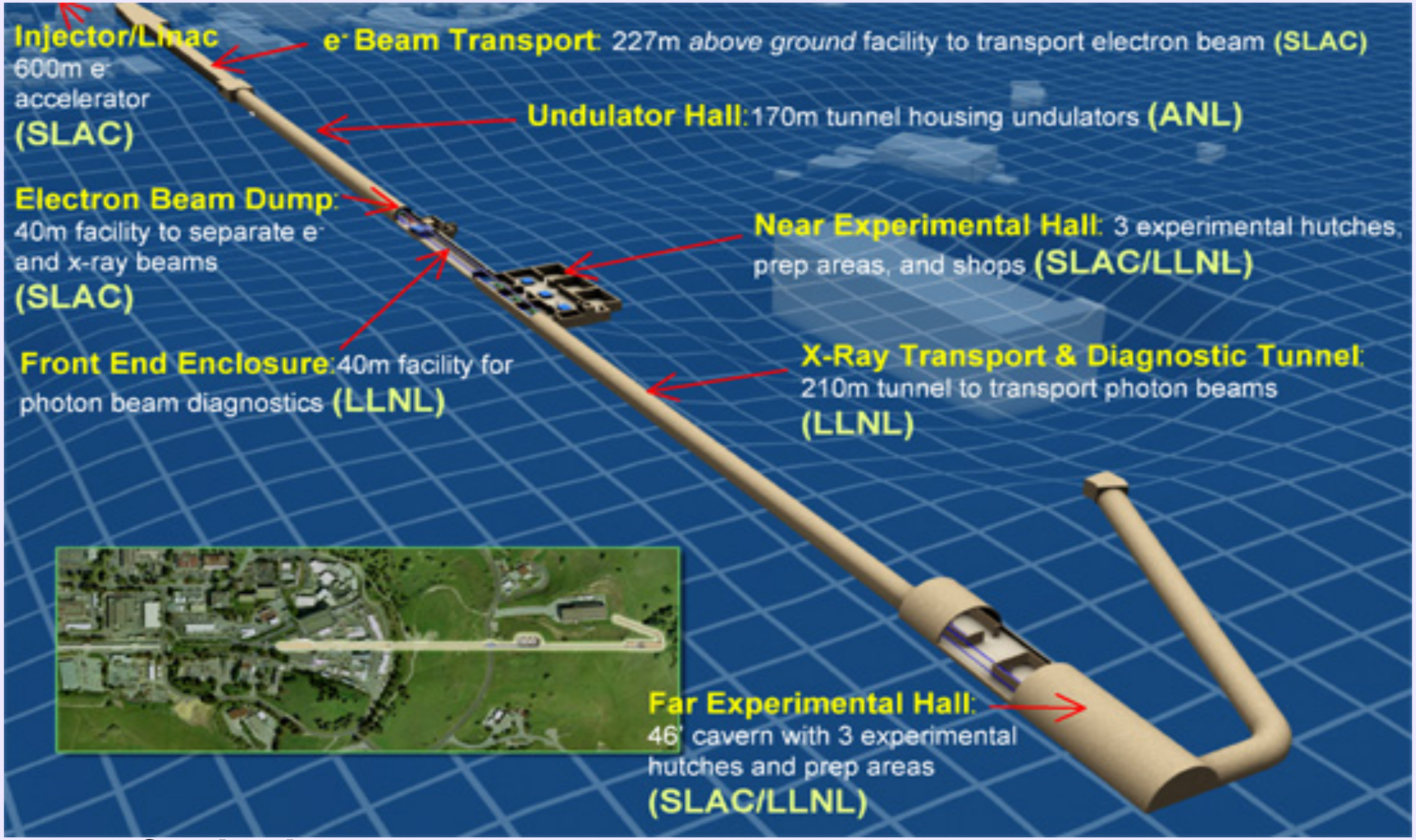
Wavelength ~ 4 – 60 nm

FLASH NIR/UV and XUV Beam Layout



(Big) X-ray FEL in Stanford University

LINAC Coherent Light Source - LCLS



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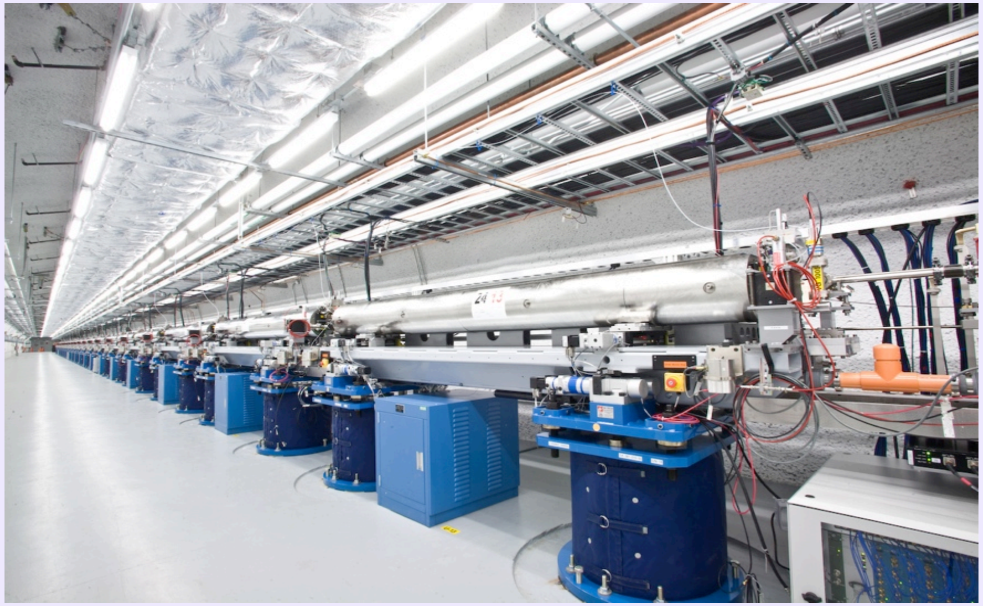
X-ray Free Electron Lasers (FEL)

LCLS Overview and Specifications



Electron Linear Accerator (LINAC) Tunnel – 4km long

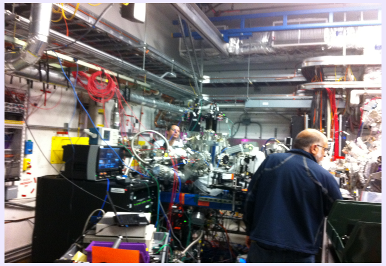
Undulators in which electron bunches create X-ray pulses

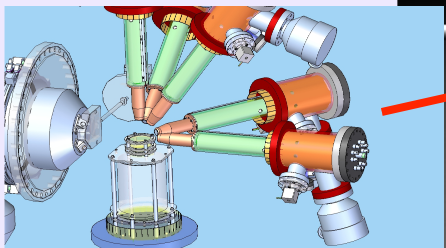
Nature Photonics 4, pp 641-647 (2010) / lcls.slac.stanford.edu

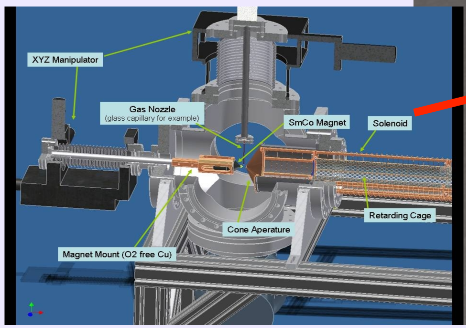
Inside the AMO Hutch at LCLS

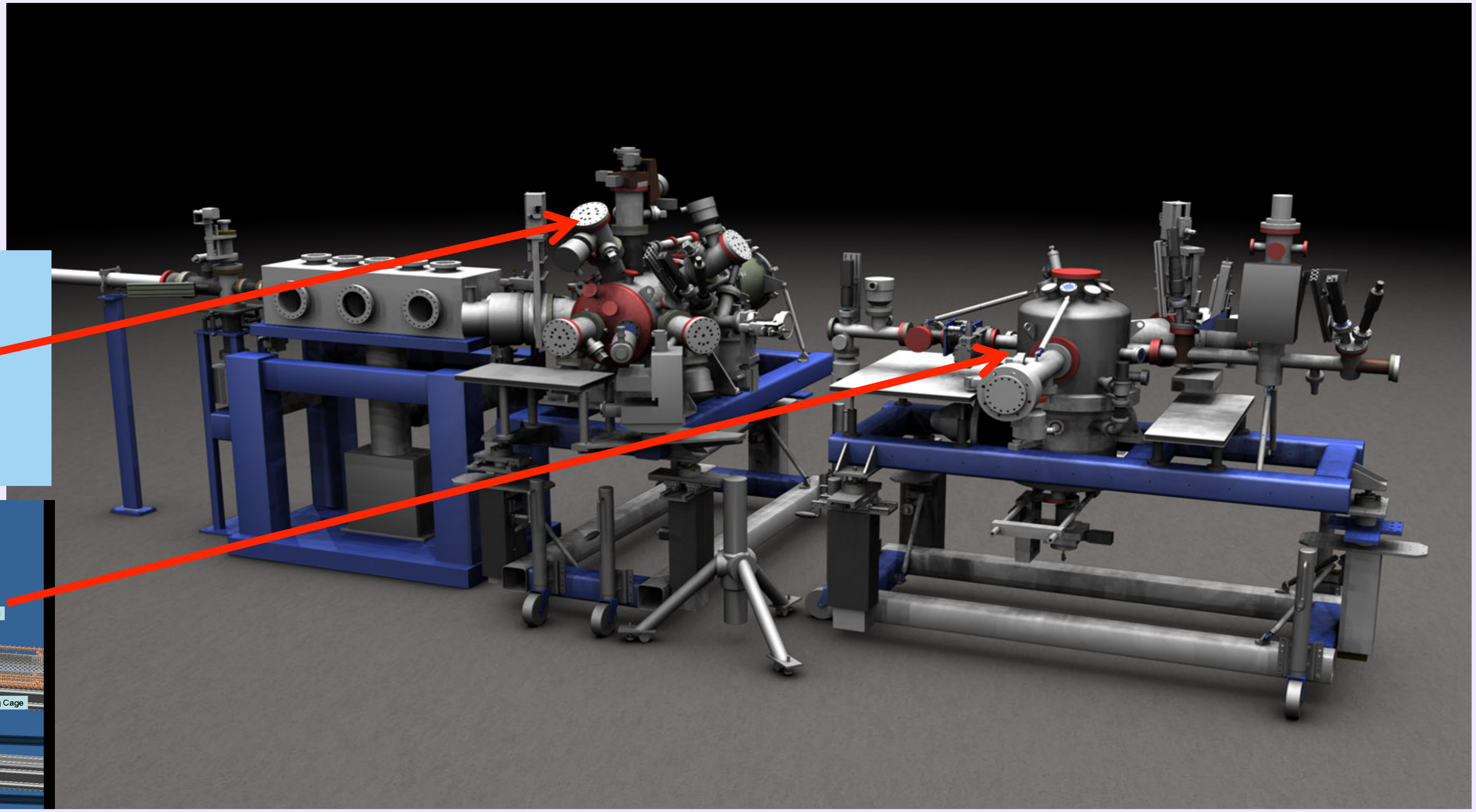
Rendered Image:

High Field Chamber (AR-ETOF) and Diagnostics (MBES) Chamber









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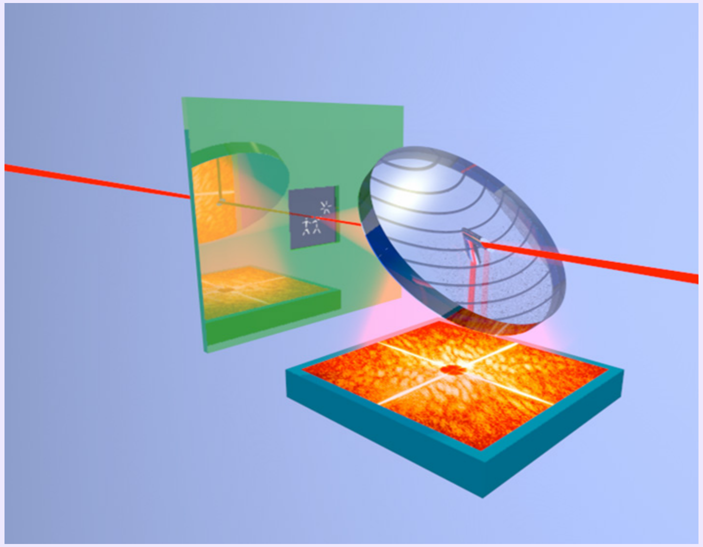
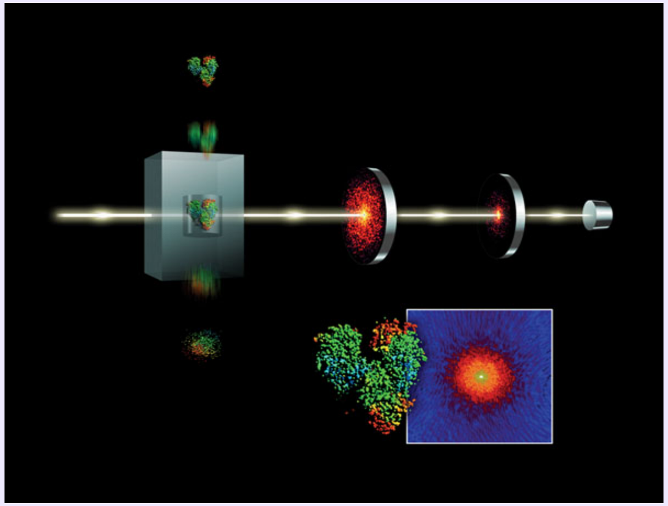
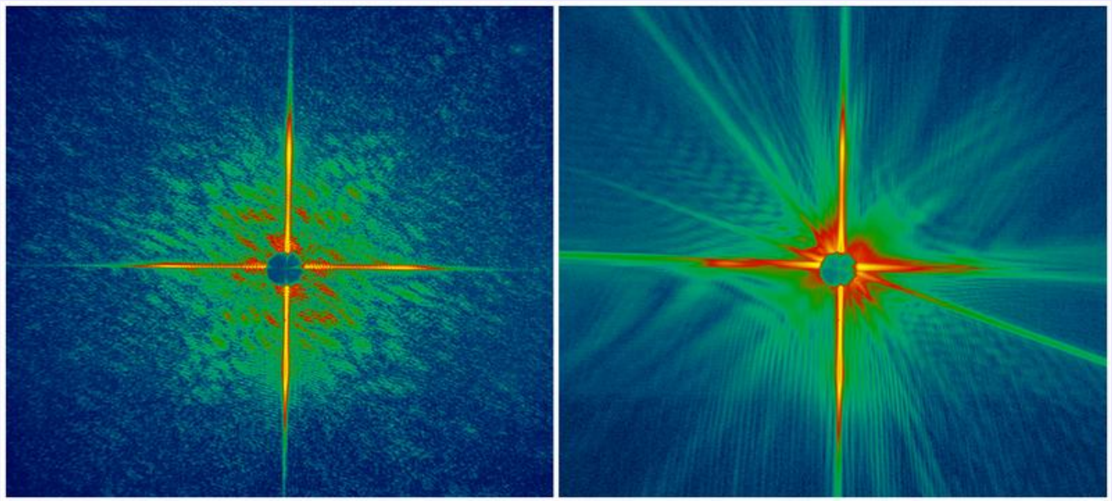
Some members of the current collaboration

Imaging single molecules !!!



Single shot dynamic nano-imaging on femtosecond timescales - soon to be used In single biomolecule Imaging !!!





X-Ray Lasers - Future

Speculation

Ordinary X-rays are used in Diagnostics (Images) and Therapeutics (Cancer/Radiography).

X-ray lasers add the possibility to make 3D images (holograms) of the molecules that cause diseases and follow them on a femtosecond timescale as they do so !!

Molecular (Nanomedicine)……

THE FUTURE FOR 'FAST' PHYSICS?

Crystal Ball - In the future we will see a transition from atomic to nuclear lasers which will permit Zeptosecond/ Etawatt Pulse Generation so that we can probe nuclear dynamics - Who, Where & When ?