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CENTRO DE APLICACIONES TECNOLÓGICAS
Y DESARROLLO NUCLEAR

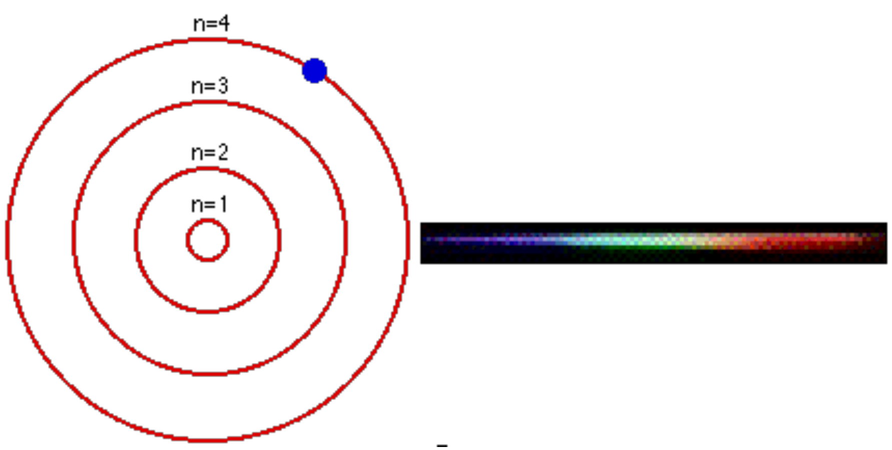
"Extreme light: Interaction mechanisms and foreseen applications"

Dr. Iván Padrón Díaz

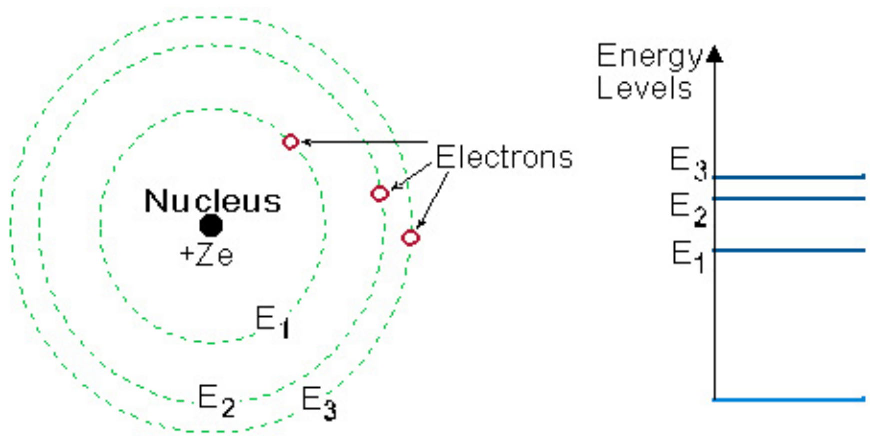
Principles of Laser action

The basic principle of the laser, as the name ”**Light Amplification by Stimulated Emission of Radiation**” indicates, is based on stimulated emission from a higher level ***f to a lower level i .***

(not necessarily the ground state)



Spontaneous Emission



Stimulated Emission

Properties of Stimulated Emission

The photon which is emitted in the stimulated emission process is identical to the incoming photon.

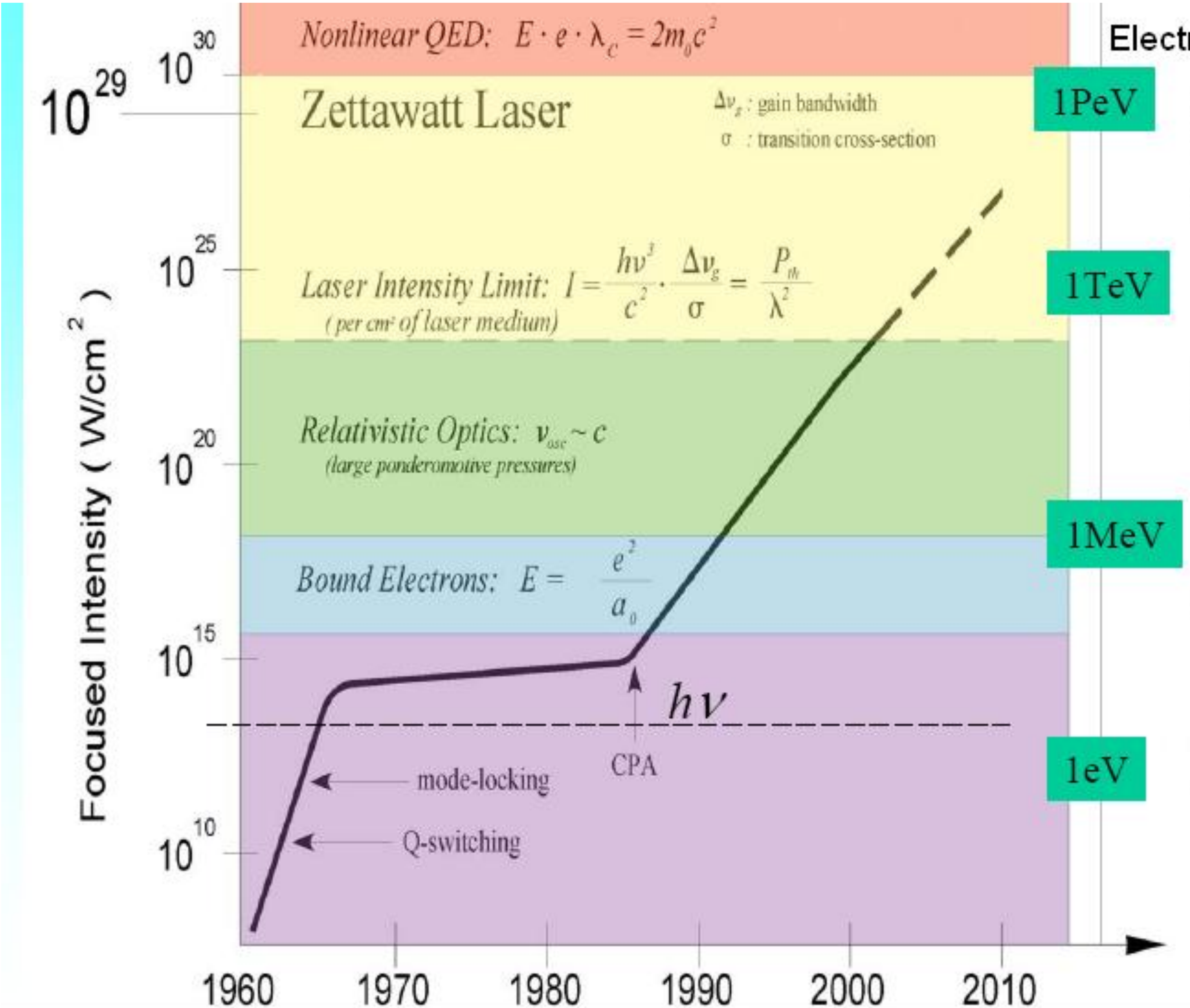
They both have:

1. Identical wavelengths - **Monochromaticity.**

2. Identical directions in space - **Directionality.**

3. Identical phase - **Coherence.**

Laser Power Evolution



10^{24}	yotta
10^{21}	zetta
10^{18}	exa
10^{15}	peta
10^{12}	tera
10^{-12}	pico
10^{-15}	fento
10^{-18}	atto

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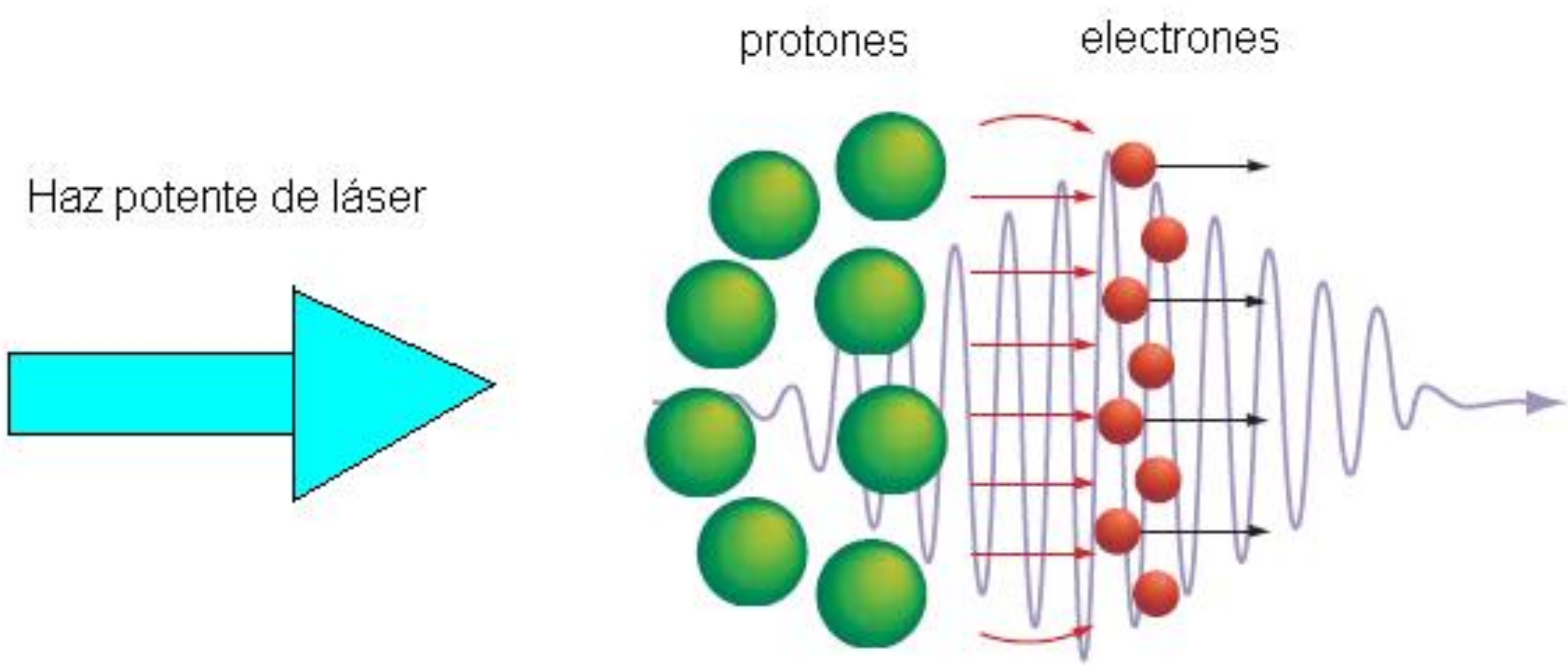
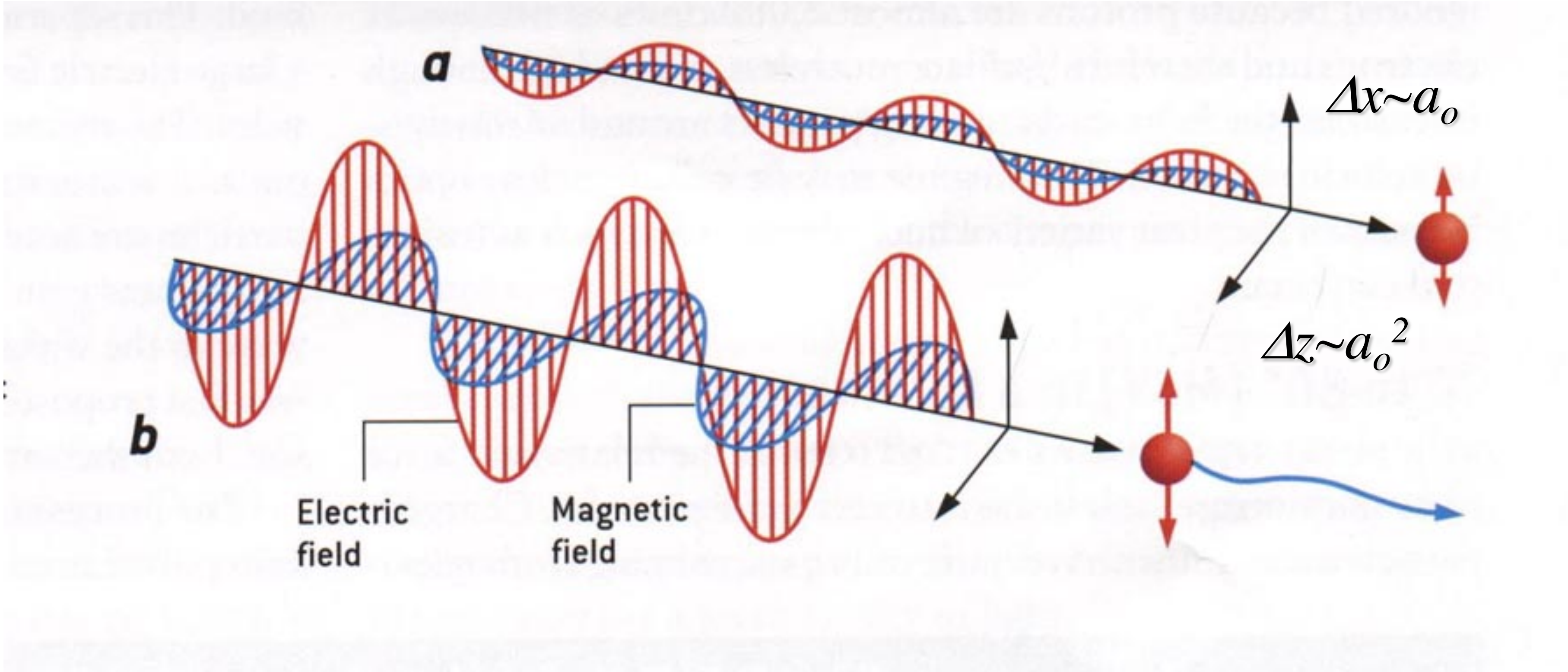
Extreme light: Interaction mechanisms (Relativistic Optics)



Relativistic Optics

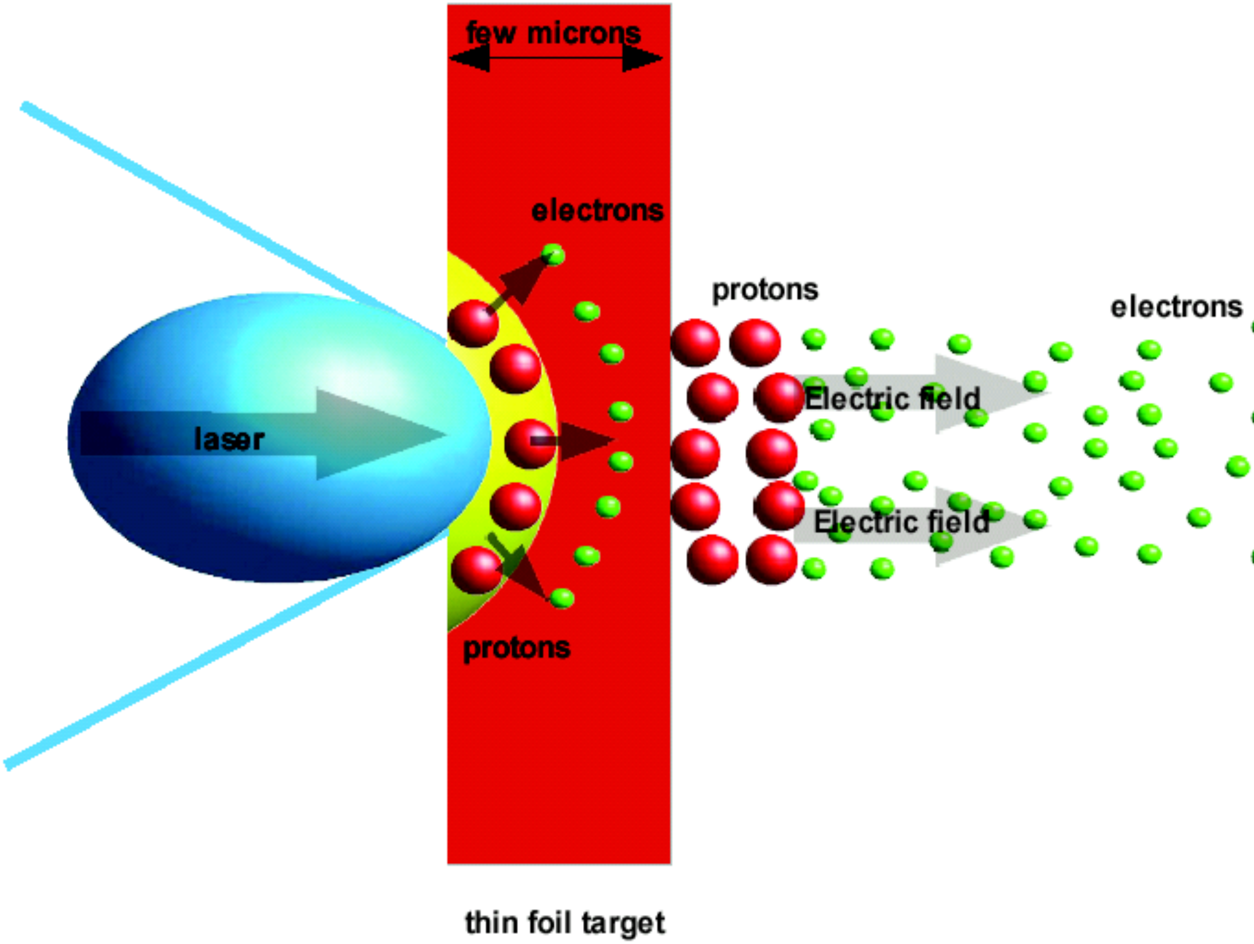
$$\vec{F} = q\left(\vec{E} + \left(\frac{\vec{v}}{c} \wedge \vec{B}\right)\right) \qquad a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$

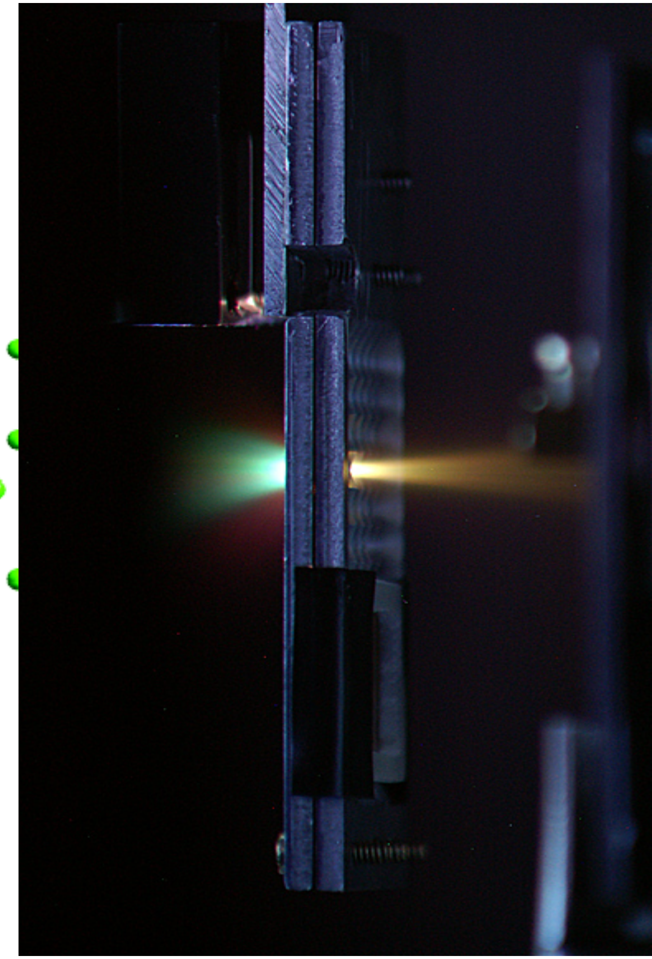
a) Classical optics v<<c, $a_0 \ll 1,\ a_0 \gg a_0^2$



b) Relativistic optics v~c, $a_0 \gg 1,\ a_0 \ll a_0^2$

Extreme light: Interaction mechanisms



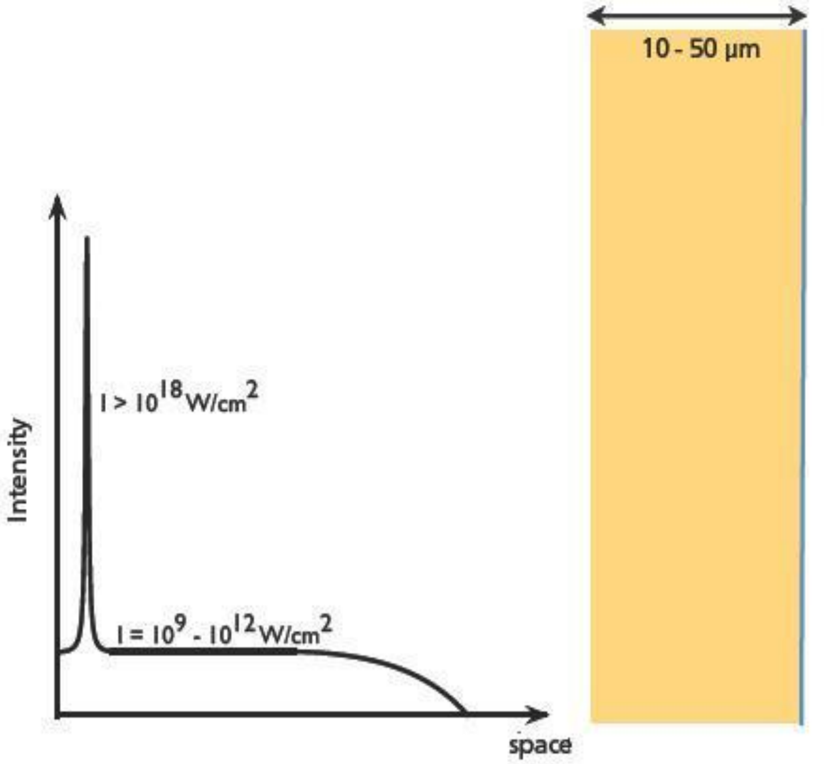


Peak energy scales as : $E_M \sim (I_L \times \lambda)^{1/2}$

Extreme light: Interaction mechanisms

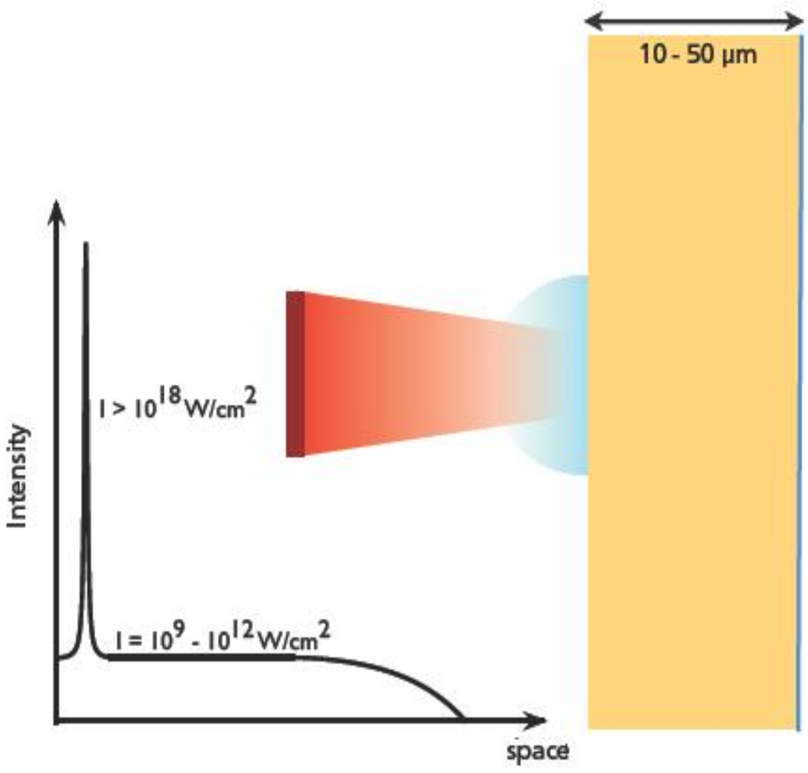
- **Target Normal Sheath Acceleration (TNSA)**
- Radiation Pressure Acceleration (RPA)
- Skin Layer Ponderomotive Acceleration
- Break Out Afterburner or Coulomb Explosion

Extreme light: Interaction mechanisms
(Target Normal Sheath Acceleration)



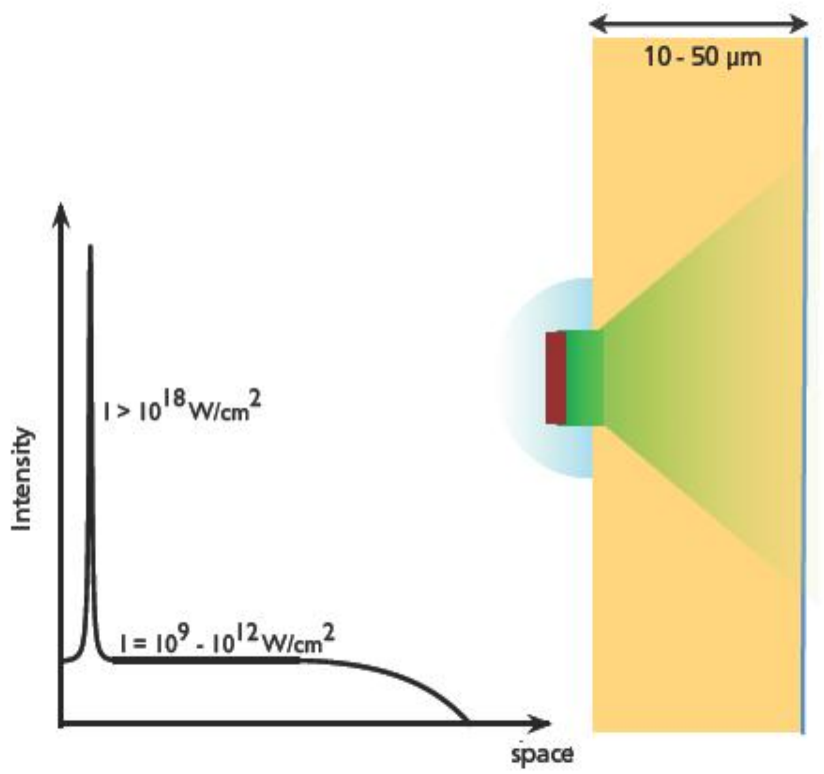
Extreme light: Interaction mechanisms
(Target Normal Sheath Acceleration)

- Laser pulse creates pre-plasma



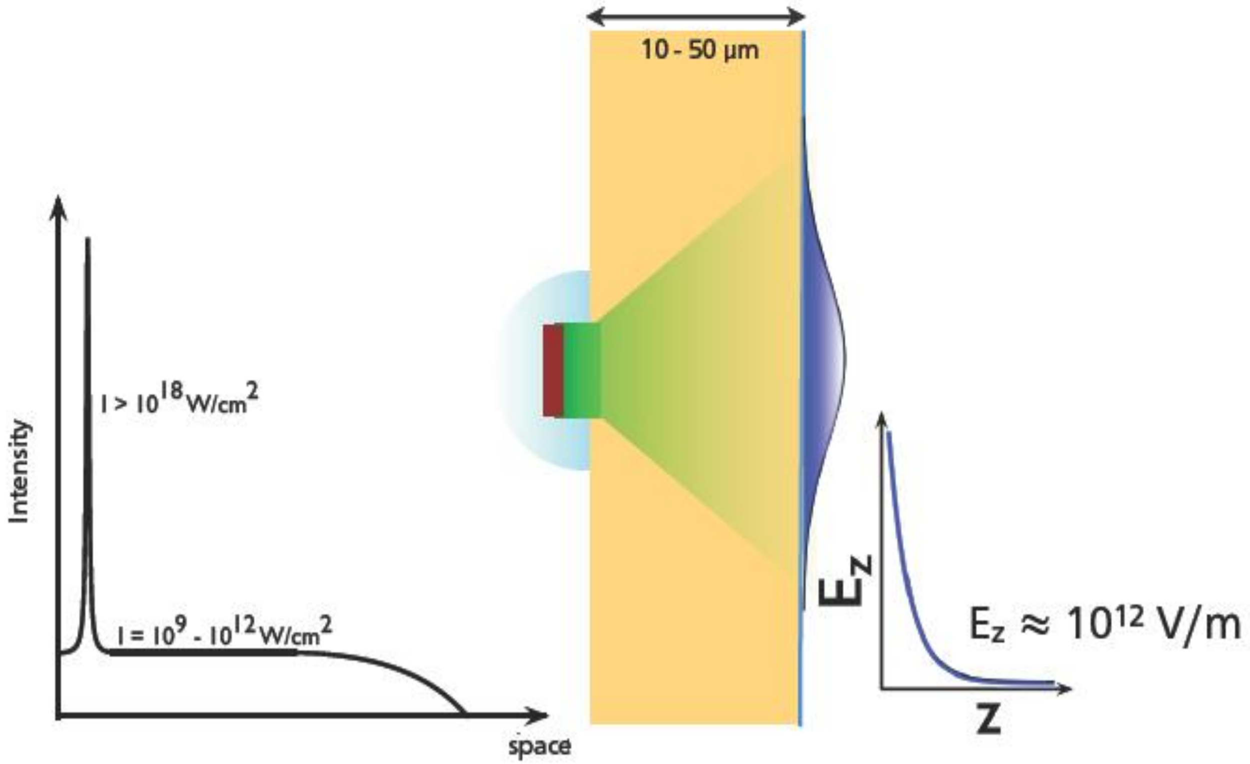
Extreme light: Interaction mechanisms
(Target Normal Sheath Acceleration)

- Laser pulse creates pre-plasma
- Main pulse accelerates electrons to MeV-energies



Extreme light: Interaction mechanisms
(Target Normal Sheath Acceleration)

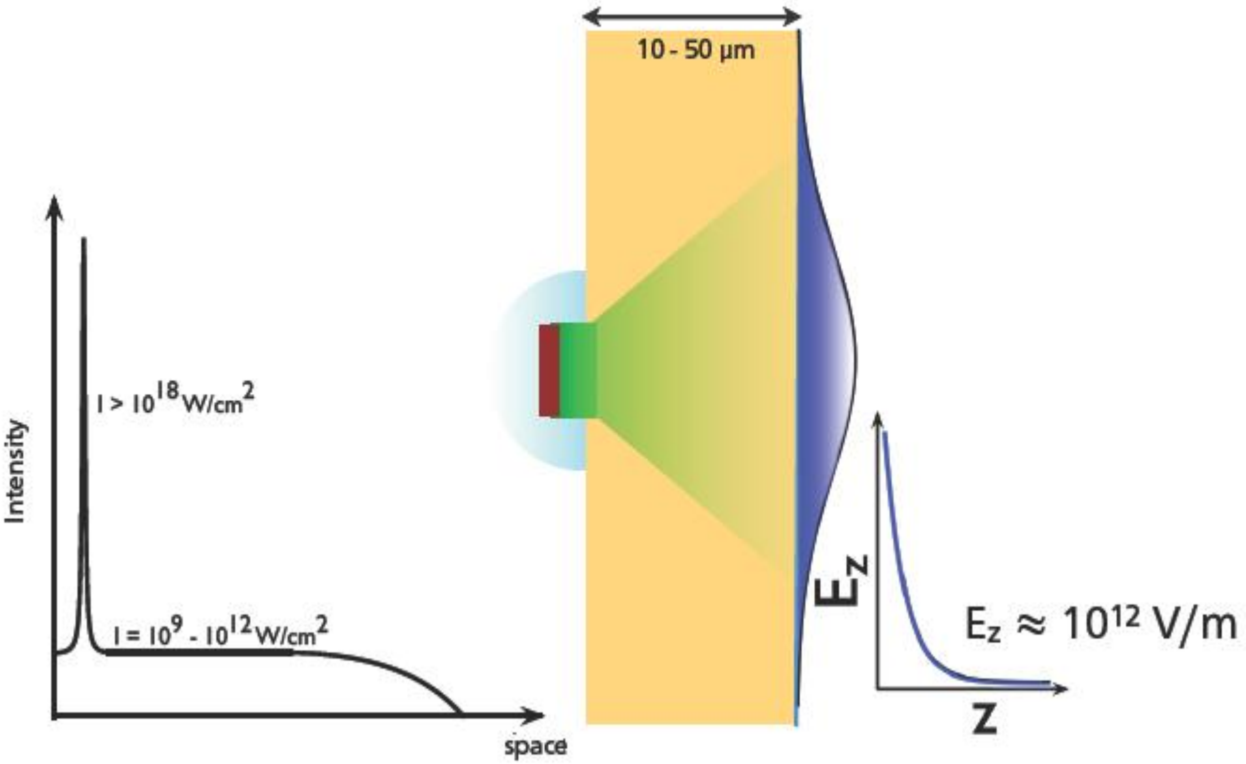
- Laser pulse creates pre-plasma
- Main pulse accelerates electrons to MeV-energies
- Electron sheath generates electric field on rear side



Extreme light: Interaction mechanisms

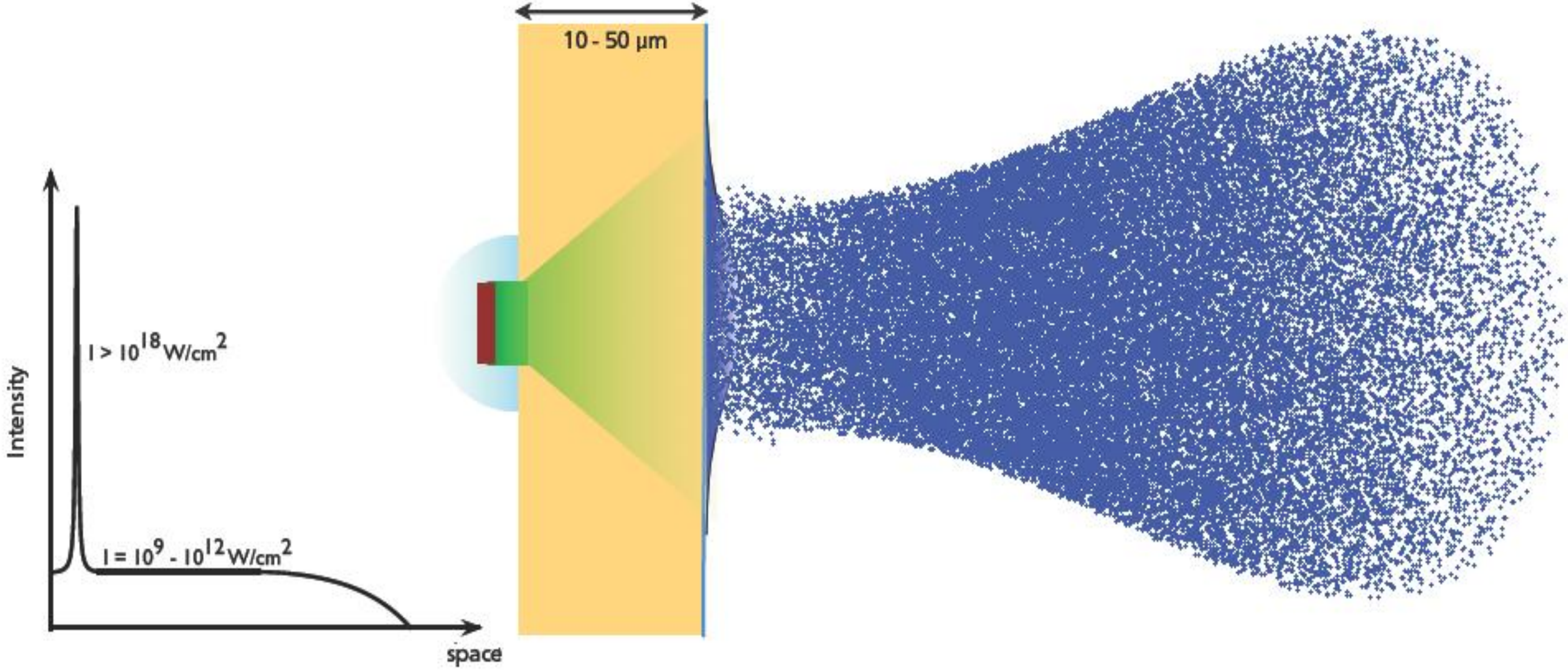
(Target Normal Sheath Acceleration)

- Laser pulse creates pre-plasma
- Main pulse accelerates electrons to MeV-energies
- Electron sheath generates electric field on rear side
- Transverse spread of sheath with speed of light



Extreme light: Interaction mechanisms
(Target Normal Sheath Acceleration)

- Laser pulse creates pre-plasma
- Main pulse accelerates electrons to MeV-energies
- Electron sheath generates electric field on rear side
- Transverse spread of sheath with speed of light
- Field ionization and ion acceleration in normal direction



Extreme light: Interaction mechanisms

(Target Normal Sheath Acceleration)

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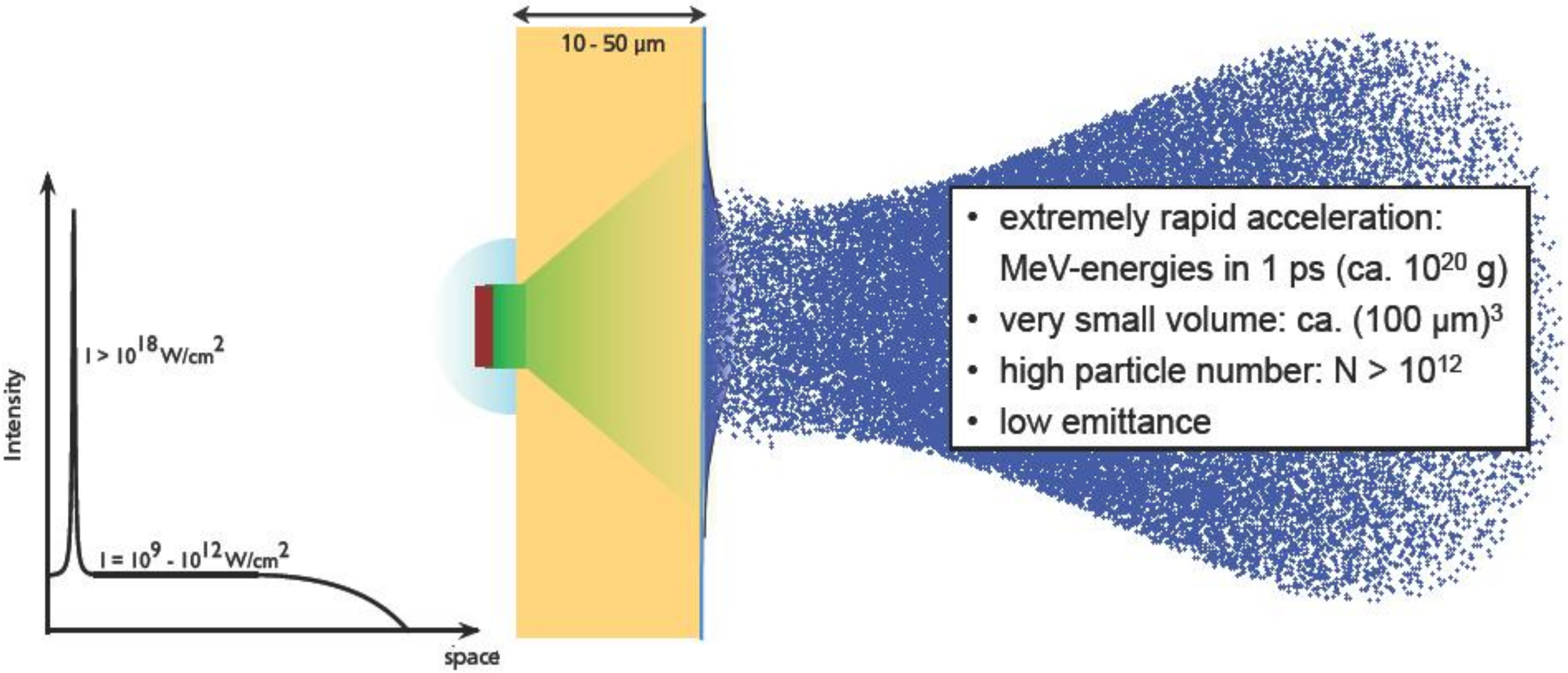


Extreme light: Interaction mechanisms

(Target Normal Sheath Acceleration)

Table 1. A summary of recent achievements in generation of light ion beams by TNSA at relativistic laser intensities.

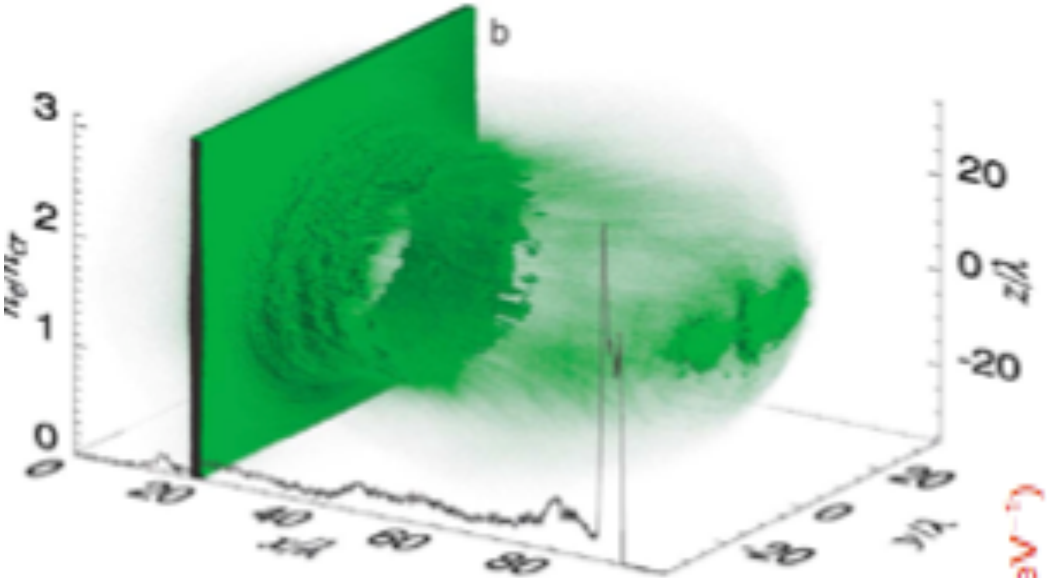
Ion beam parameter	protons	lights ions ($1 < Z < 10$)
Maximum ion energy	50 MeV	100 MeV (5–6 MeV/amu)
Total mumber of ions	10^{13}	10^{11}
Ion current at the source	≥ 1 MA	≥ 10 kA
Ion current density at the source	≥ 1 GA/cm^2	≥ 10 MA/cm^2
Angular divergence	10°–20°	20°
Transverse emittance	< 0.01 mm mrad	
Longitudinal emittance	< 10^{-4} eVs	

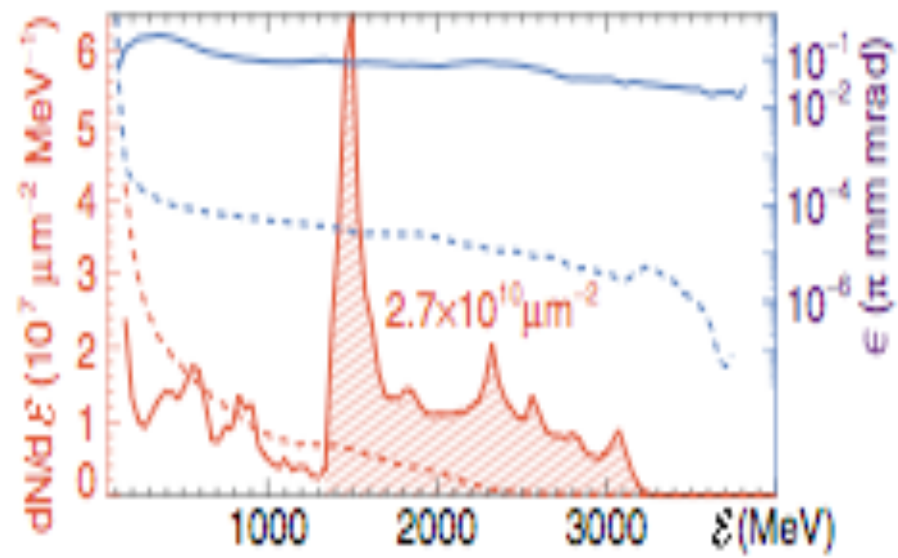
Extreme light: Interaction mechanisms

- Target Normal Sheath Acceleration (TNSA)
- **Radiation Pressure Acceleration (RPA)**
- Skin Layer Ponderomotive Acceleration
- Break Out Afterburner or Coulomb Explosion

3D Simulations: Radiation Pressure Acceleration dominated regime with Linear Polarization

$I = 10^{23}$ W/cm^2, Target thickness = 1μm, N_e=5x10^{22}cm^{-3}

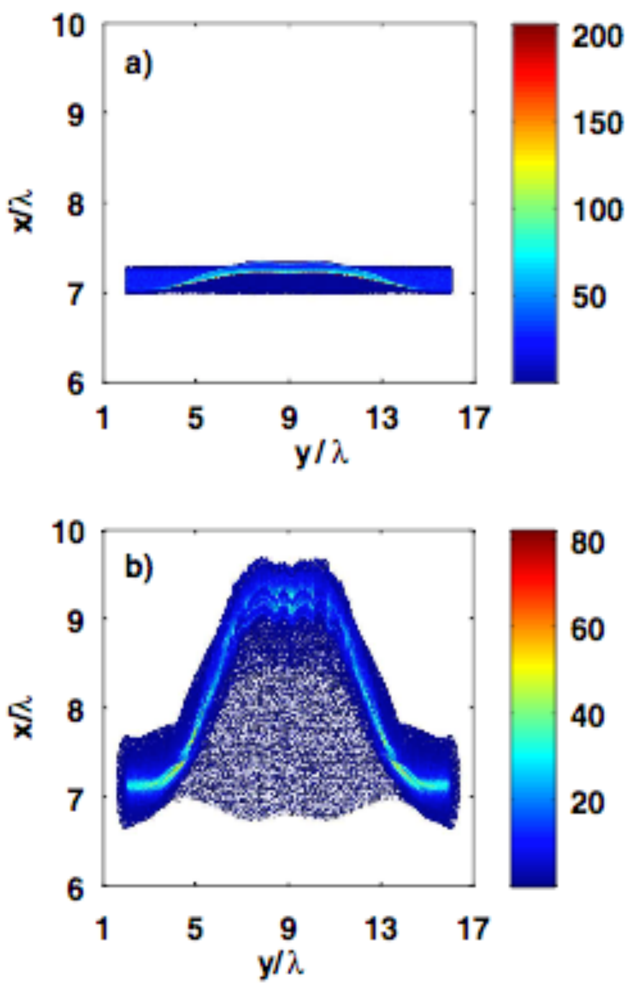


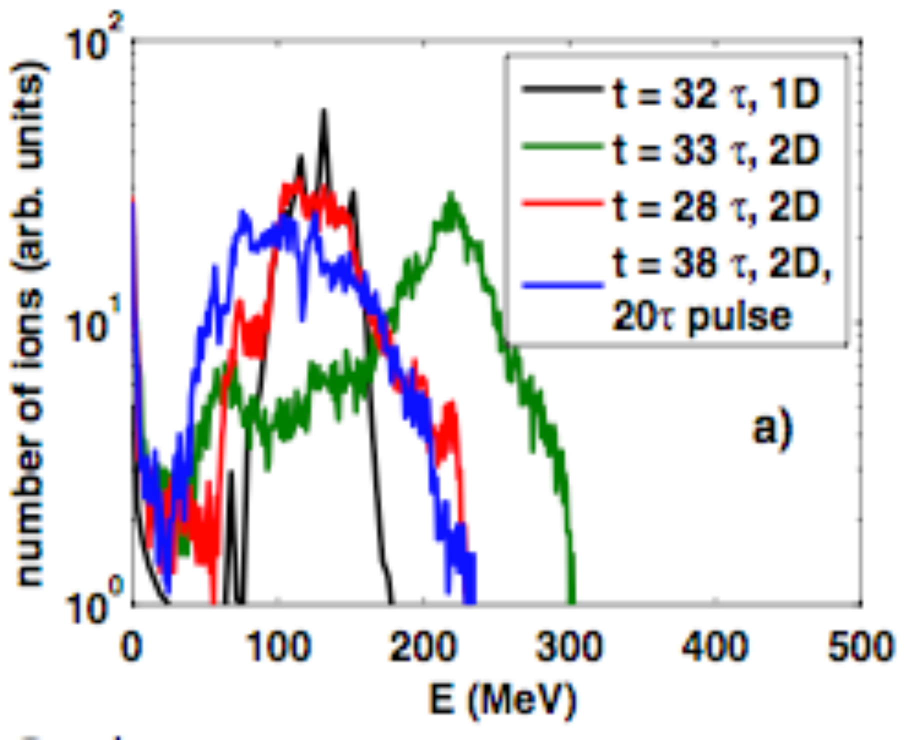


Laser Piston Model
By Esirkepov, Bulanov, PRL 2004

2 D Simulations: Radiation Pressure Acceleration dominated regime with Circular Polarization

I = 3×10^{20} W/cm^2, N_e=1.5 10^{22}cm^{-3}, Target thickness = 0.2 μm





Macchi A *et al 2005 Phys. Rev. Lett.* ***94 165003***
Robinson A P L *et al 2008 New J. Phys.* ***10 013021***
Klimo O *et al 2008 Phys. Rev. ST-AB* ***11 031301***

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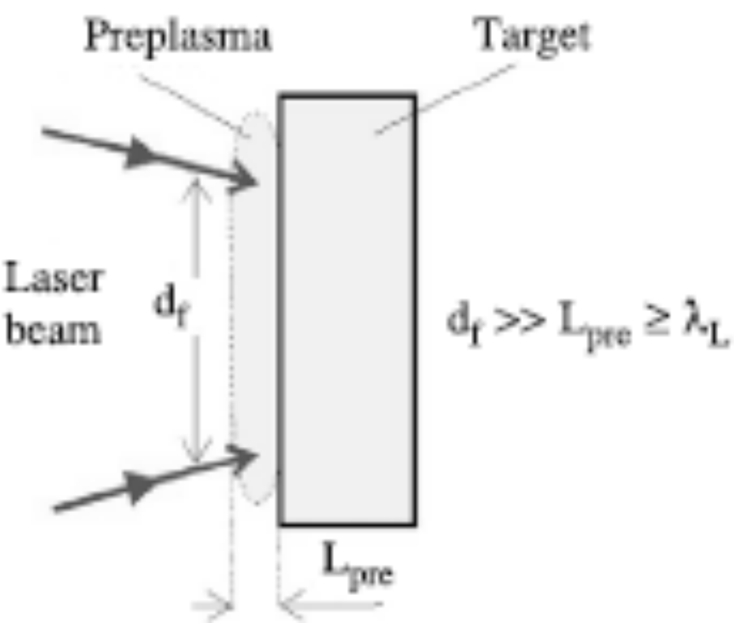
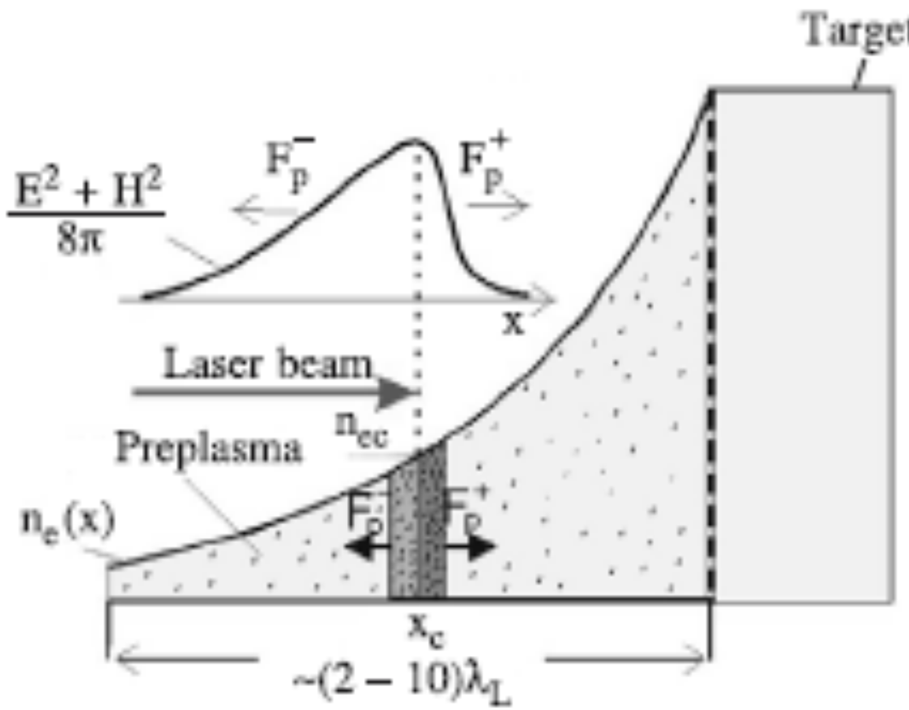
Extreme light: Interaction mechanisms

- Target Normal Sheath Acceleration (TNSA)
- Radiation Pressure Acceleration (RPA)
- **Skin Layer Ponderomotive Acceleration**
- Break Out Afterburner or Coulomb Explosion

Extreme light: Interaction mechanisms (Skin Layer Ponderomotive Acceleration)





Idea of production of ion beams by S-LPA.

(**J. BADZIAK**, Opto-Electron. Rev., **15**, no. 1, 2007)

Extreme light: Interaction mechanisms (Skin Layer Ponderomotive Acceleration)

Method	Laser beam	Mean proton energy, MeV	Proton current density at the source estimated for 10° angle cone, $GAcm^{-2}$	Proton beam intensity at the source estimated for 10° angle cone, 10^{15} Wcm^{-2}	Proton density at the source estimated for 10° angle cone, 10^{18} cm^{-3}
S-LPA	0.5 J/1 ps 10^{17} W/cm^2	0.017	26	0.44	900
	30 J/0.35 ps 10^{19} W/cm^2 LULI	4	0.3	1.2	0.7
TNSA	50 J/1 ps 8×10^{19} W/cm^2 VULCAN	4	0.4	1.6	0.9
	500 J/0.5 ps 3×10^{20} W/cm^2 PETAWATT	6	0.5	3	0.9

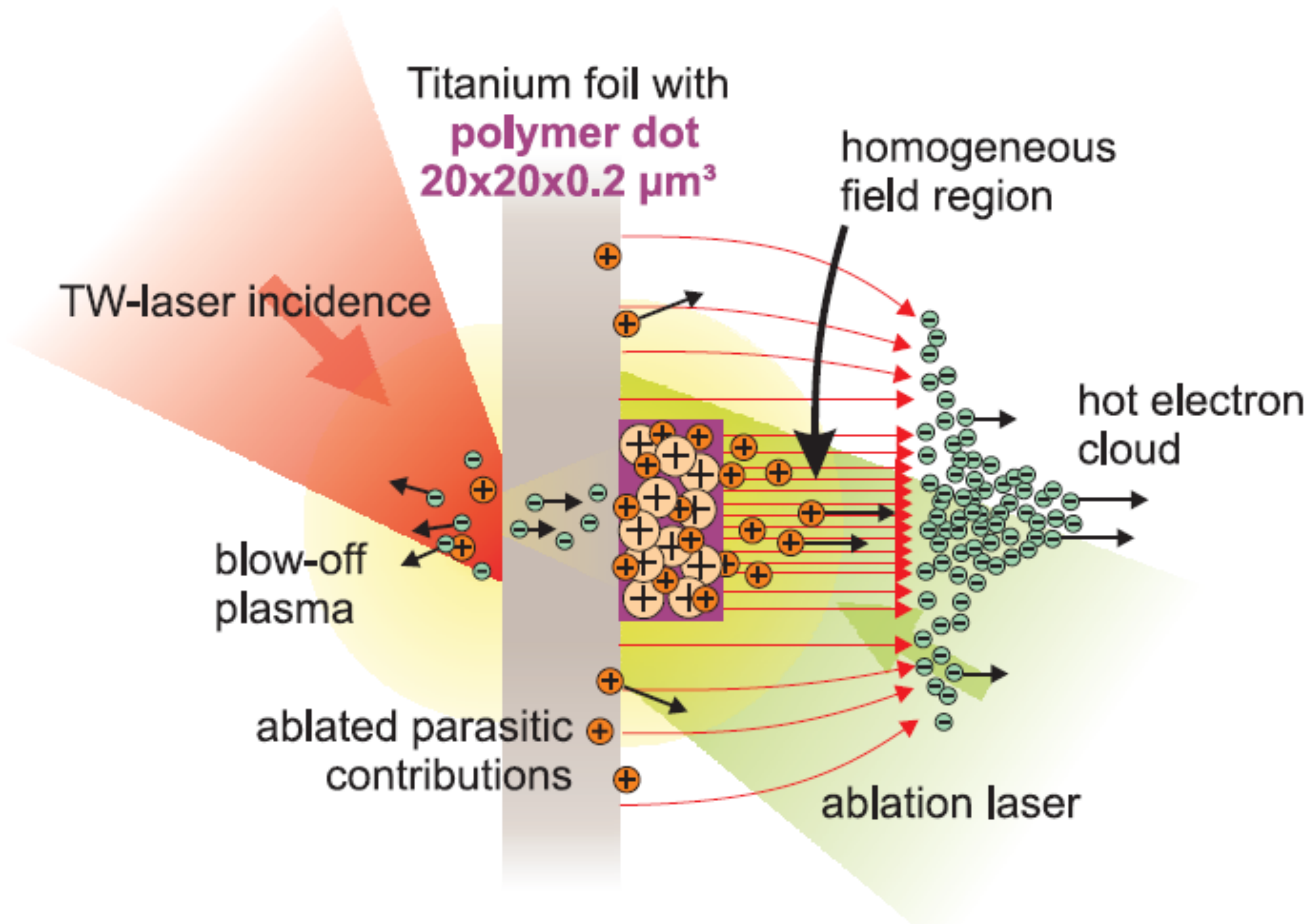
A comparison of proton beams produced by S-LPA and TNSA.

The potential advantage of the laser ion injector is the high ion current, the small transverse and longitudinal emittances as well as the possibility of production of ions of arbitrary elements.

Extreme light: Interaction mechanisms

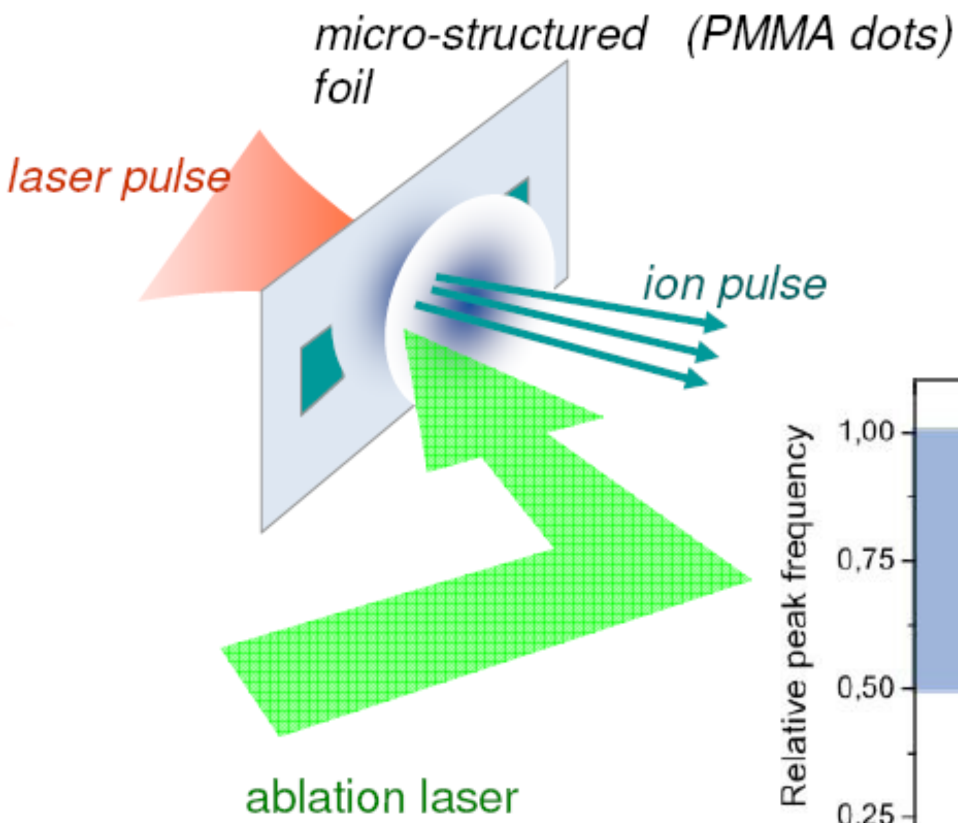
- Target Normal Sheath Acceleration (TNSA)
- Radiation Pressure Acceleration (RPA)
- Skin Layer Ponderomotive Acceleration
- Break Out Afterburner or Coulomb Explosion

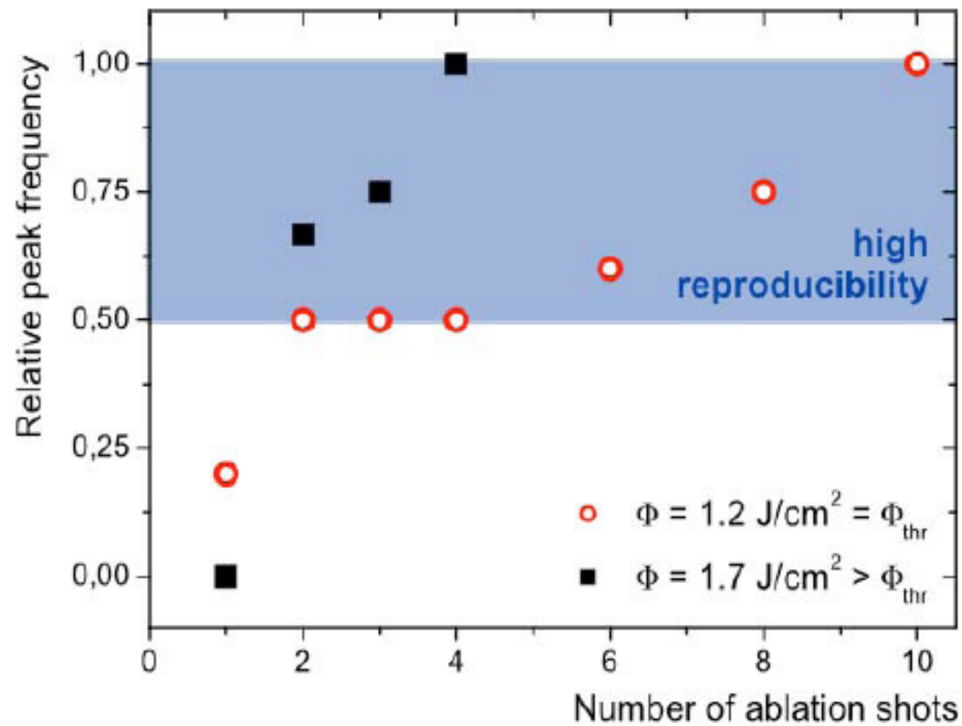
Extreme light: Interaction mechanisms
(Break Out Afterburner or Coulomb Explosion



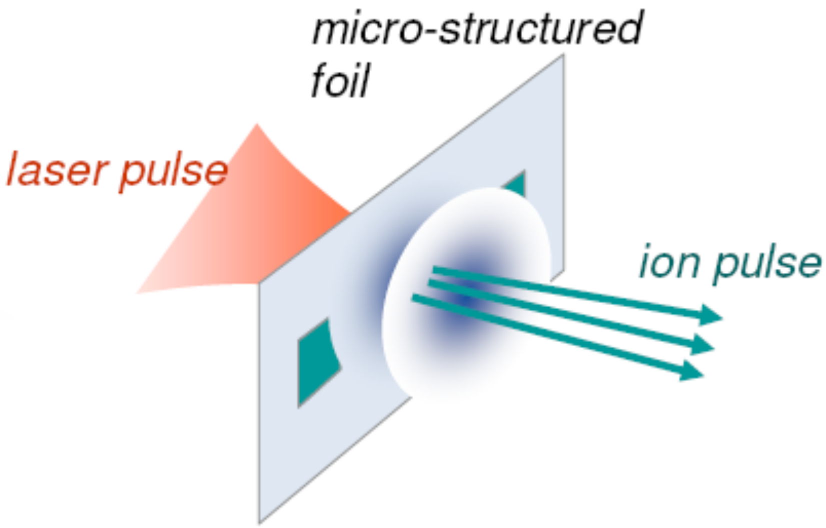
Peak energy scales as : $E_M \sim (I_L \times \lambda)^{1/2}$

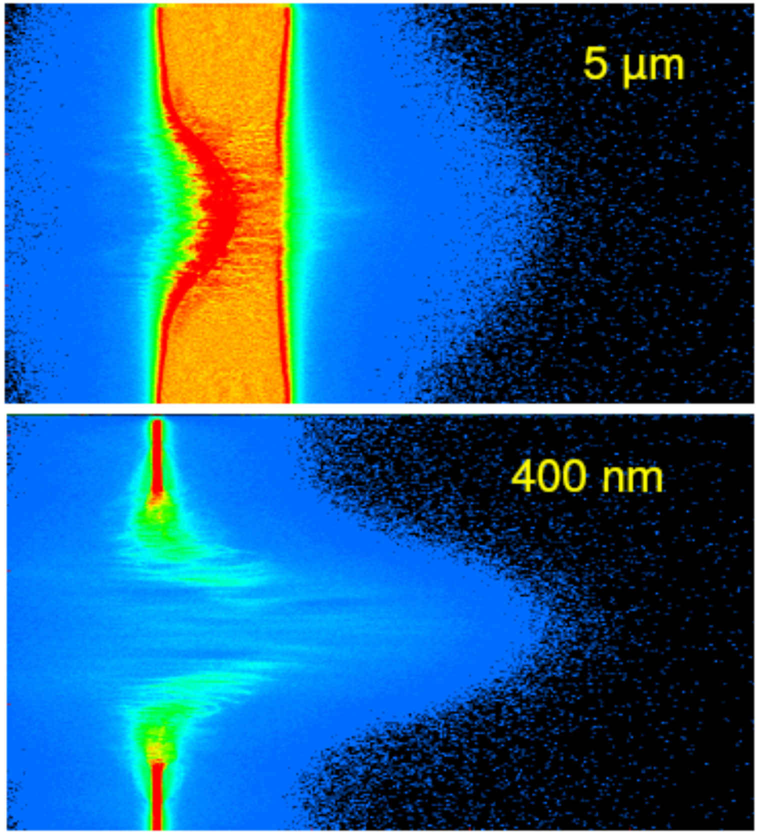
Extreme light: Interaction mechanisms (Break Out Afterburner or Coulomb Explosion

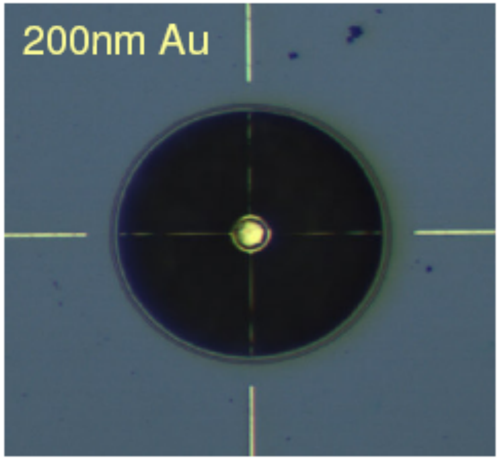




Extreme light: Interaction mechanisms
(Break Out Afterburner or Coulomb Explosion



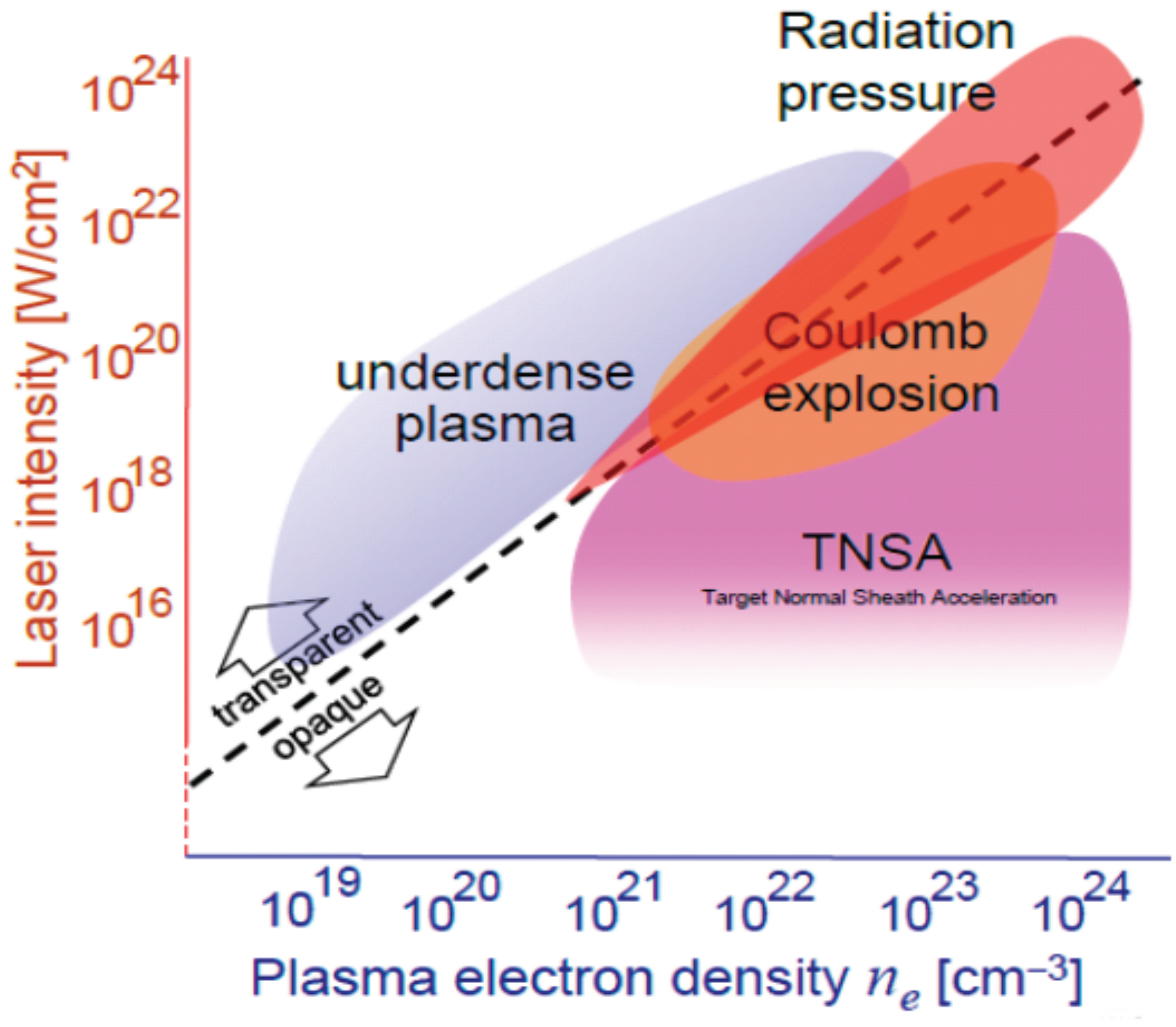




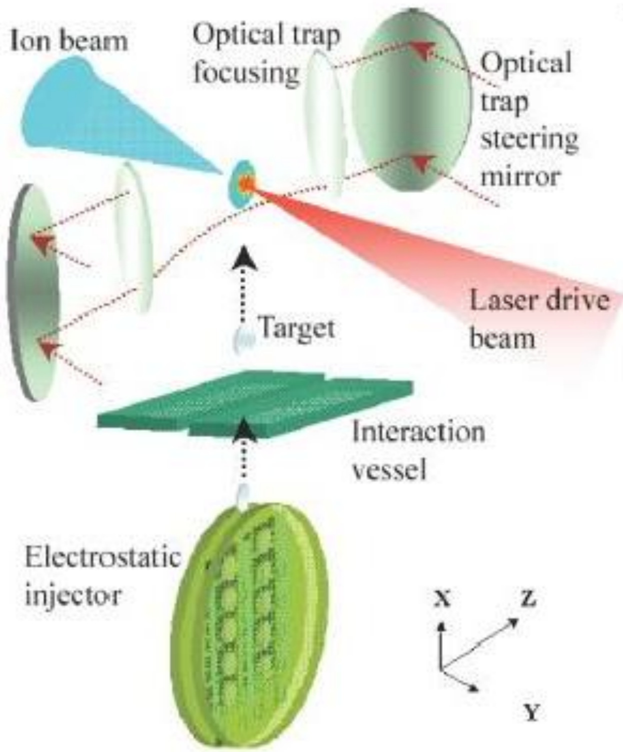
$I = 10^{20}$ W/cm^2, 20 fs (FWHM)

Si wafer-based target design

Extreme light: Interaction mechanisms



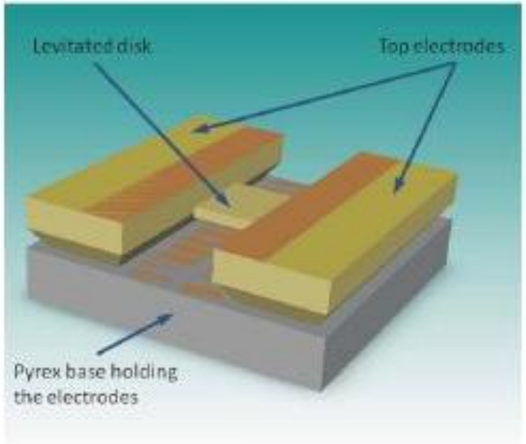
Extreme light: Foreseen applications
(Targetry improvements)



Limited mass, isolated, high-rep

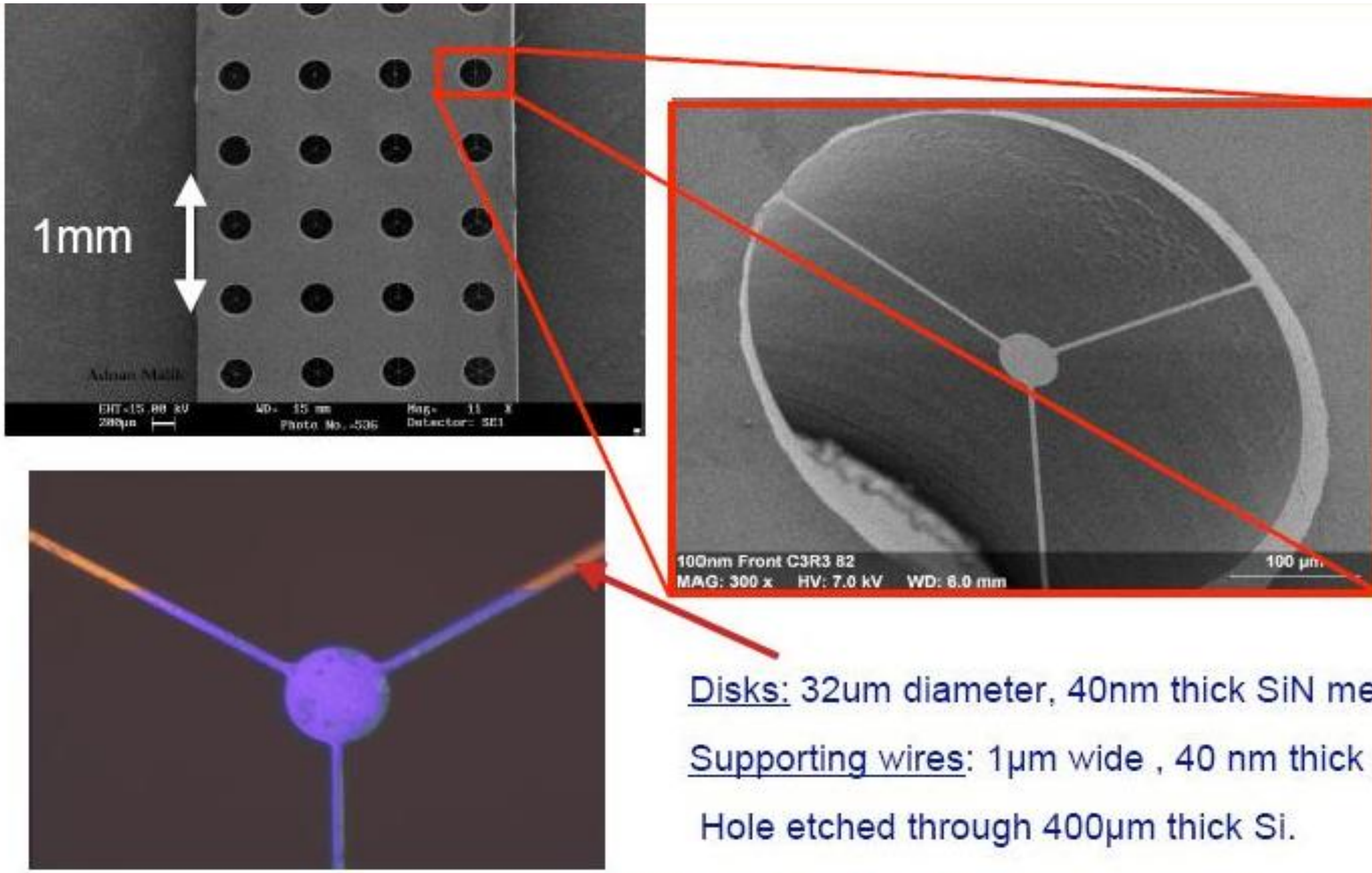
- Volume manufacturing of disk targets
  (B. Stevens, RAL)
- Electrostatic injection
  (M.Kraft, Southampton)
- Laser trapping
  (A. Ward, RAL)

Use of thin disks allow minimal gamma production and low debris



Combination of different existing advanced technologies

Extreme light: Foreseen applications (Targetry improvements)



Disks: 32um diameter, 40nm thick SiN membranes

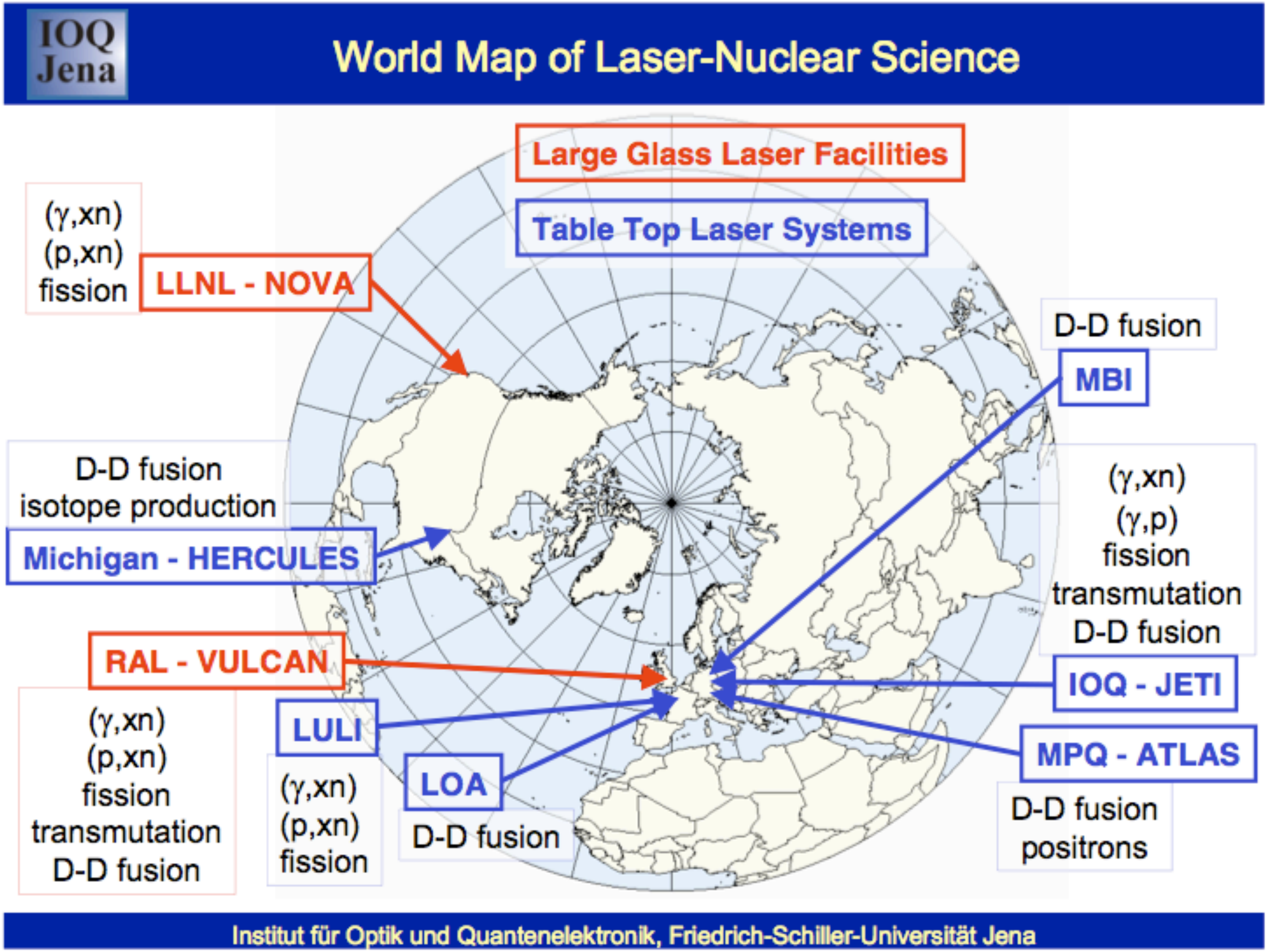
Supporting wires: 1µm wide , 40 nm thick

Hole etched through 400µm thick Si.

Potential for further miniaturization !

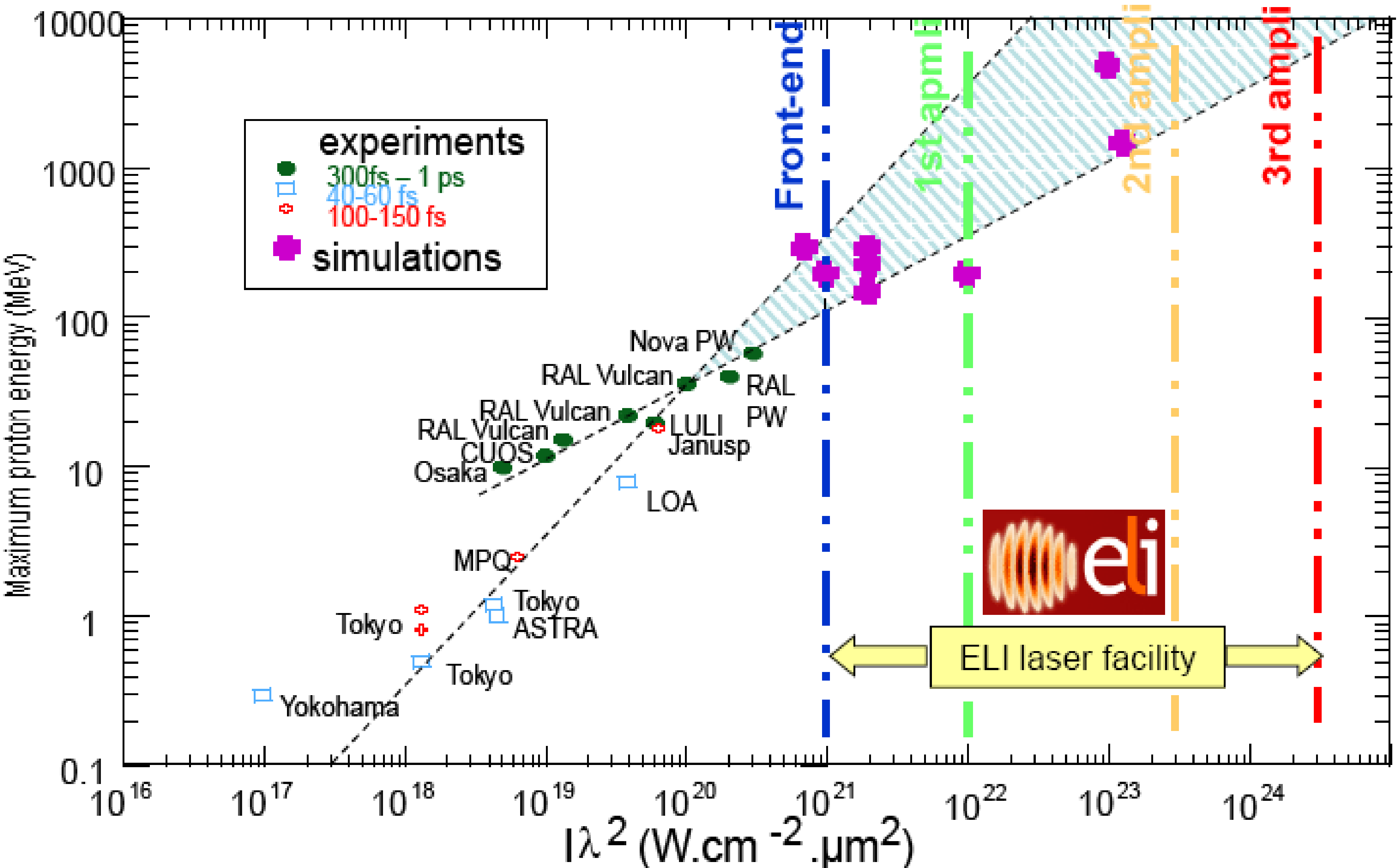
MEMS Manufacture and raster delivery

Extreme light: Foreseen applications (Worldwide Laser facilities)



Extreme light: Foreseen applications
(Worldwide Laser facilities)

J. Fuchs et al., Nature Physics **2**, 48 (2006)



Extreme light: Foreseen applications (Laser facilities)

Ultrahigh Intensity Laser is associated with Extremely large Electric field.

$$E_L^2 = Z_0 * I_L$$

Medium Impedance (Z_0) — Laser Intensity (I_L)

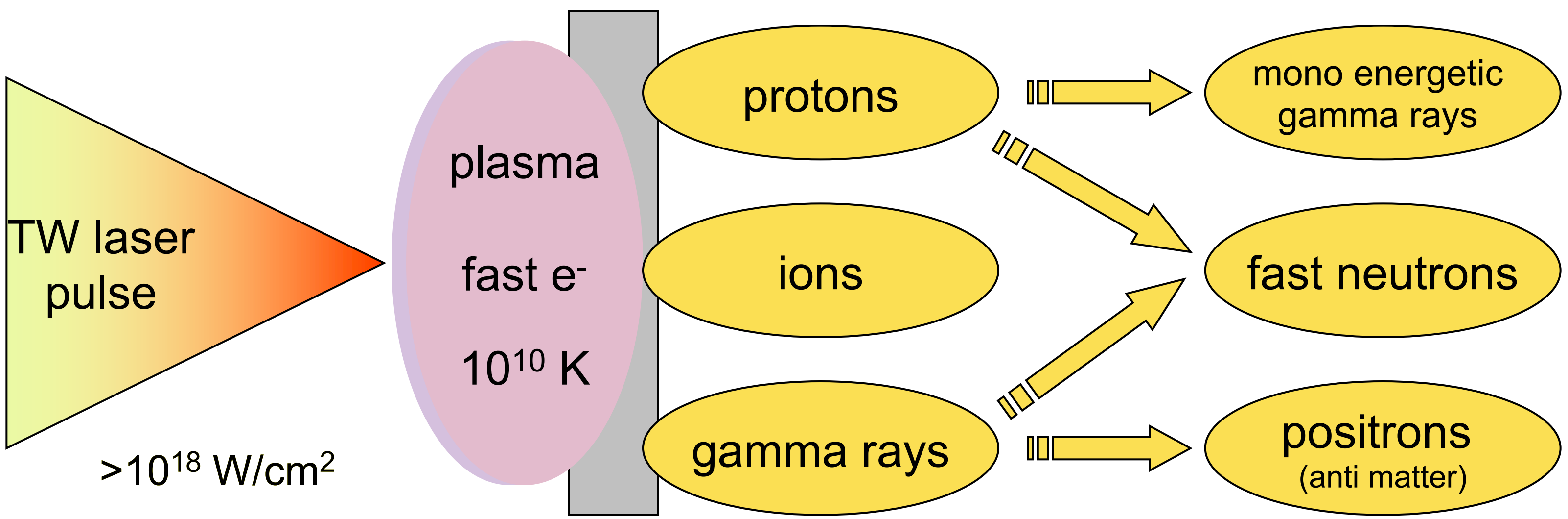
$$I_L = 10^{18} W/cm^2 \Rightarrow E_L = 2 \quad TV/m$$

$$I_L = 10^{23} W/cm^2 \Rightarrow E_L = 0.6\ PV/m \quad (0.6\,10^{15} Volts/meter)$$

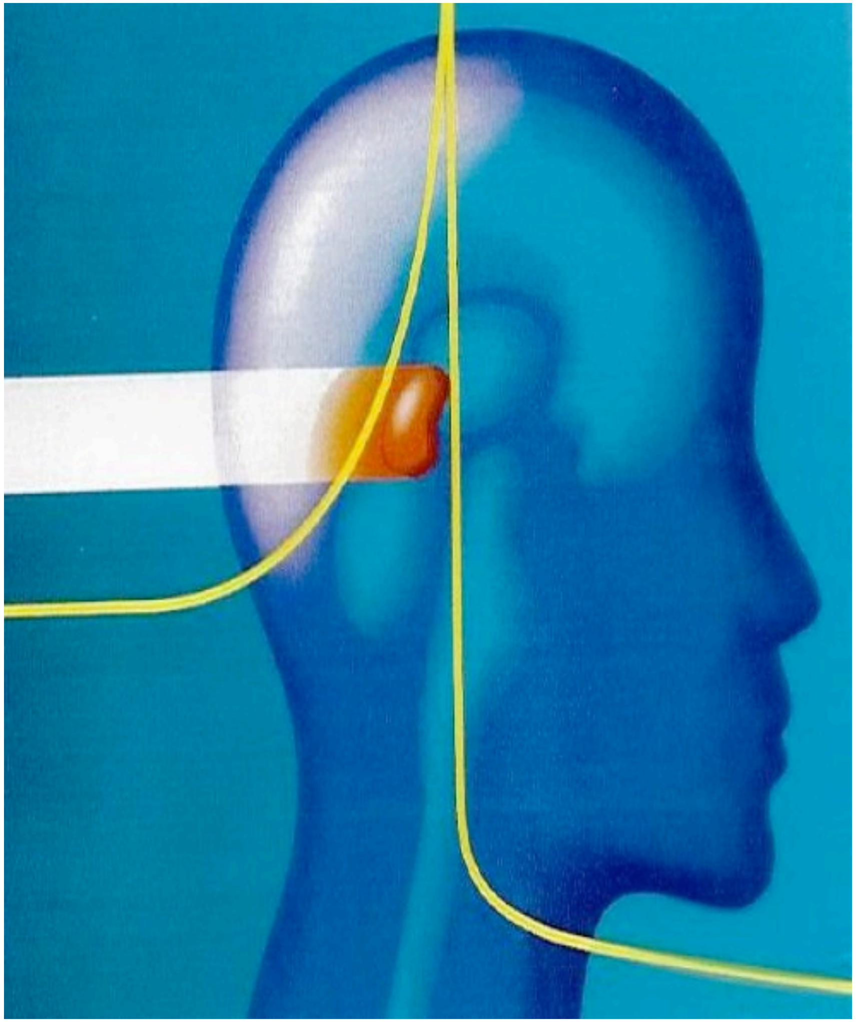
- ✓ *At 10^{23} W/cm^2 , E= 0.6 PV/m, it is equivalent to the Stanford Linear Collider SLAC (50 GeV, 3km long) obtained on 10µm*

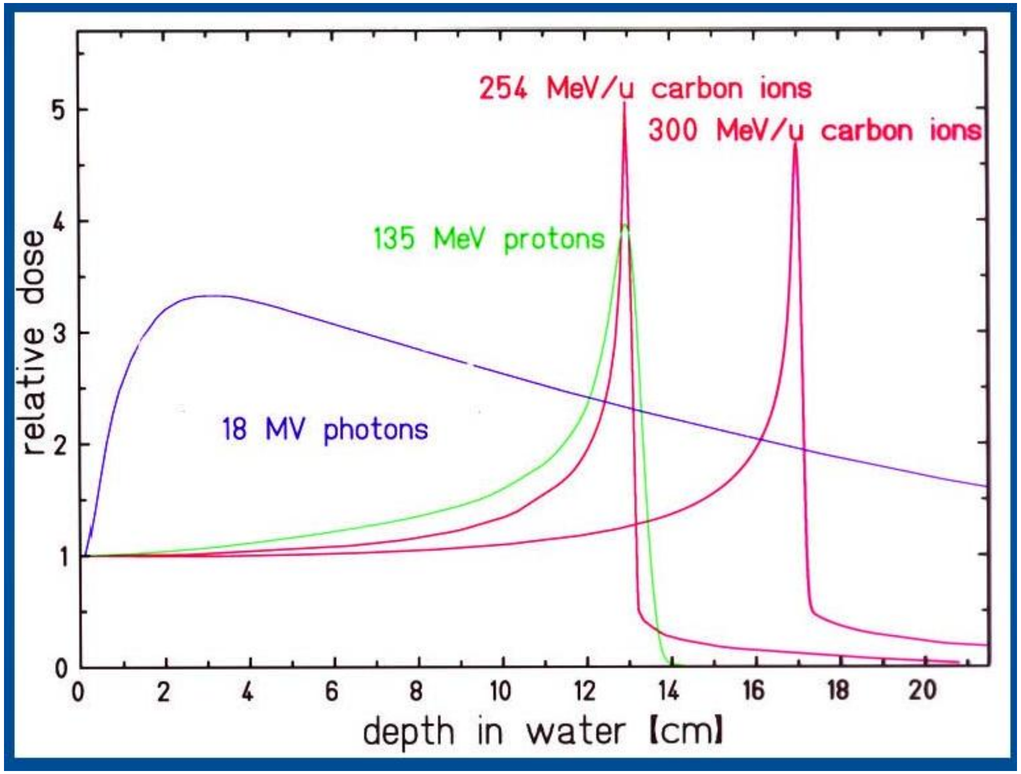
The cascade process of energy transfer from the laser pulse to the radiations

- Primary processes are due to the action of the laser EM field on a plasma
- Fast electrons initiate secondary processes

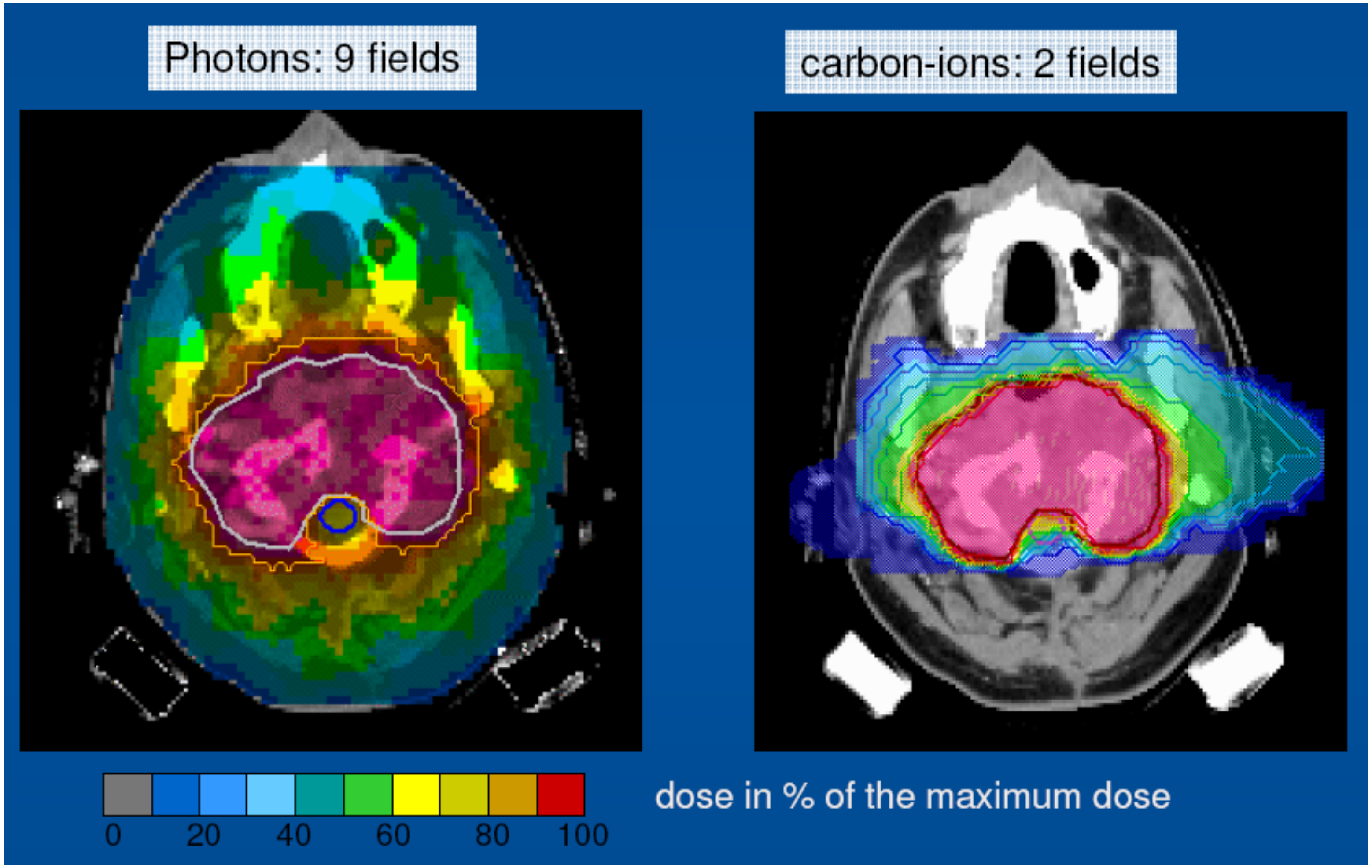


Extreme light: Foreseen applications (Laser driven cancer therapy)





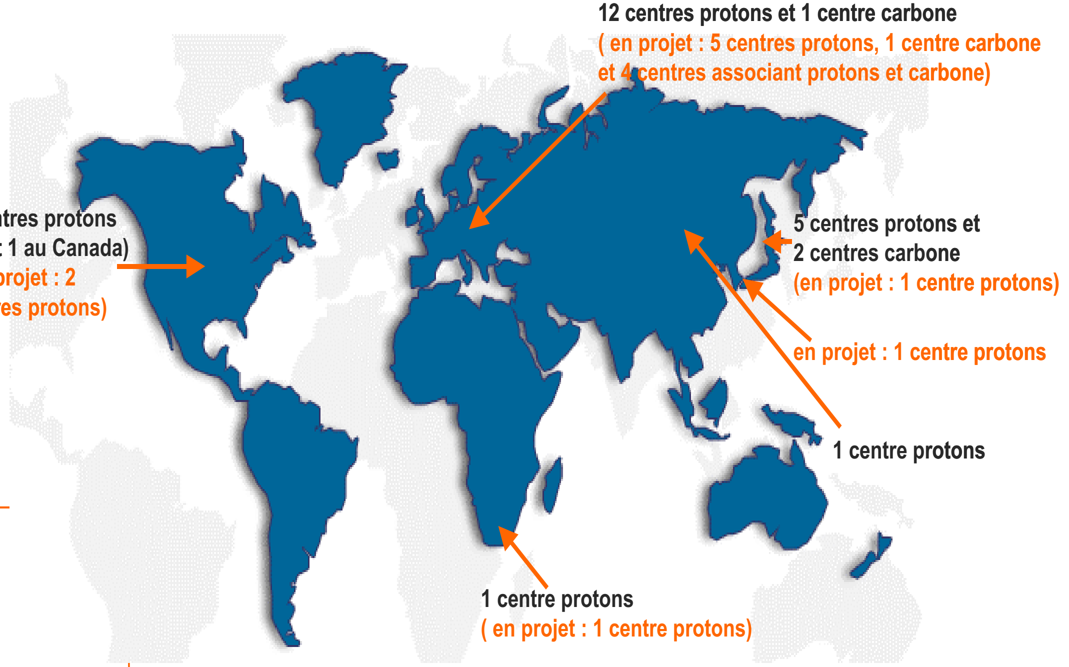
Extreme light: Foreseen applications
(Laser driven cancer therapy: Treatment planning)

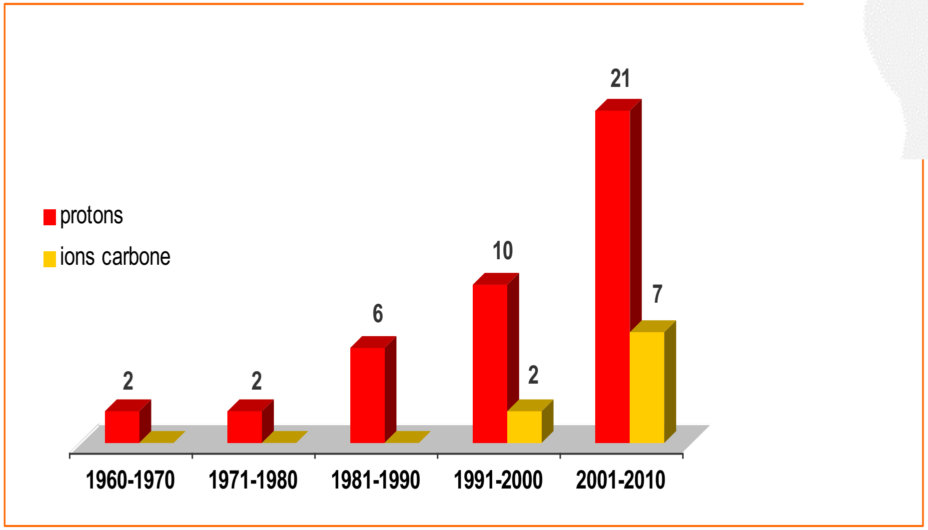


- **Precision absolute beam positioning better than 1mm**
- **Dose control (local) ≈ 1%**
- **Dose 40-80 Gray distributed over 10-20 fractions (10^9-10^{10} ions per fraction and few minutes)**

Hadron Therapy: The raisons of a non satisfied medical need

- •2 protontherapy center in France (Orsay et Nice)
- •30 centres in « modern » countries
- •Limitation due :
  - •Overall Cost : 80 à 140 M€
  - •Size of the installation : 1000 to 2000 m²





Estimation of the needed protontherapy center in the world (based on the hypothesis that 15% of patients are treated by proton beam) :

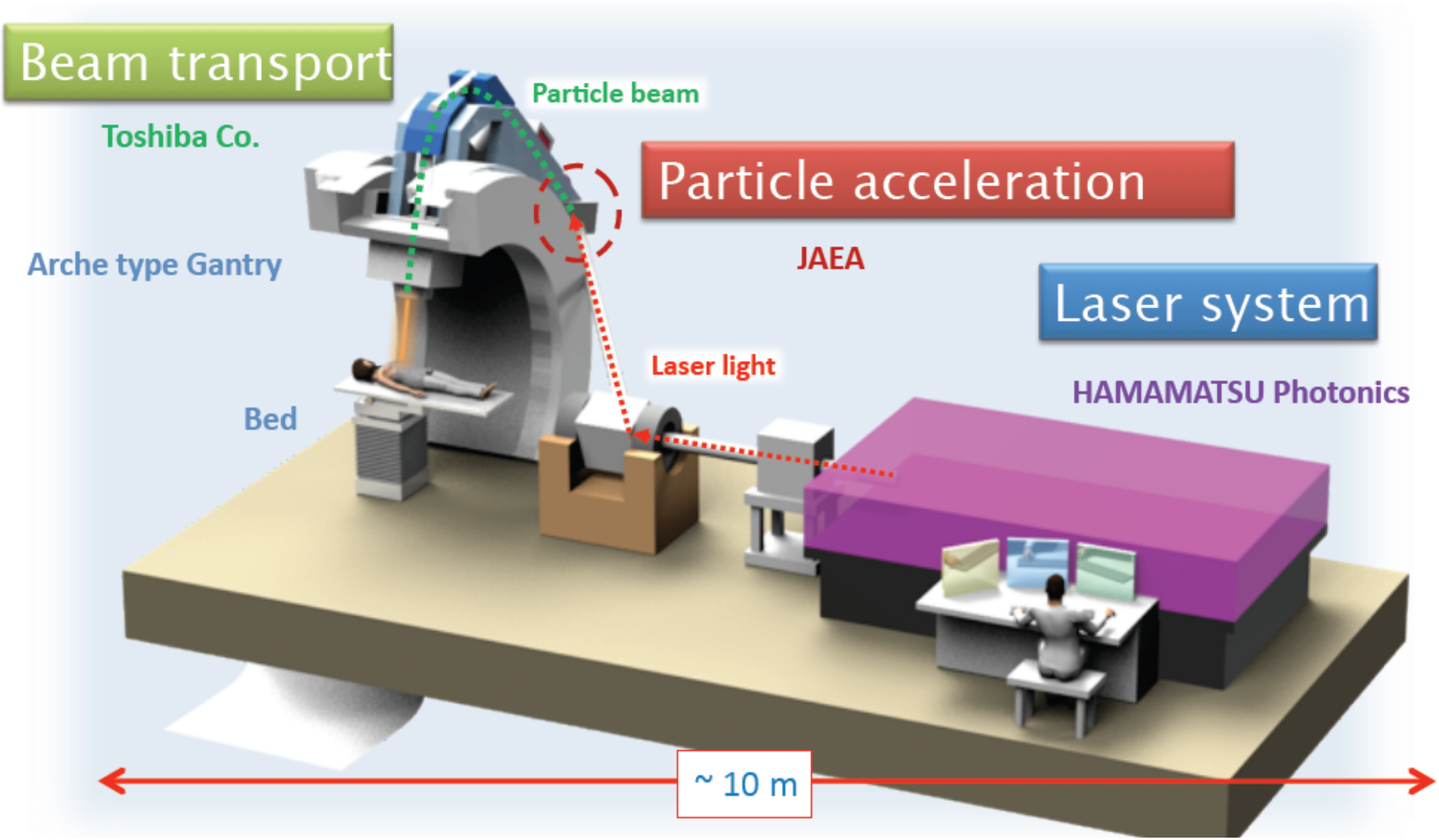
- In Europe : 300
- In USA : 150

Market in progress but still limited by the cost and the size of the installation

Hadron therapy center : large & expensive & performant

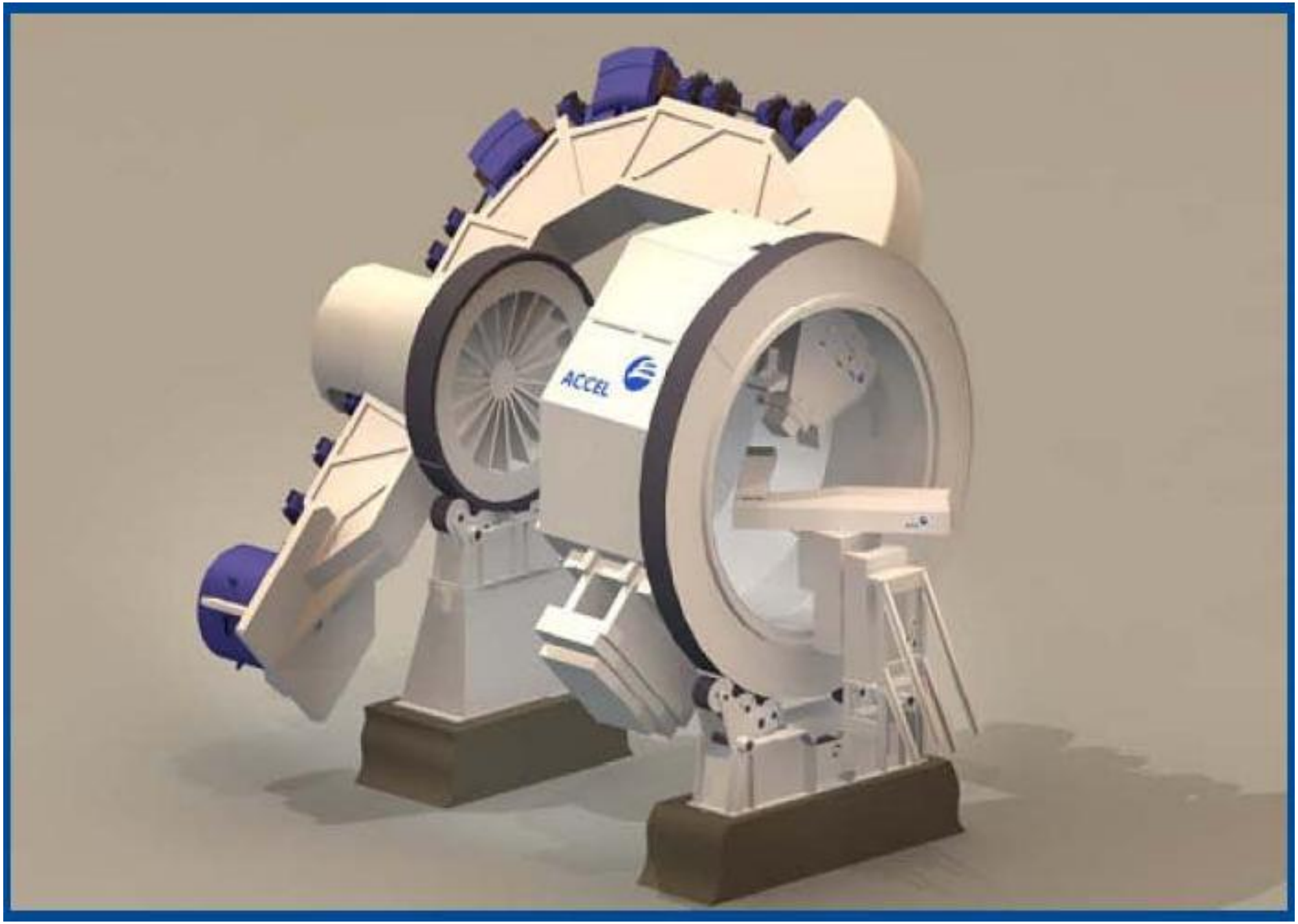
Costo estimado ≈ 200 Millones USD, Pacientes anuales ≤ 1000

Extreme light: Foreseen applications (Laser driven cancer therapy machine)

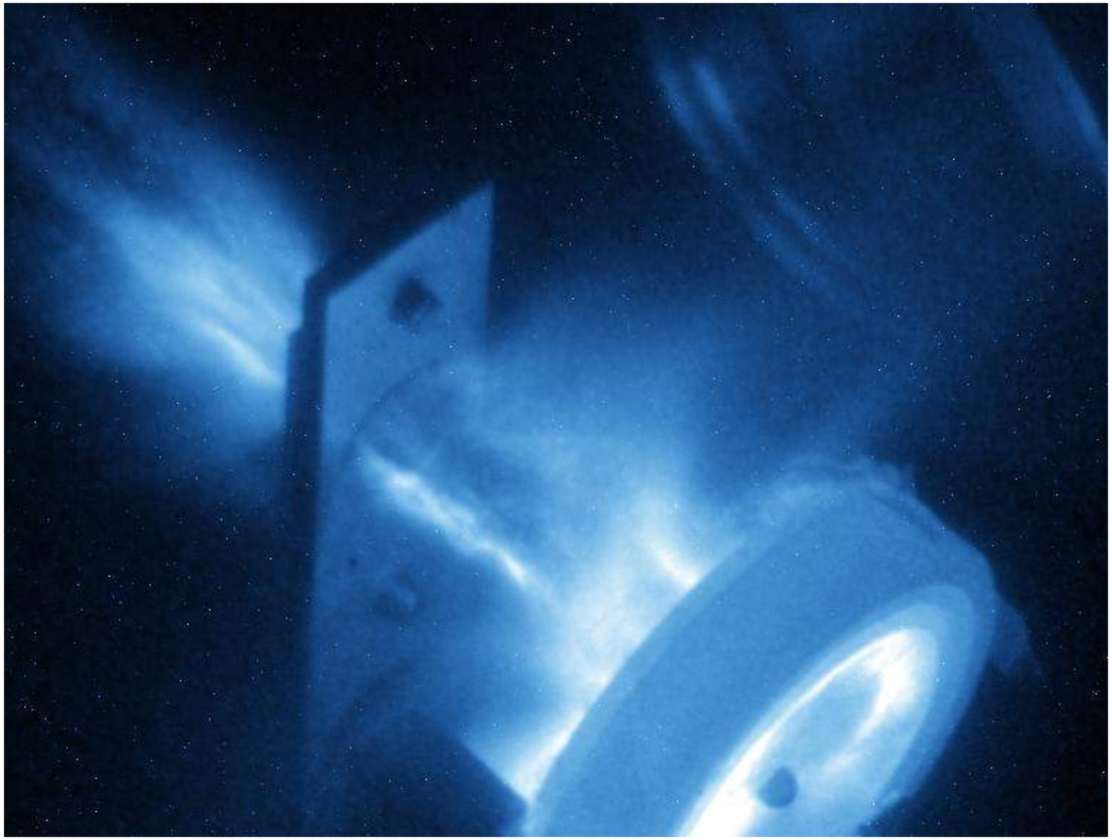


Particle Energy = 80 MeV/nucleon, which corresponds to reach 5 cm from the body surface.

Extreme light: Foreseen applications (Laser driven cancer therapy machine)



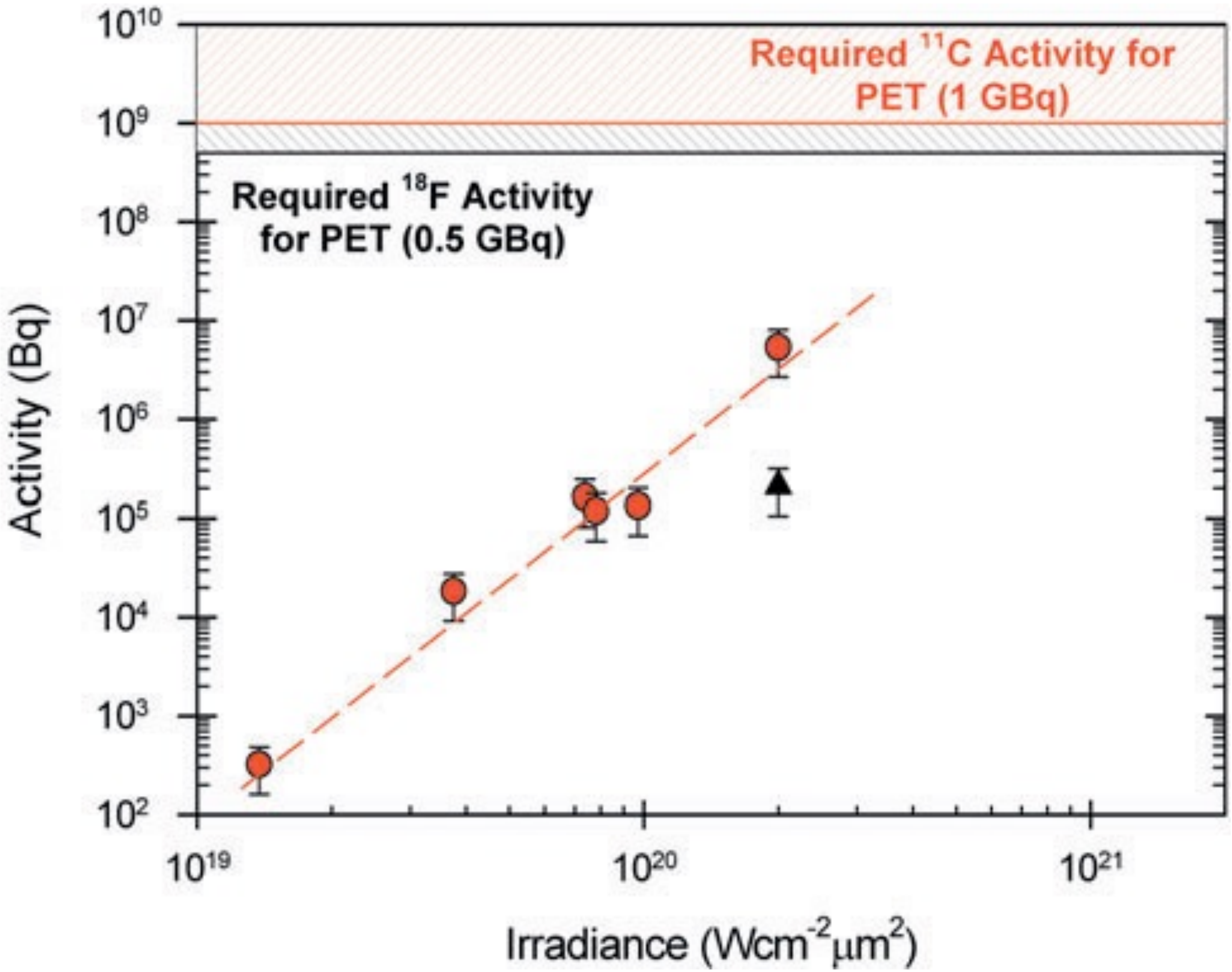
Extreme light: Foreseen applications (Radioisotopes for Positron Emission Tomography)



Ne19 17,3 s	Ne20 stable 90,48%	Ne21 stable 0,27%
F 18 1,83 h	F 19 stable 100%	F 20 11,16 s
O 17 stable 0,038%	O 18 stable 0,2%	O 19 26,46 s

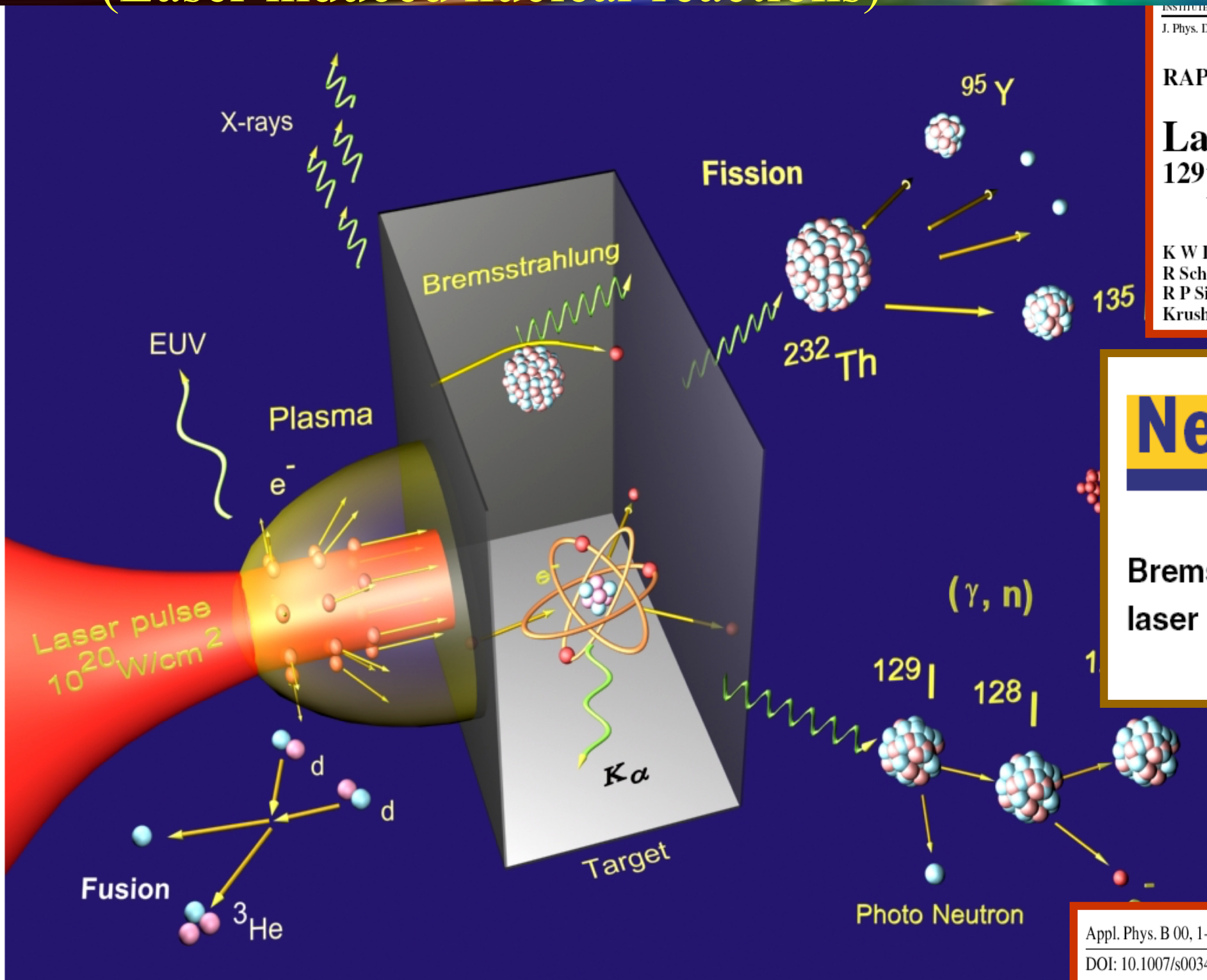
High power laser production of short-lived isotopes (^{18}F, ^{11}C, ^{13}N, ^{15}O) for positron emission tomography (PET).

Extreme light: Foreseen applications
(Radioisotopes for Positron Emission Tomography)



Total activity generated by a single laser shot (pulse energies from 15 to 300 J)

Extreme light: Foreseen applications
(Laser induced nuclear reactions)



INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS D: APPLIED PHYSICS
J. Phys. D: Appl. Phys. 36 (2003) L79–L82 PII: S0022-3727(03)67481-4

RAPID COMMUNICATION

Laser-driven photo-transmutation of ^{129}I—a long-lived nuclear waste product

K W D Ledingham[1,6], J Magill[2], P McKenna[1], J Yang[1], J Galy[2], R Schenkel[2], J Rebizant[2], T McCanny[1], S Shimizu[1], L Robson[1], R P Singhal[3], M S Wei[4], S P D Mangles[4], P Nilson[4], K Krushelnick[4], R J Clarke[5] and P A Norreys[5]

New Journal of Physics
The open-access journal for physics

Bremsstrahlung production with high-intensity laser matter interactions and applications

J Galy[1], M Maučec[2,3], D J Hamilton[1], R Edwards[4] and J Magill[1]

Appl. Phys. B 00, 1–4 (2003)
DOI: 10.1007/s00340-003-1306-4
Applied Physics B
Lasers and Optics

Laser transmutation of iodine-129

[1] European Commission, Institute for Transuranium Elements, Postfach 2340, 76125 Karlsruhe, Germany
[2] Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany

PRL 94, 084801 (2005) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2005

Broad Energy Spectrum of Laser-Accelerated Protons for Spallation-Related Physics

P. McKenna,[1,*] K. W. D. Ledingham,[1,†] S. Shimizu,[1,‡] J. M. Yang,[1,§] L. Robson,[1,†] T. McCanny,[1] J. Galy,[2] J. Magill,[2] R. J. Clarke,[3] D. Neely,[3] P. A. Norreys,[3] R. P. Singhal,[4] K. Krushelnick,[5] and M. S. Wei[5]

Extreme light: Foreseen applications
Laser induced neutron sources

Big Stationary Neutron Sources	
	Flux [neutrons/cm^{2}s]
Traditional Reactor	from 10^7 to 10^{13}
High Flux Research Reactor	up to 10^{15}
Accelerator Driven Spallation	up to 10^{14}
Compact and Portable Neutron Sources	
	Typical Source Strength [neutrons/s]
Radioactive Neutron Sources	10^5 to 10^7
Spontaneous Fission Sources	around 10^{10}
Portable Neutron Generators	10^8 to 10^{10}

Lasers on Solid Targets			
	Reaction(s) Used	**Measured Source Strength [neutrons/shot]**	**Laser Energy [J/shot]**
Lancaster	^{7}Li(p,n)^{7}Be	2×10^8 sr^{-1}	69
Yang	^{nat}Zn(p,xn)Ga	$\approx 10^{10}$	230
Yang	^{7}Li(p,n)^{7}Be	5×10^{10}	230
Zagar	^{nat}Pb(p,xn)Bi	2×10^9	400

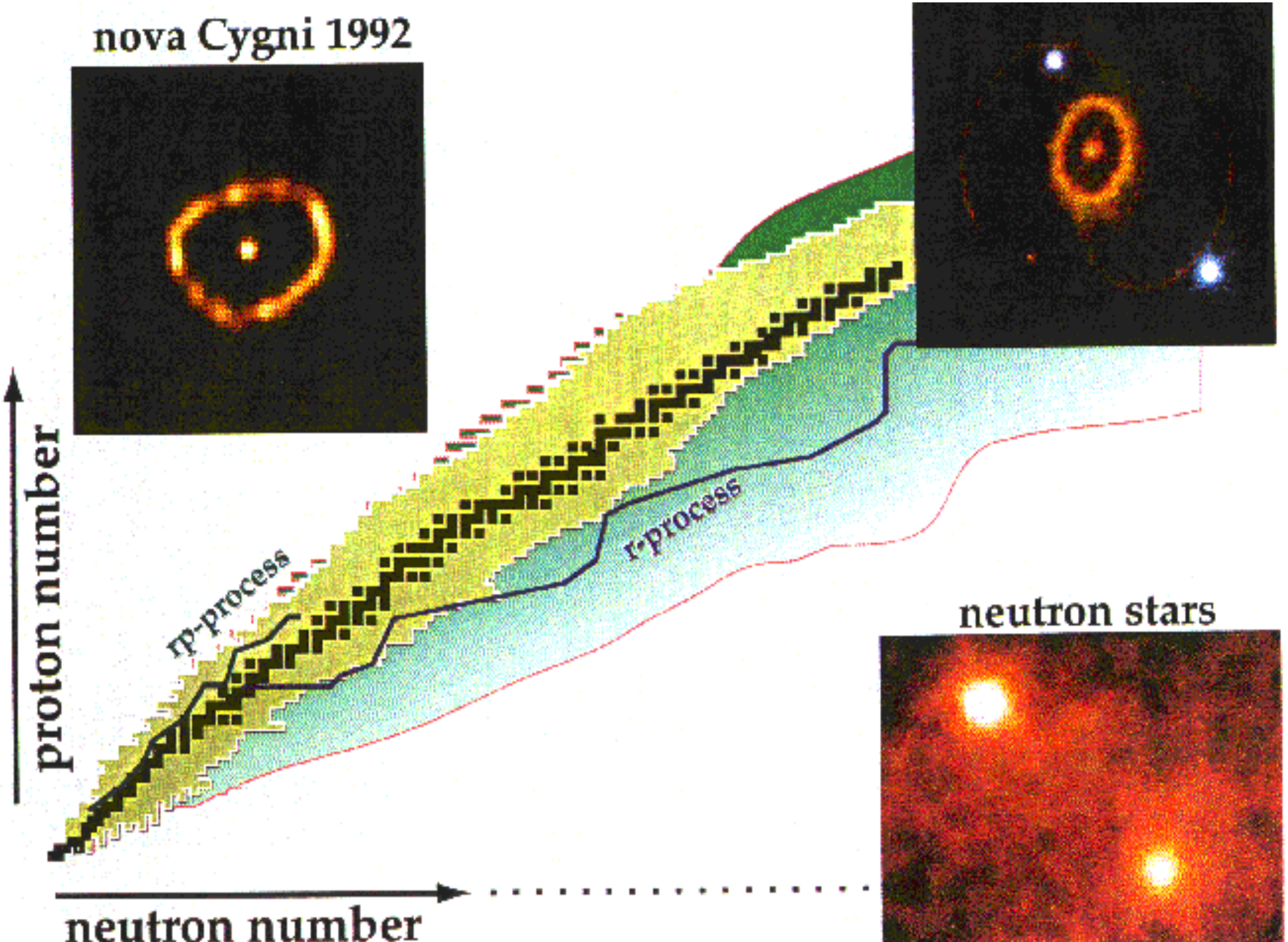
Some General Properties

- Compact Table-Top Sources (!)
- Forward Directed Beams
- Pulsed Operation
- Very Short Pulse Durations (!)
- High Repetition Rates
- Useful Source Strengths

Main applications of neutron sources:

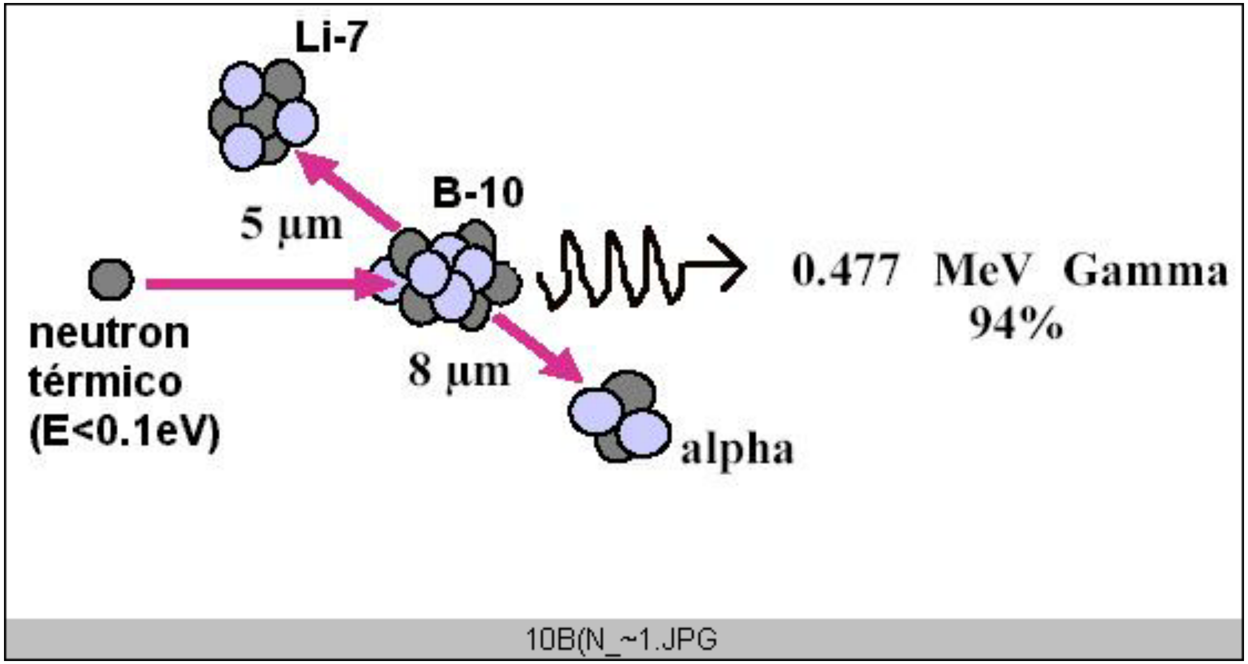
- Neutron Capture on Astrophysical studies.
- Boron Neutron Capture Therapy (**BNCT**)
- Neutron Radiography detection of illicit substances.
- High Resolution Neutron Radiography
- Neutrons as essential tools for Nanoscience Research

Extreme light: Foreseen applications
Laser induced neutron sources for Astrophysical studies

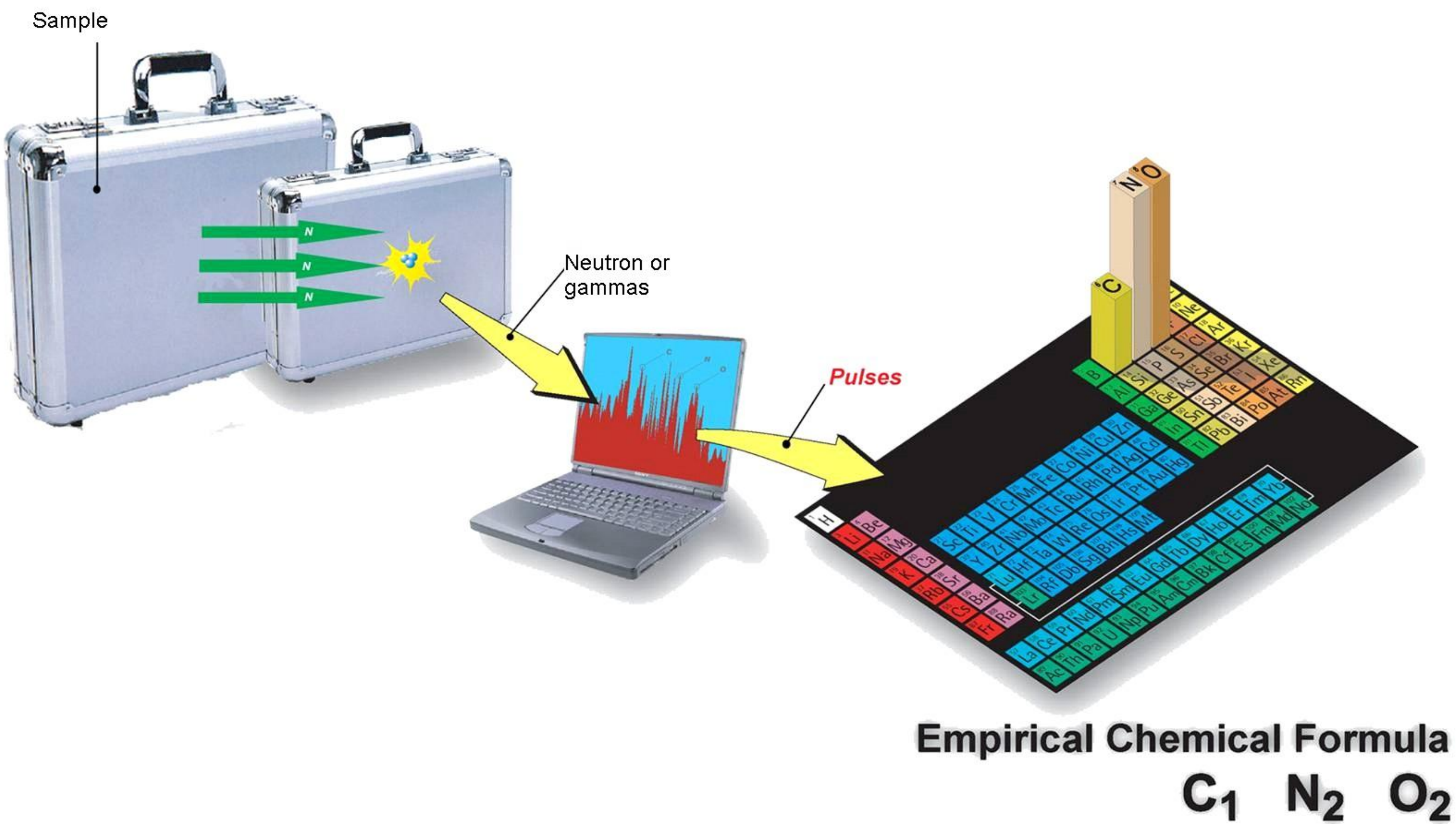


Extreme light: Foreseen applications
Laser induced neutron sources for BNCT

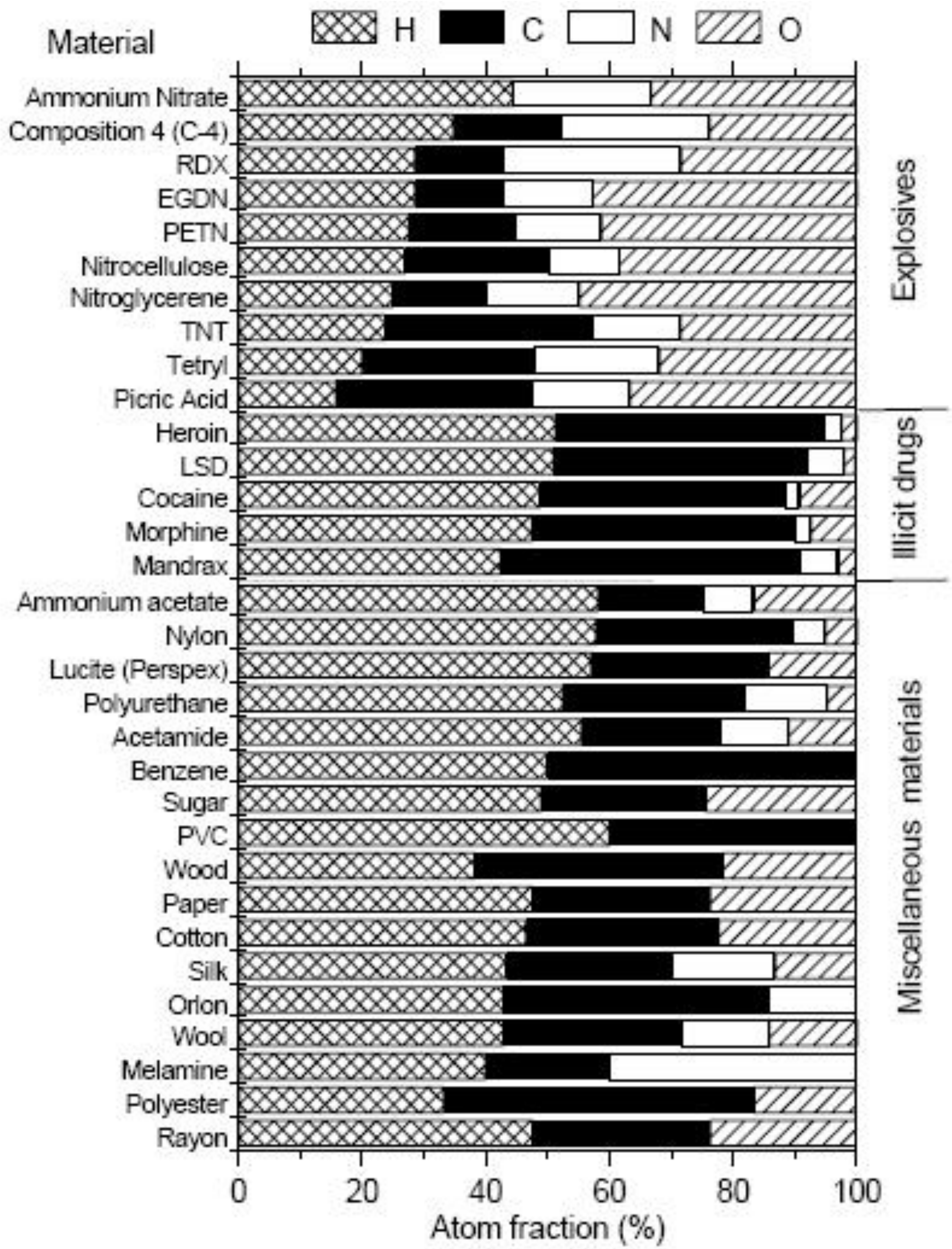
- Boron Neutron Capture Therapy (**BNCT**) is an experimental binary radiotherapy modality for certain types of currently intractable malignancies such as Glioblastoma Multiforme (GBM) and metastases of Malignant Melanoma.
- This binary system of radiation therapy is based on the high probability of thermal neutron capture by boron nucleus 10B compared with other elements in human tissue.



Extreme light: Foreseen applications
Laser induced neutron sources



Elemental composition of explosives and illicit drugs

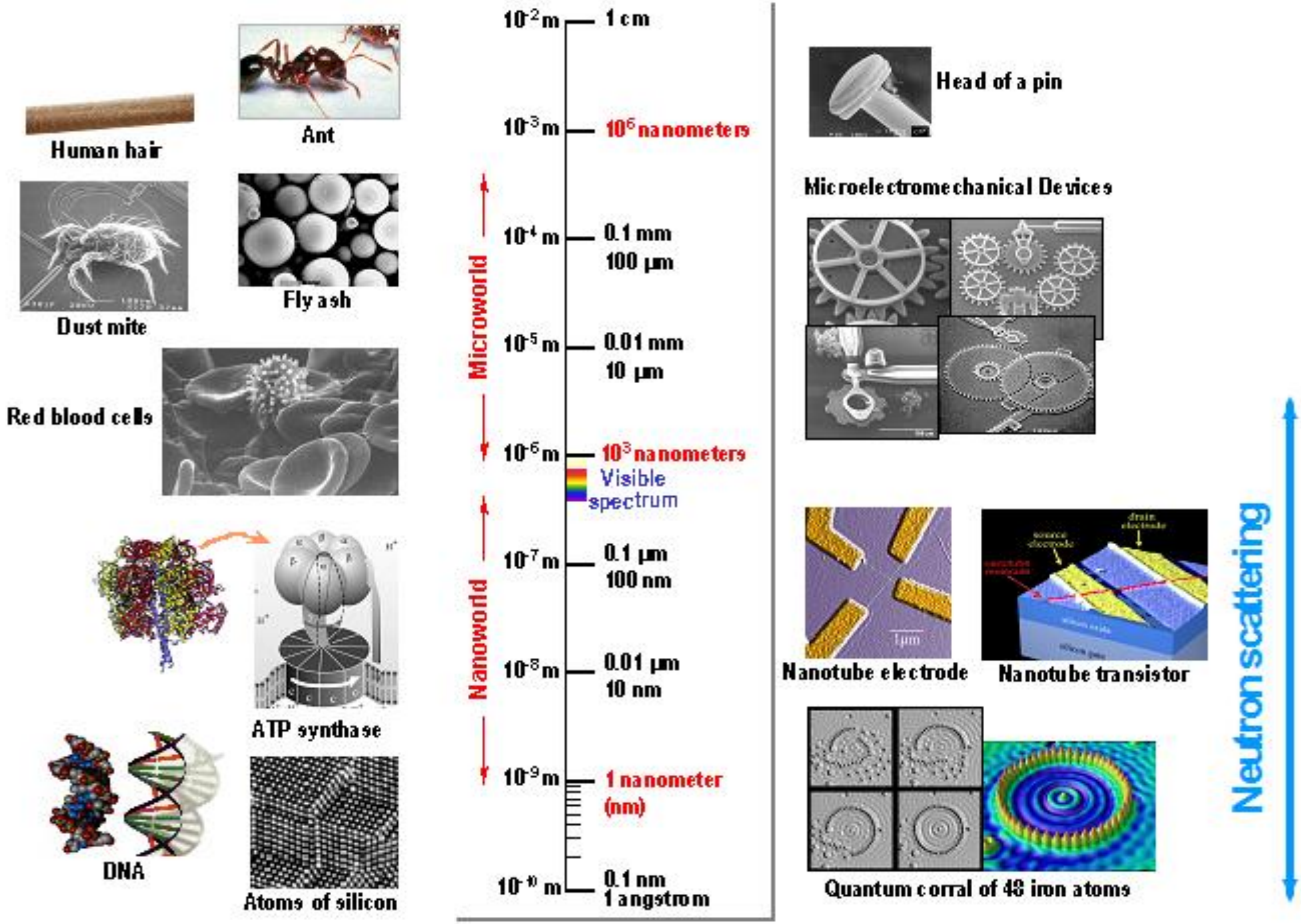


Extreme light: Foreseen applications
Laser induced neutron sources for Nanoscience Research

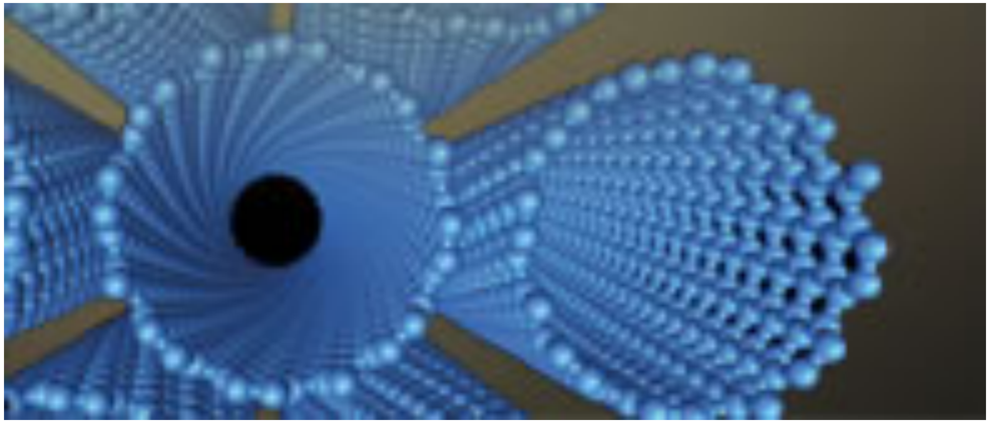
The neutrons are superb probes for exploring the frontiers of nanoscience because they are sensitive to:

- ✓ Structural features with lengths from 10^{-3} to 10^{3} nm.
- ✓ Dynamic properties with characteristic time scales from 10^{-18} to 10^{-6} seconds.
- ✓ The neutrons are produced with wavelengths that are comparable to the atomic spacing in solids and liquids.
- ✓ Its kinetic energies are comparable to those of dynamic processes in materials.

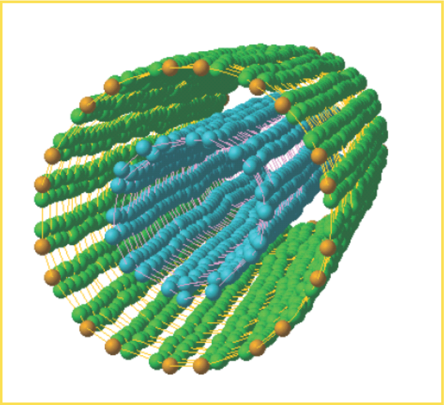
Neutrons probe a broad range of length scales



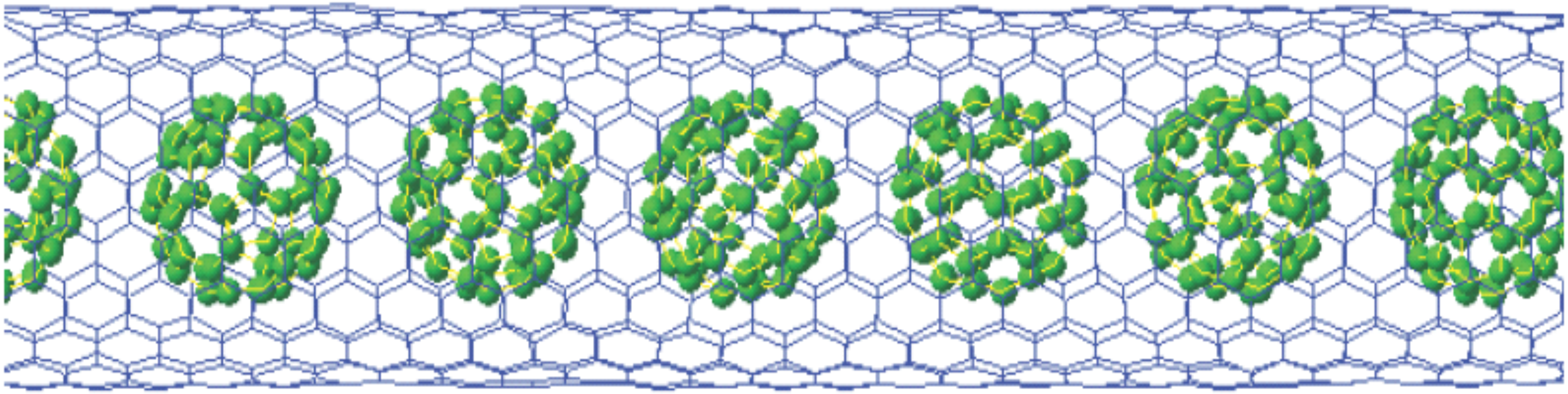
Neutron Scattering Studies of Hydrogenation / Dehydrogenation of Carbon Nano-Materials.



SWNT

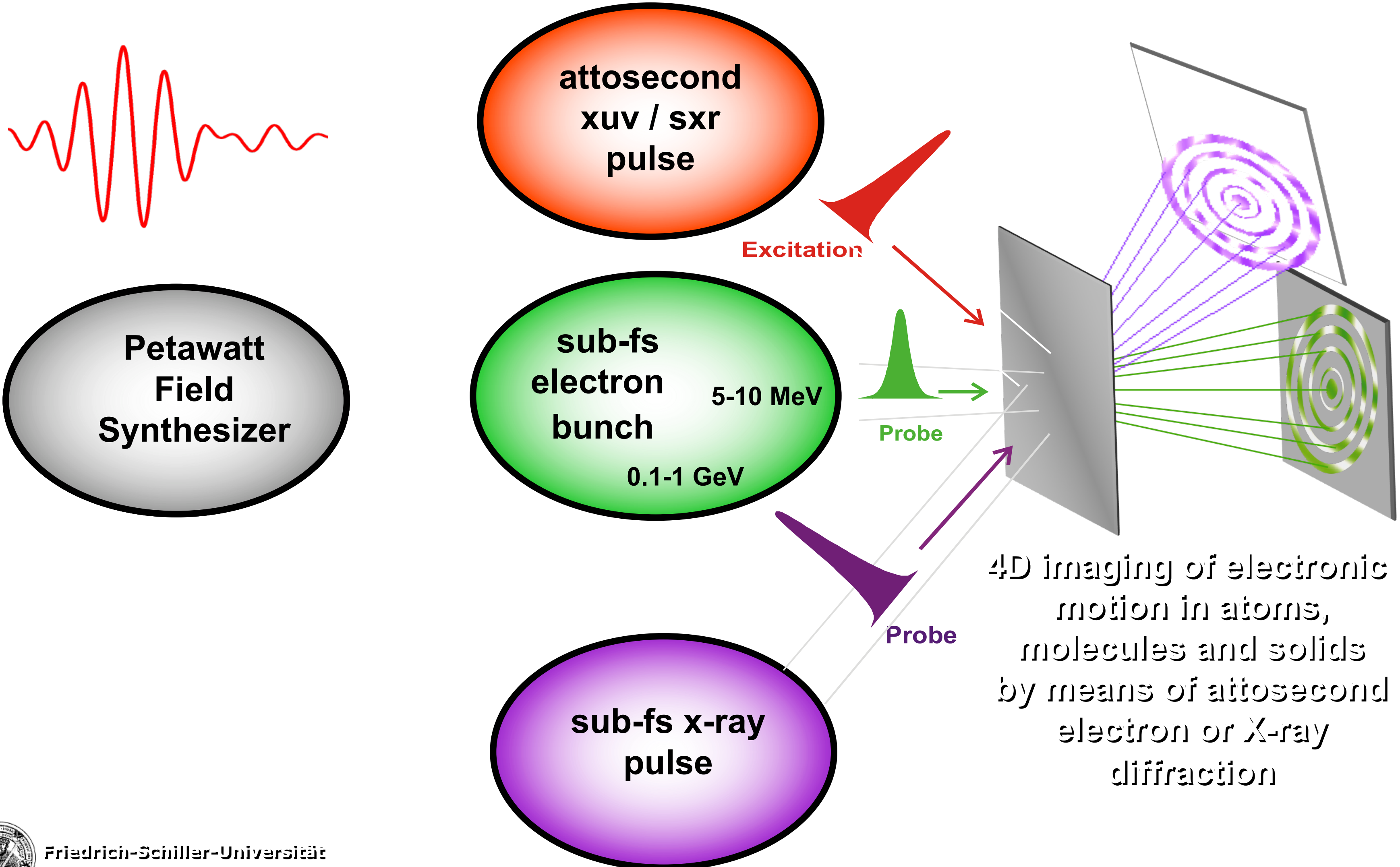


DWNT



C_{60}-peapods

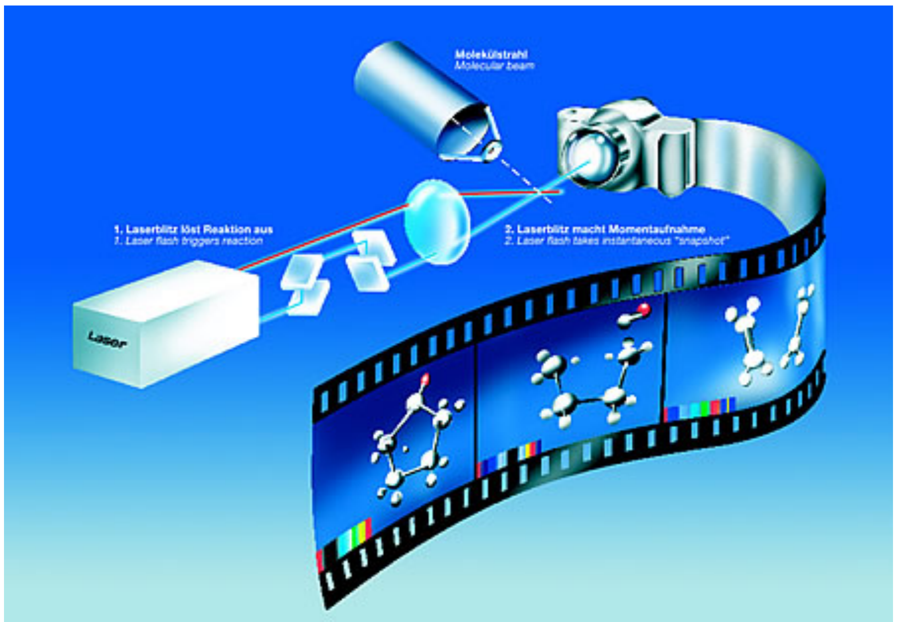
Control & 4D imaging of valence & core electrons with sub-atomic resolution

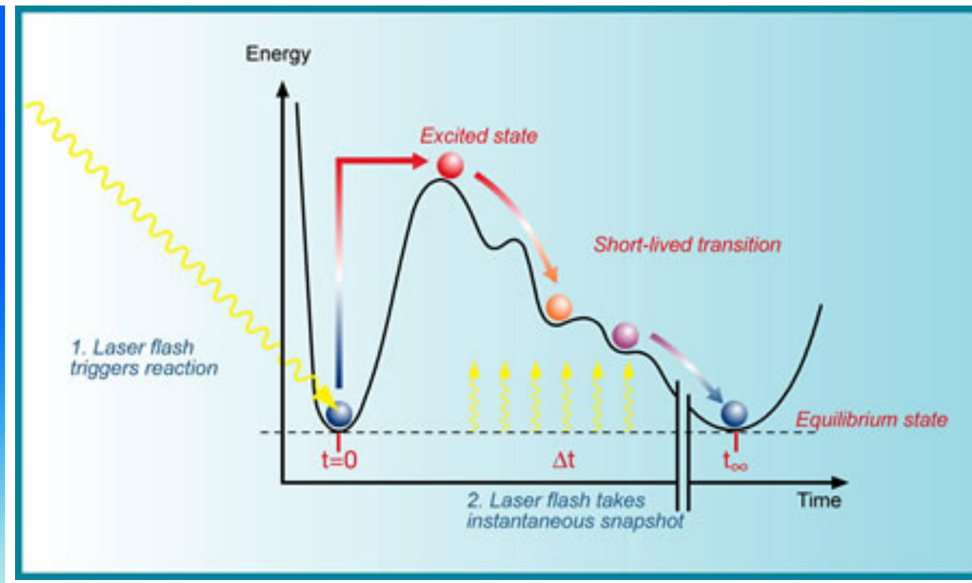


4D imaging of electronic motion in atoms, molecules and solids by means of attosecond electron or X-ray diffraction

Femtochemistry

- Capturing chemical reactions on film

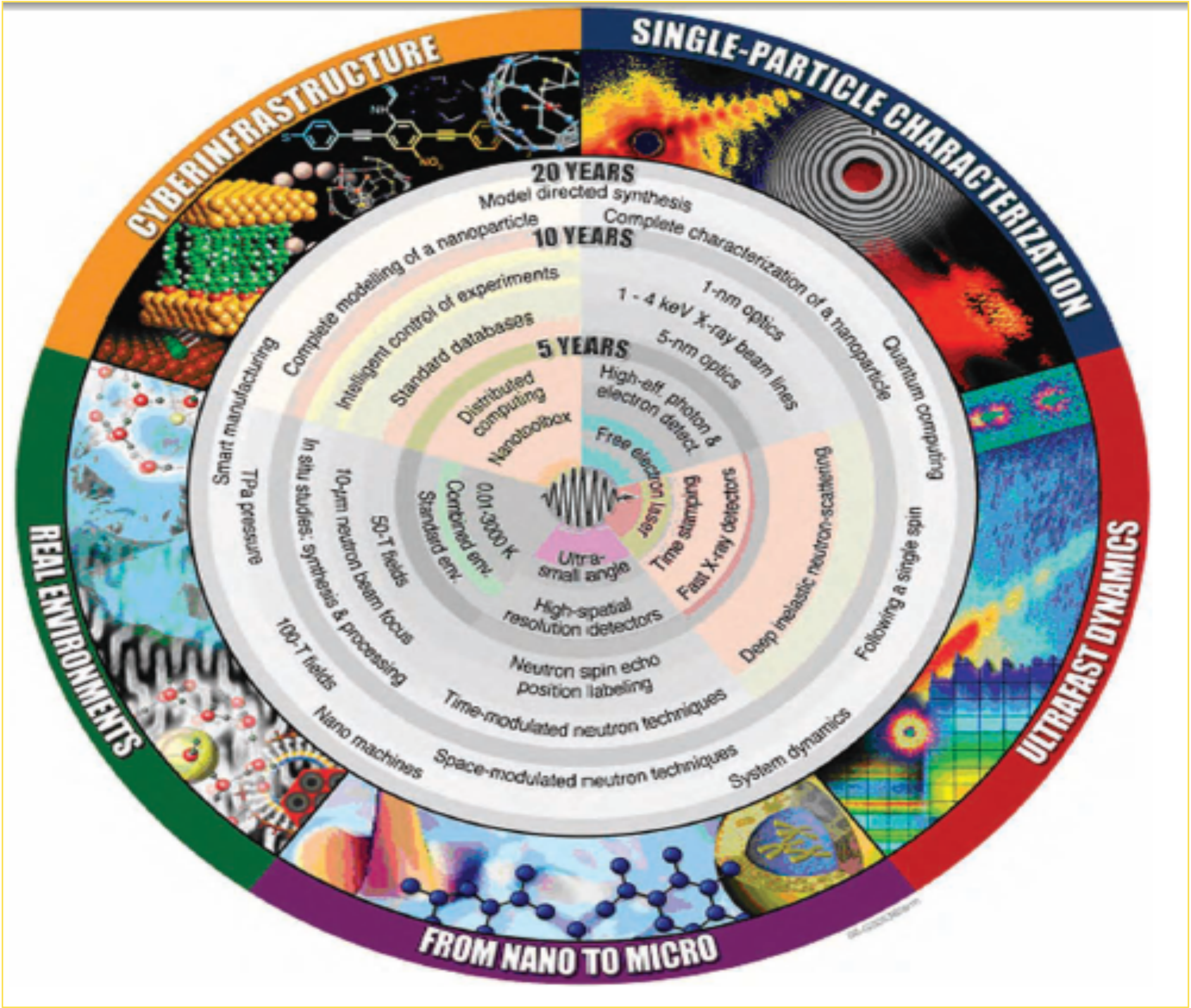




"Filming" chemical reactions using ultra-fast lasers.

A chemical reaction is triggered by a laser flash. A second laser pulse is then sent at varying intervals after the first one to take instantaneous snapshots.

Road map for the Future of X-ray and Neutron Nanoscience



Conclusions and perspectives

- Giant pulse single shot and high repetition rate tabletop laser have demonstrated their abilities to produced beam of electron, protons and ions.
- This research field is developing fast with fast development of high intensity laser.
- Lasers do offer a new approach to studying material behavior under neutral and charge particle irradiation without resource to reactors or accelerators.
- Currently laser light can directly accelerate electrons to relativistic speeds, and can consequently accelerate protons and other ions. In near future lasers will be able to accelerate protons to relativistic speeds directly.
- New table-top radiation sources will become available (positrons, radioactive ion sources.
- We have shown possible applications of laser producing accelerated beams of electrons, protons, gammas and neutrons.
- One can expect that these systems can be put to use as strong, and possibly compact sources, for nuclear applications.

Table-top lasers

Table-top radiation sources

CEADEN
CENTRO DE APLICACIONES TECNOLÓGICAS
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