ON HIGH FIELD PLASMONICS AND A POTENTIAL NUCLEAR FUSION APPLICATION

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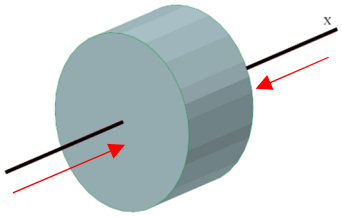
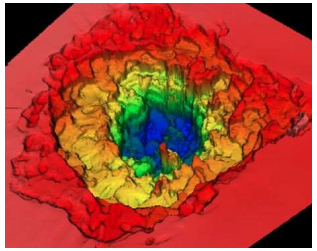
HUNGARIAN ACADEMY OF SCIENCES

Motto: Only those, who are prepared to go too far, can know how far they may go.

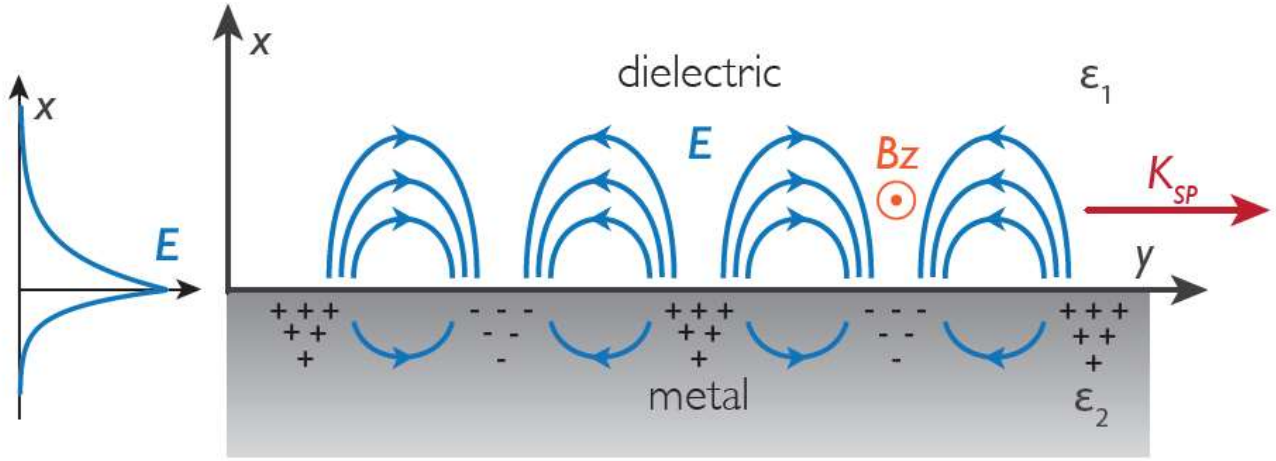




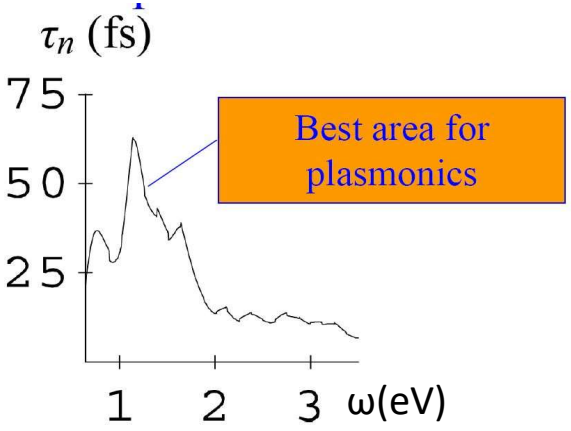
CASPER, 07.21.2023

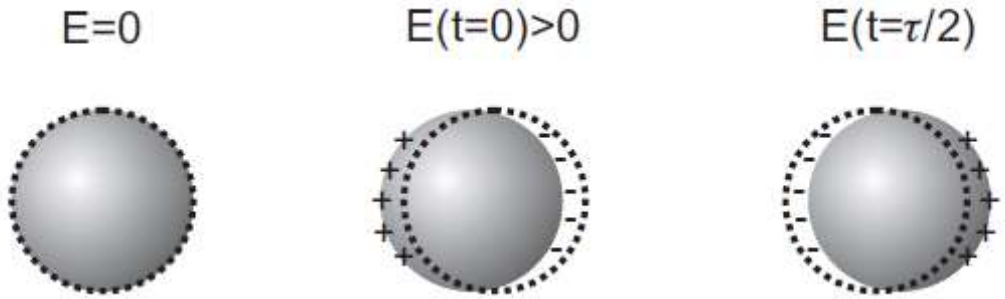
PLASMONICS AND HIGH FIELDS APPLICATIONS

Special type of the optical near field



SPP

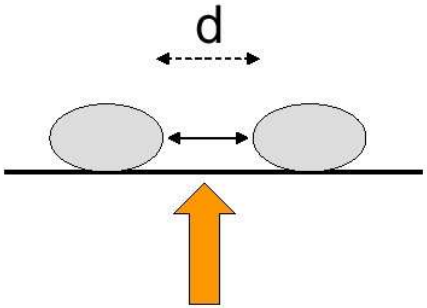




LSPP

Ti:Sa laser: λ=800nm (~1.55eV) ; $t_{(SPP)}$~20fs

LSPP



d << λ

"Near-field coupling"

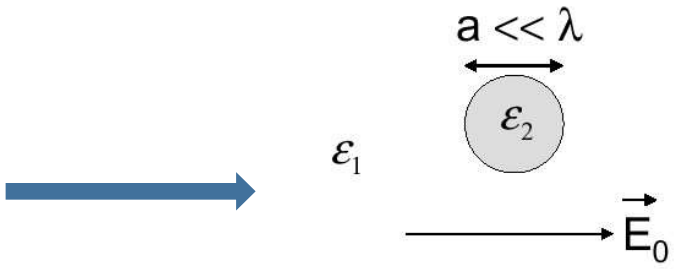
⇒ Resonator coupling

d >> λ

"Dipole-dipole coupling"

⇒ Interferences

If a << λ ⇒ dipole :



$$p = \varepsilon_2 \, \alpha \, E_0$$

with:

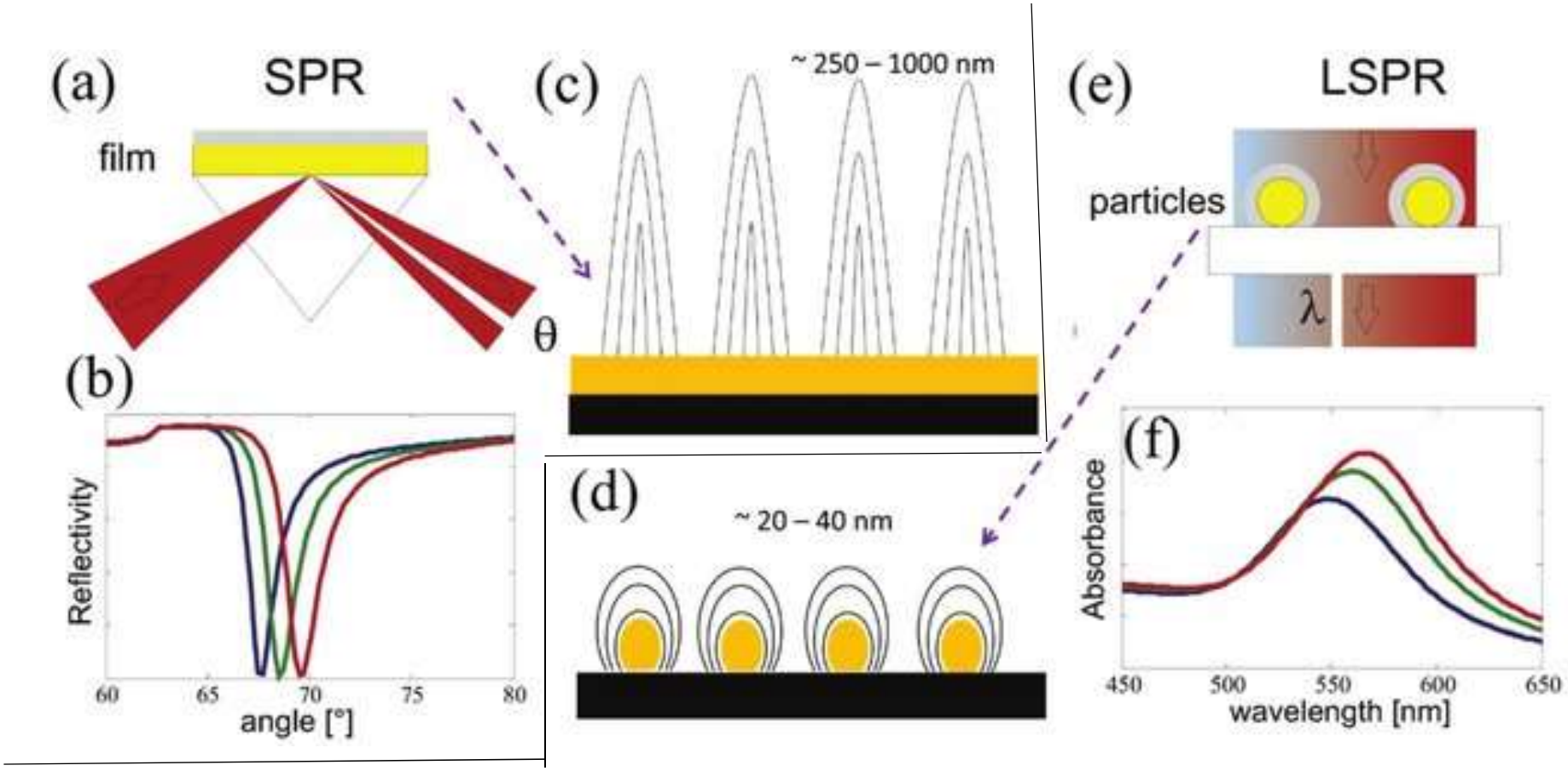
$$\alpha = 4\pi \, a^3 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}$$

Resonance when $\varepsilon_2(\omega) = -2 \times \varepsilon_1(\omega)$

- Enhanced absorption
- Enhancement of the near-field & scattering

LOCALIZED PLASMONS (LSPP) UP TO 10^{20} W/cm^2)

(The basic difference between SPP-s and LSPP-s)



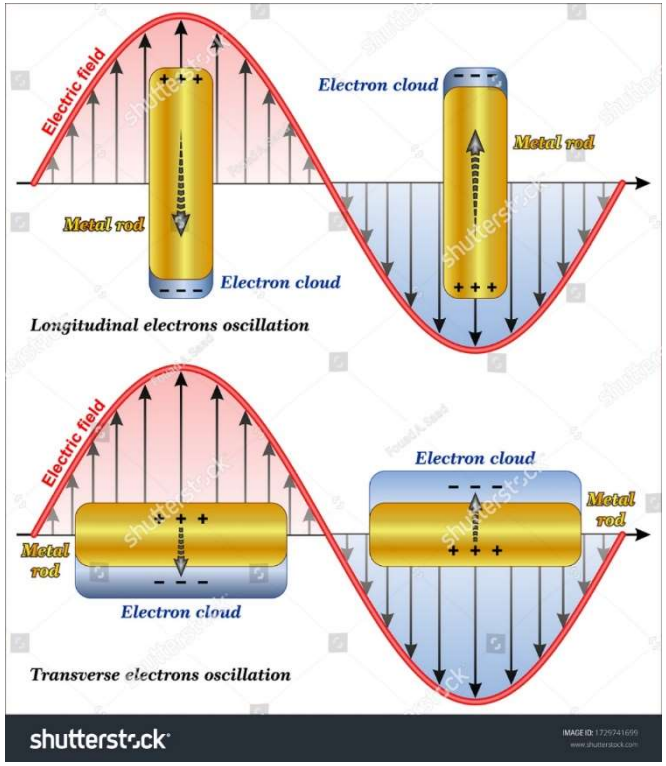
LSPP: - NO PENETRATION INTO THE PLASMONIC MATERIAL (e.g. metal)

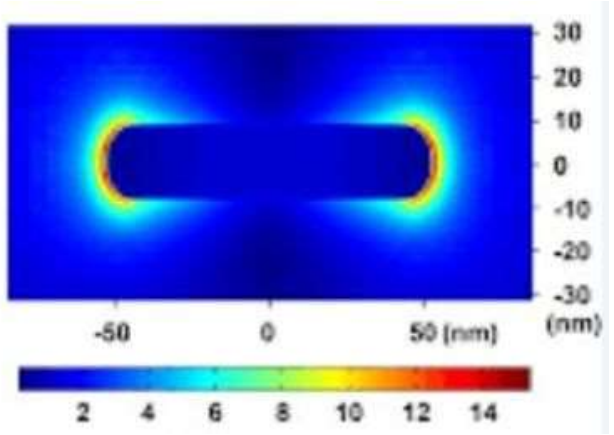
- SMALLER PENETRATION INTO THE DIELECTRIC /VACUUM

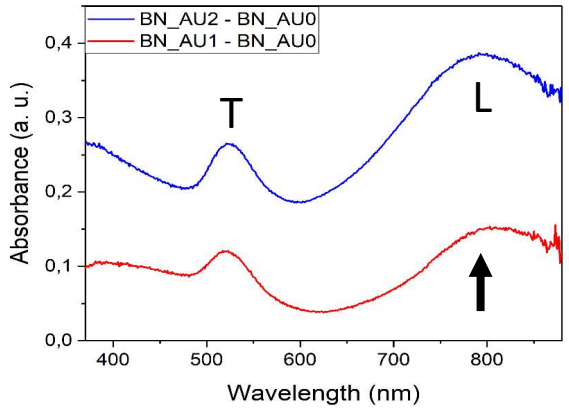
-NO DISPERSION

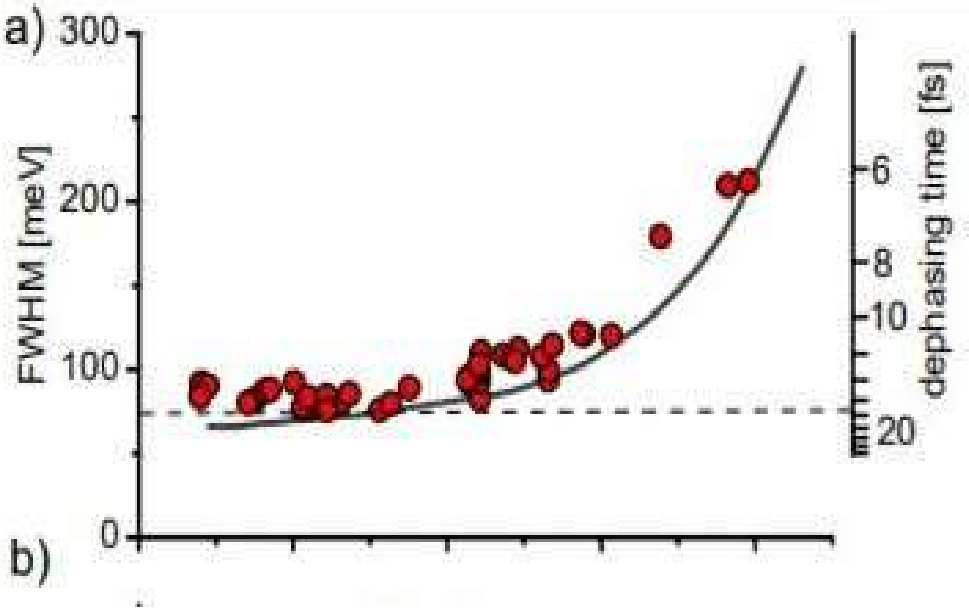
-BROADER RESONANCE

Nanorod:Transverse and longitudinal modes!



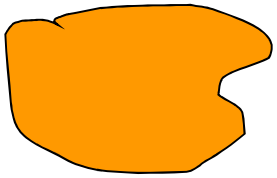






PLASMONREONANCE OF NANOPARTICLES SHAPE AND- ÉS SIZEDEPENDENT!

$$\omega_B = \sqrt{\frac{4\pi e^2 n}{m_e}}$$

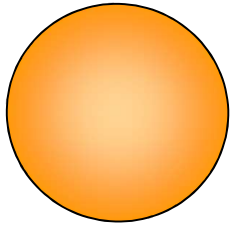


Bulk

$$\omega_{surf} = \frac{\omega_B}{\sqrt{2}}$$

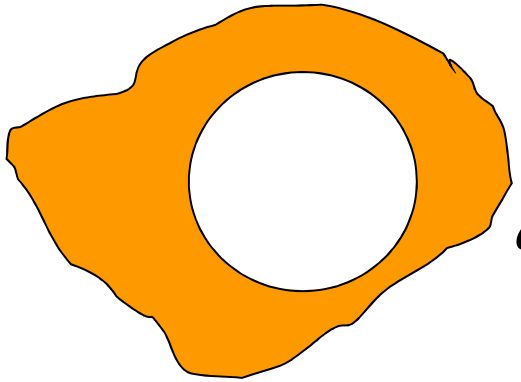
Surface

$$\omega_{S,l} = \omega_B \sqrt{\frac{l}{2l+1}}$$



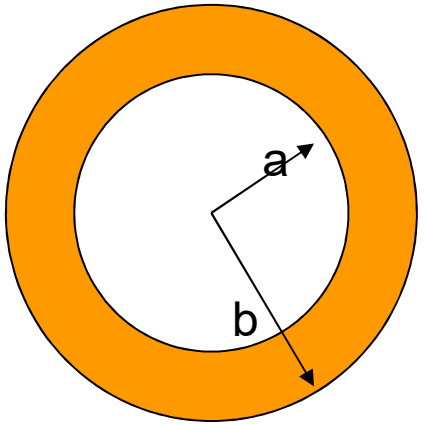
Sphere

Üreg



$$\omega_{C,l} = \omega_B \sqrt{\frac{l+1}{2l+1}}$$

Nanoshell:

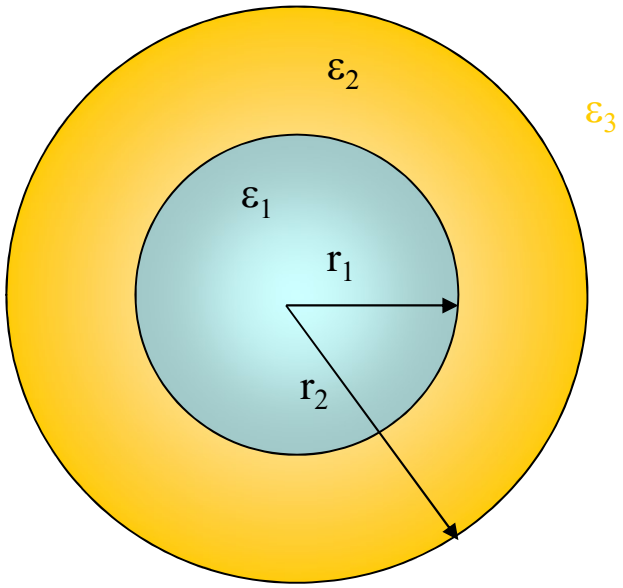


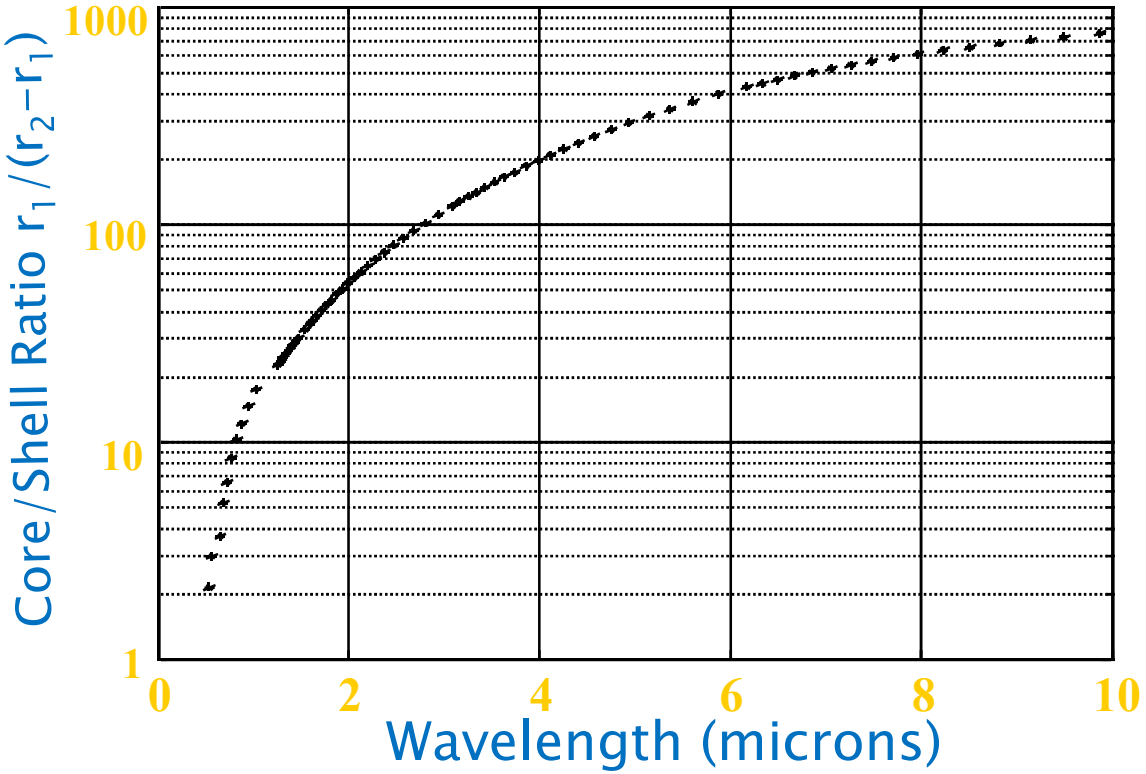
$$x = \frac{a}{b}$$

$$\omega_{l\pm}^2 = \frac{\omega_B^2}{2}\left[1 \pm \frac{1}{2l+1}\sqrt{1+4l(l+1)x^{2l+1}}\right]$$

Nanoshell plasmon resonance depends on the x ratio .

Spectral tuning range
nanoshell plasmon rezonance

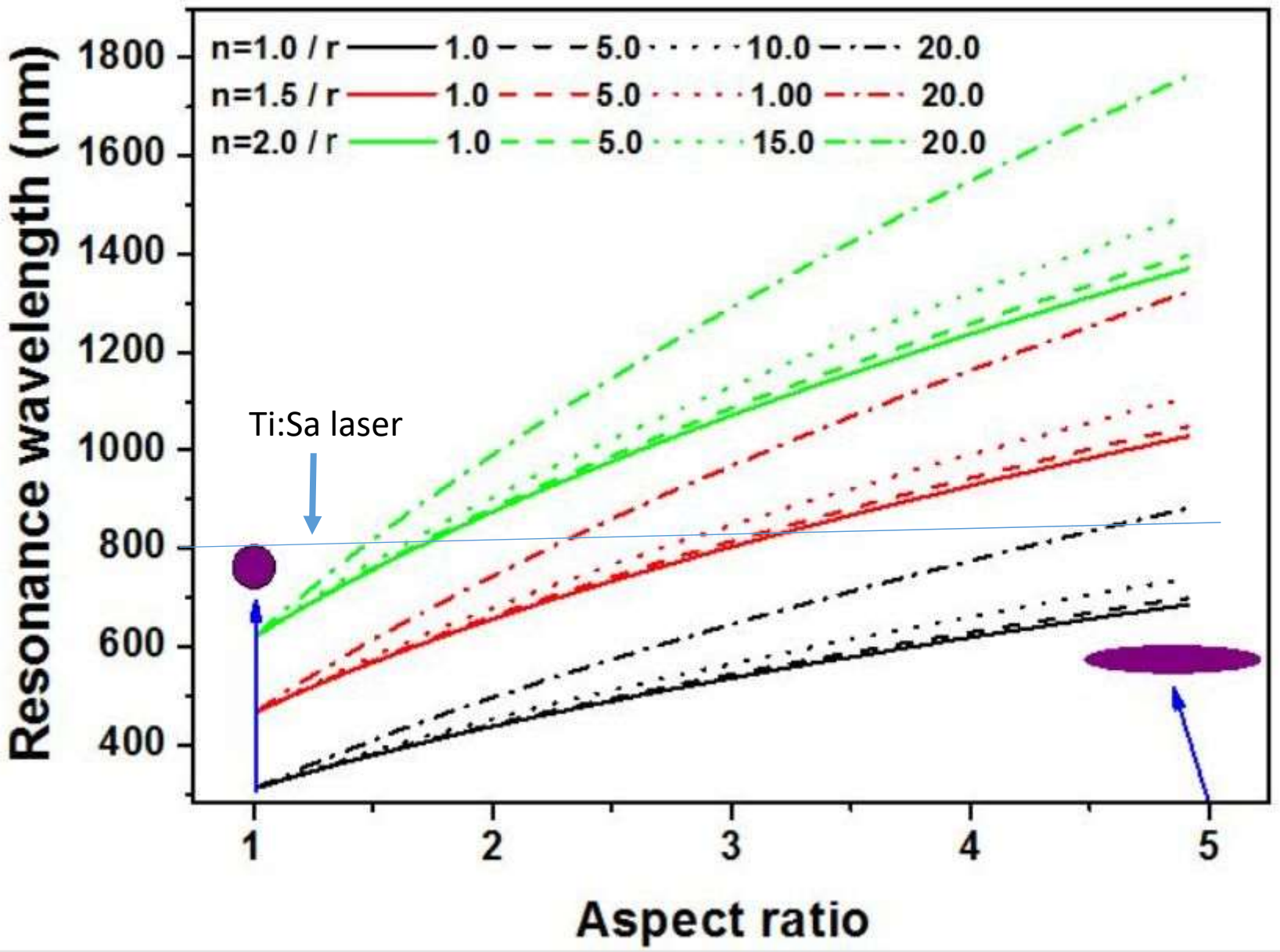


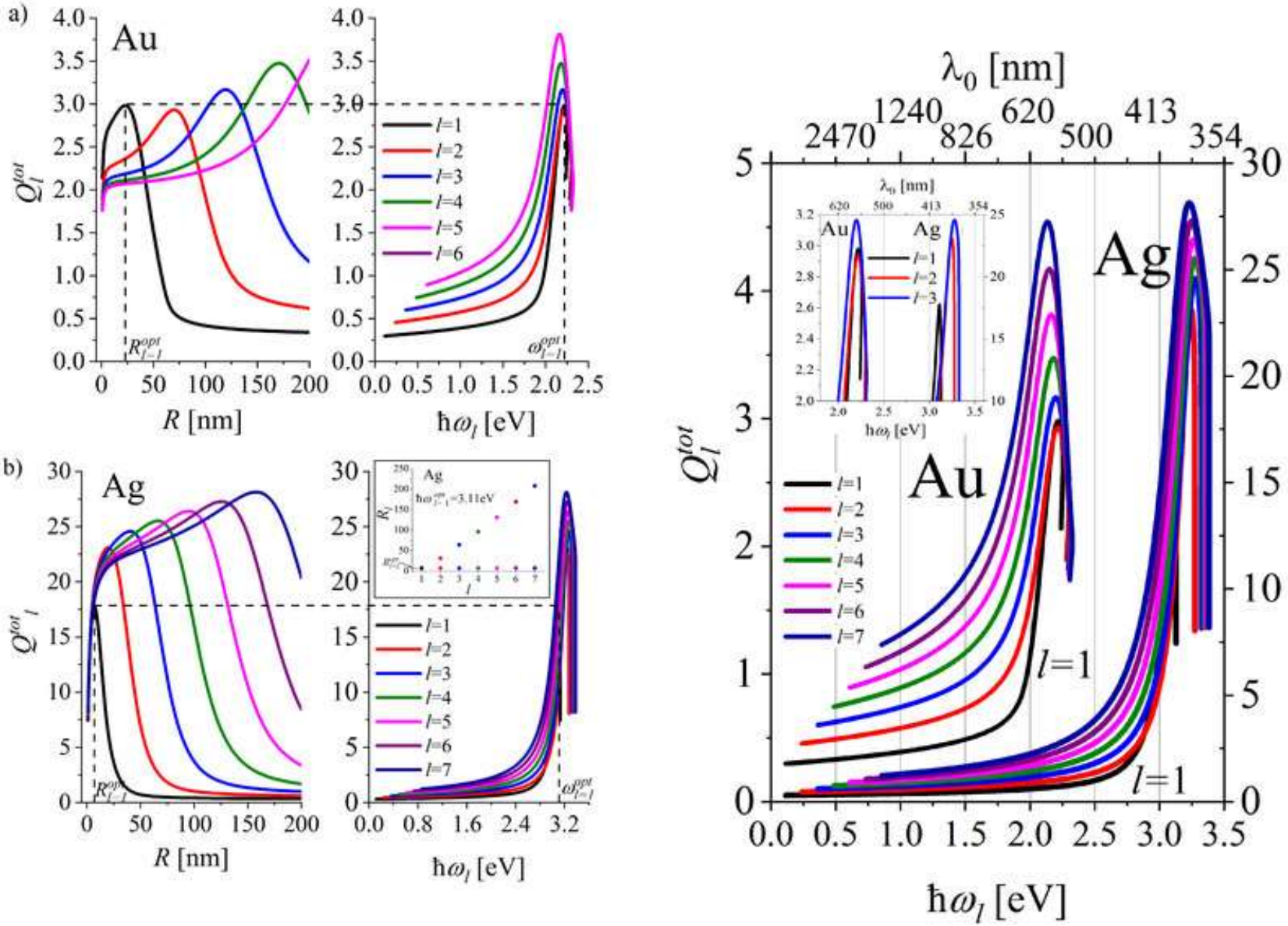


1.24 ← electron volts → 0.124

300 ← THz → 30

10,000 ← cm^{-1} → 1,000


n=1.0 / r
1.0
5.0
10.0
20.0
n=1.5 / r
1.0
5.0
1.00
20.0
n=2.0 / r
1.0
5.0
15.0
20.0
Ti:Sa laser
Resonance wavelength (nm)
1800
1600
1400
1200
1000
800
600
400
1
2
3
4
5
Aspect ratio



Krystina Kolwas: Materials 2023, 16,1801, pp1-15

SPP and LSPP are a „NEW TYPE OF LIGHT", they are

1. BOUND TO THE (METAL) SURFACE (SPP and LSPP)

2. HAVE SPECIFIC DISPERSION PROPERTIES (LSPP no dispersion)

3.THE DIFFRACTION LIMIT DOES NOT APPLY,

4.CAN BE SQUEEZED TO NANOSIZED VOLUMES

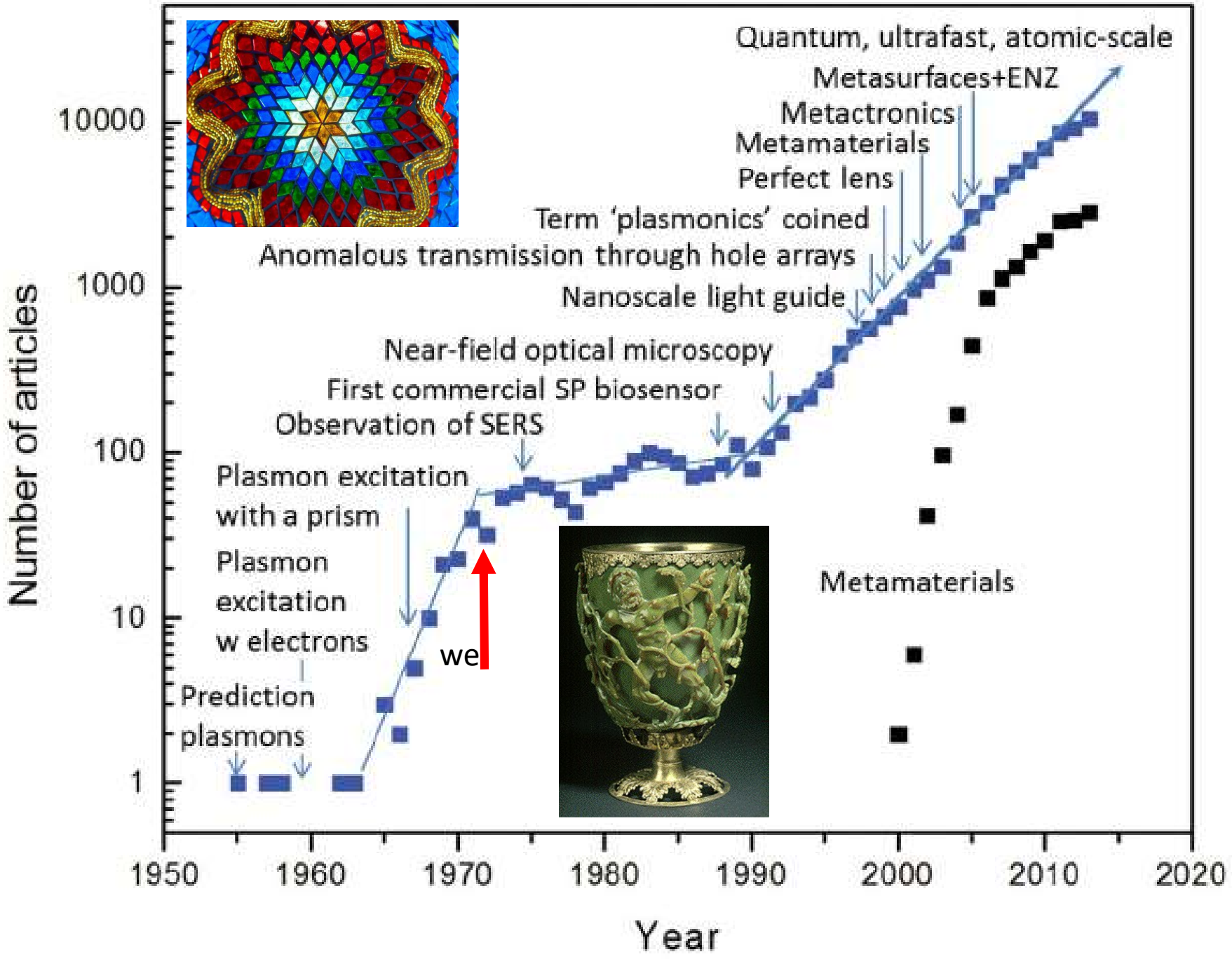
5. SCREEN POSITIVE (e.g.proton) PARTICLE FIELDS

6. IS CORRELATED MOTION OF A HIGH NUMBER OF CONDUCTION ELECTRONS

7. COULD REPRESENT VERY HIGH ELECTRIC FIELDS (hot spots)

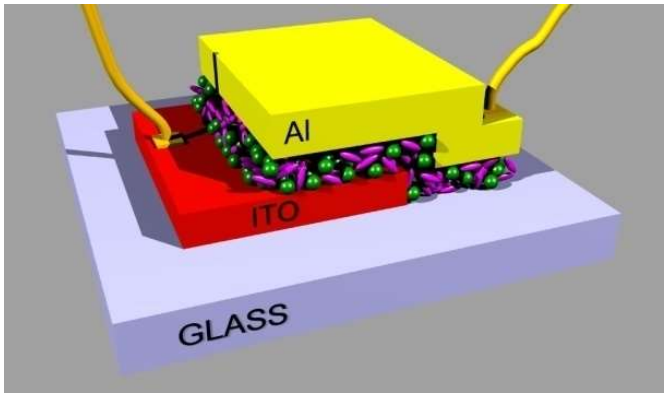
8. MAY BE THE SOURCE OF DIFFERENT NONLINEAR PROCESSES

9.SHOW NON-CLASSICAL PROPERTIES

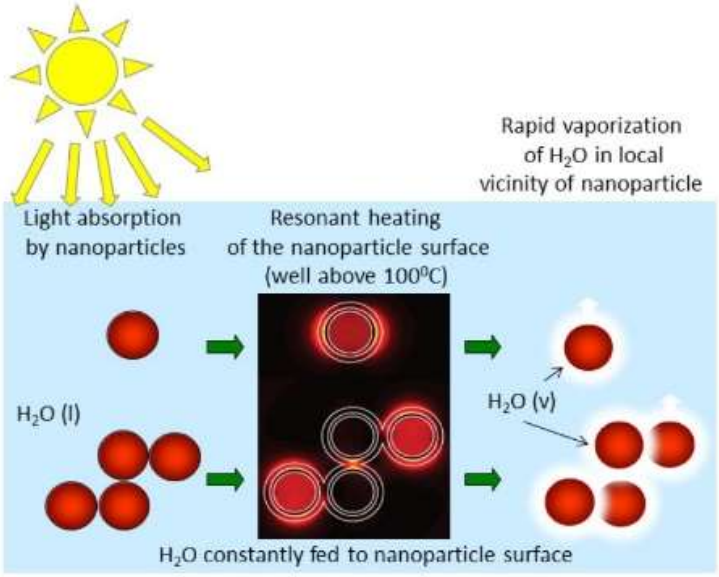

Quantum, ultrafast, atomic-scale
Metasurfaces+ENZ
Metactronics
Metamaterials
Perfect lens
Term 'plasmonics' coined
Anomalous transmission through hole arrays
Nanoscale light guide
Near-field optical microscopy
First commercial SP biosensor
Observation of SERS
Plasmon excitation with a prism
Plasmon excitation w electrons
Prediction plasmons
we
Metamaterials
Number of articles
10000
1000
100
10
1
1950
1960
1970
1980
1990
2000
2010
2020
Year

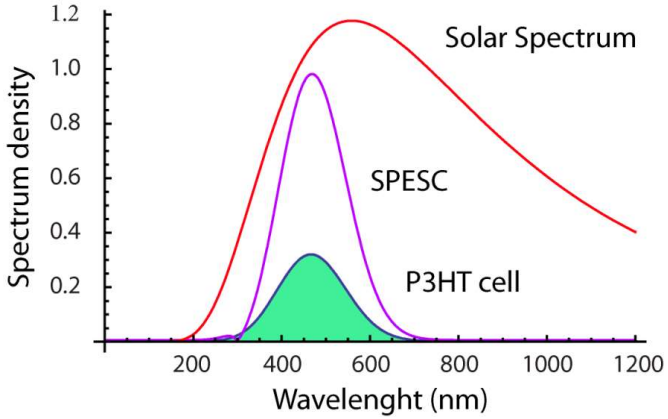
Some potential new energy technologies

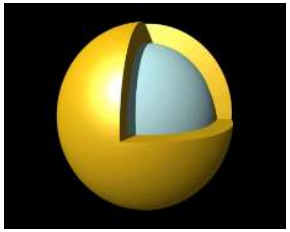
(involving nanotechnologies)

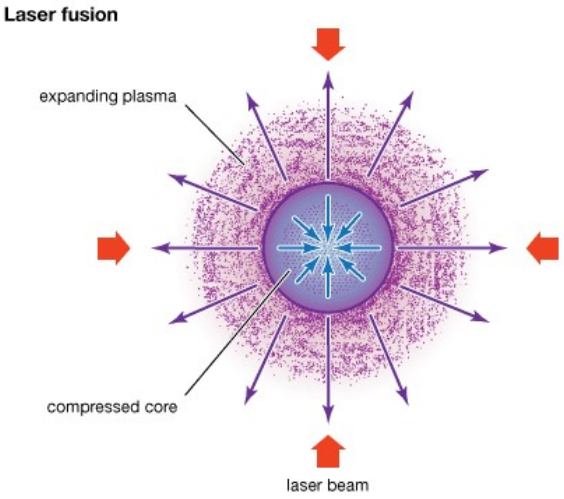


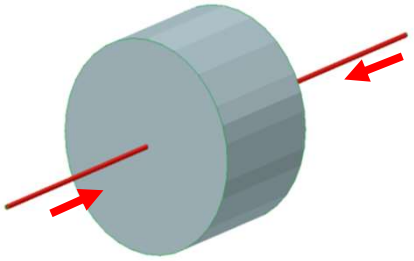
P3HT Cell efficiency = 6%
SPESC (P3HT) efficiency = 17.5%



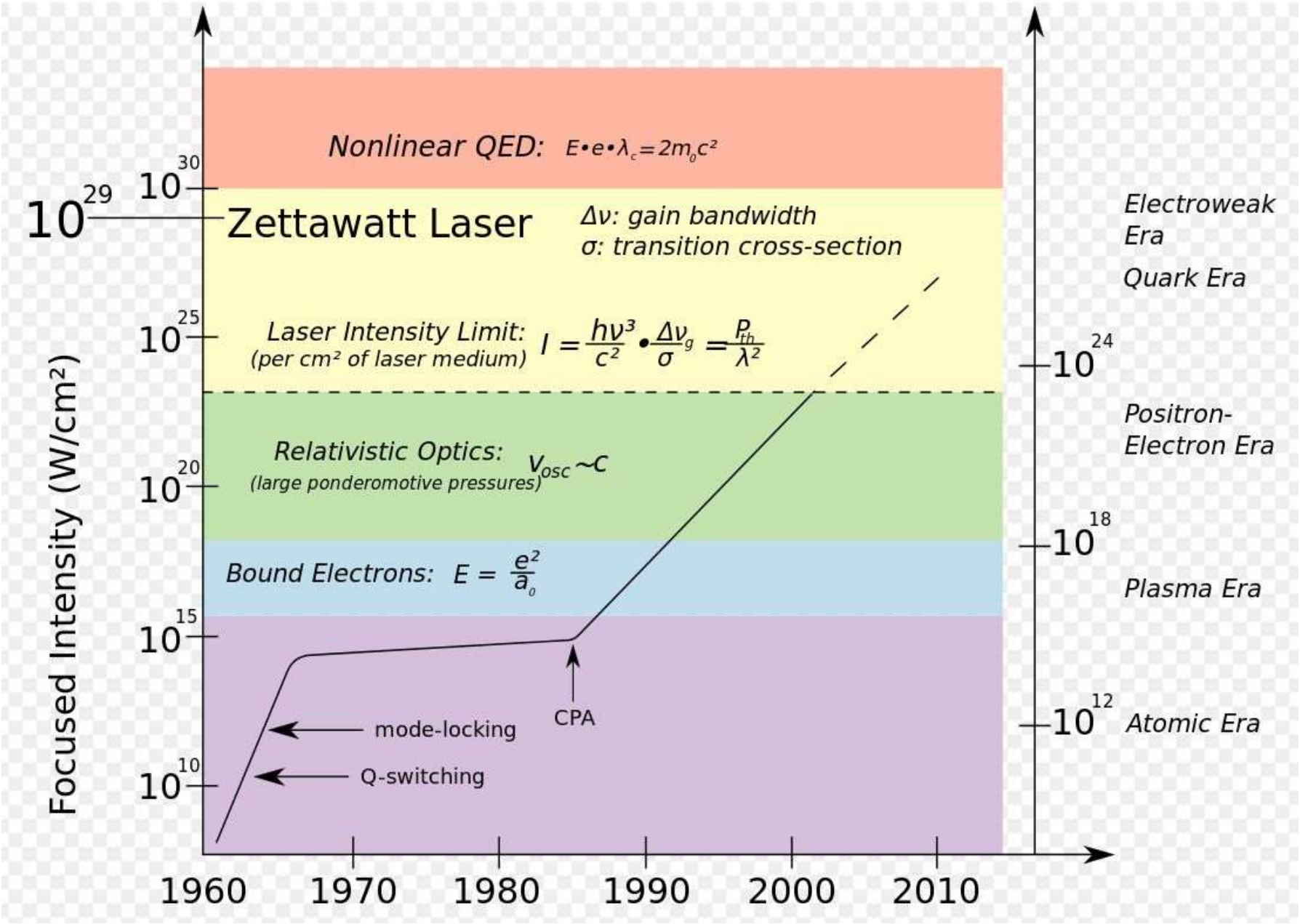




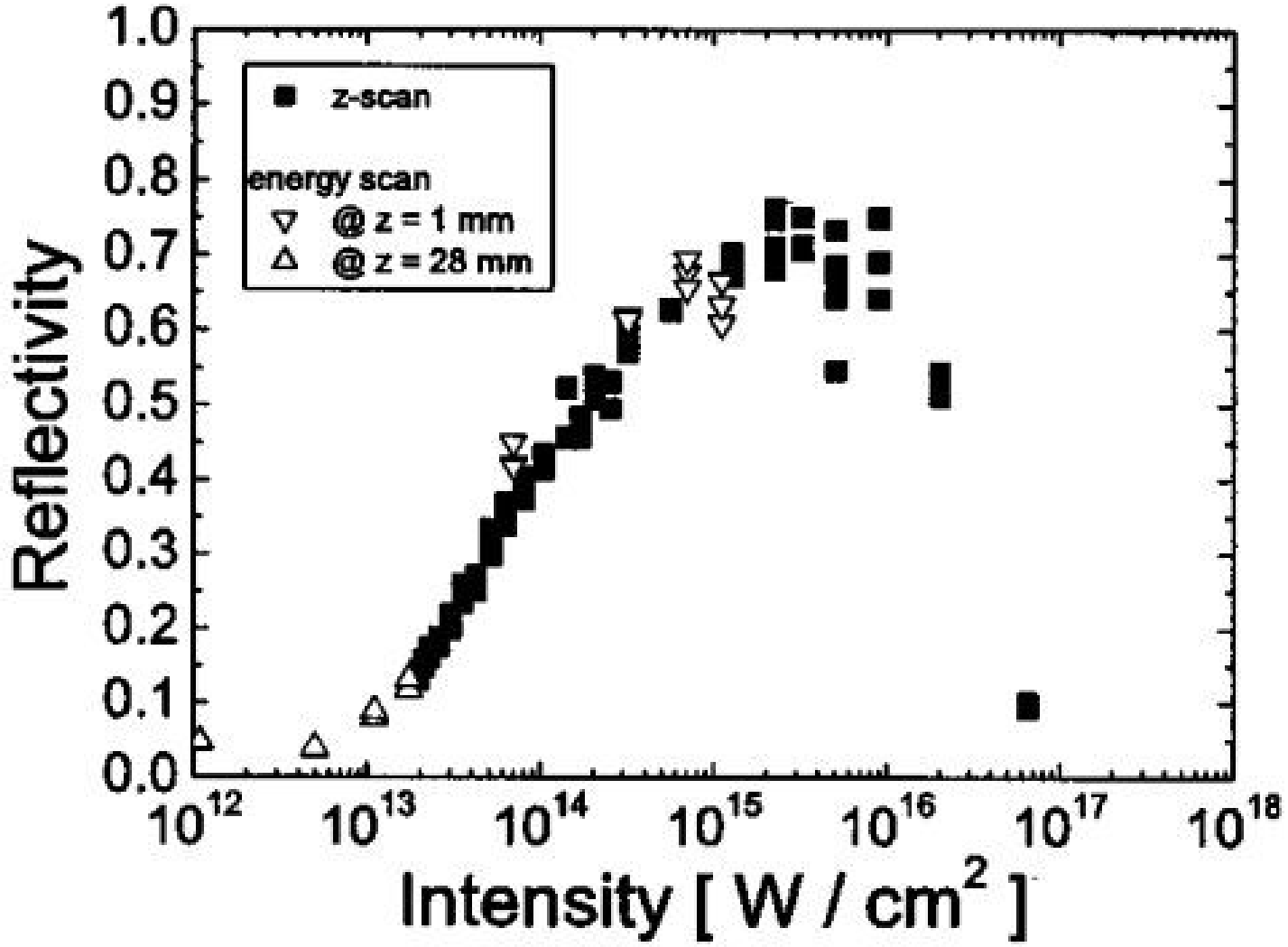




Toward our proposal


Nonlinear QED: $E \bullet e \bullet \lambda_c = 2m_0c^2$
10^{30}
10^{29}
Zettawatt Laser
Δν: gain bandwidth
σ: transition cross-section
Laser Intensity Limit:
(per cm² of laser medium)
$I = \frac{h\nu^3}{c^2} \bullet \frac{\Delta\nu_g}{\sigma} = \frac{P_{th}}{\lambda^2}$
10^{25}
Relativistic Optics: $v_{osc} \sim c$
(large ponderomotive pressures)
10^{20}
Bound Electrons: $E = \frac{e^2}{a_0}$
10^{15}
mode-locking
Q-switching
CPA
10^{10}
Focused Intensity (W/cm²)
1960
1970
1980
1990
2000
2010
10^{24}
10^{18}
10^{12}
Electroweak Era
Quark Era
Positron-Electron Era
Plasma Era
Atomic Era

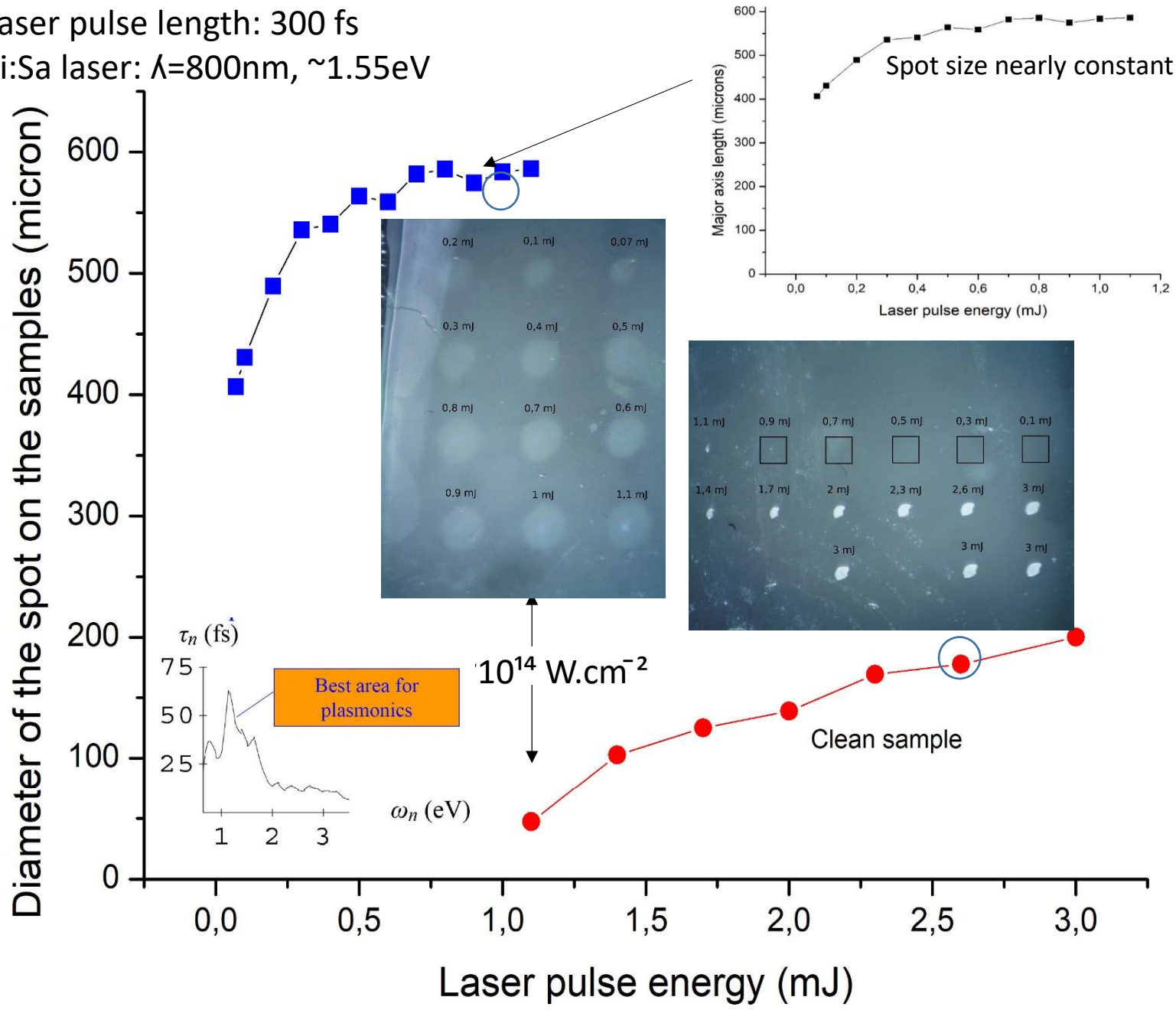
PLASMA MIRROR REFLECTIVITY



Ch.Ziener at al : J.Appl.Phys. 93,768 (2013)

Laser pulse length: 300 fs

Ti:Sa laser: ʎ=800nm, ~1.55eV



Giant plasmonic amplification; the laserlight reaches the nanoantennas;

LIGHT PENETRATION INTO THE TARGET

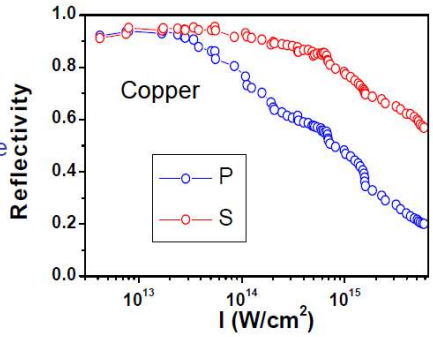
Plasma absorption

- A = 1-R

I < 3 x 10^{13} W cm^{-2}, A is almost polarization independent & obeys Fresnel laws, as IB is dominant

- at higher intensities, there is a clear polarization dependence of absorption

- the difference in absorption should account for extra absorption mechanisms, which are polarization dependent



R vs I at 45°

TIFR data

G.R.Kumar: www.tifr.res.in/~uphill

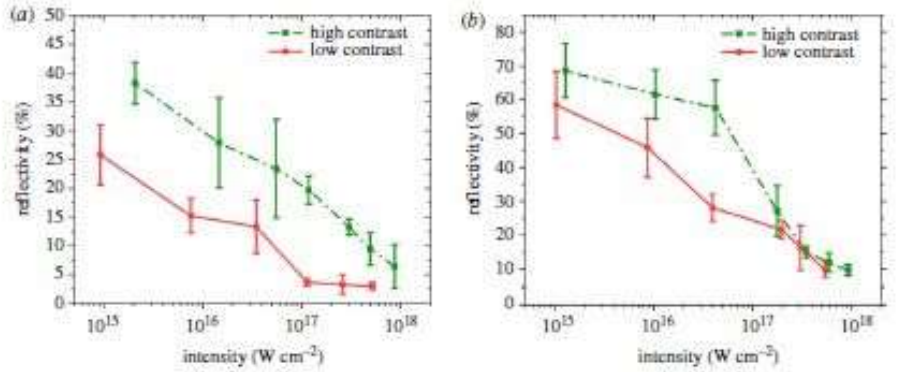
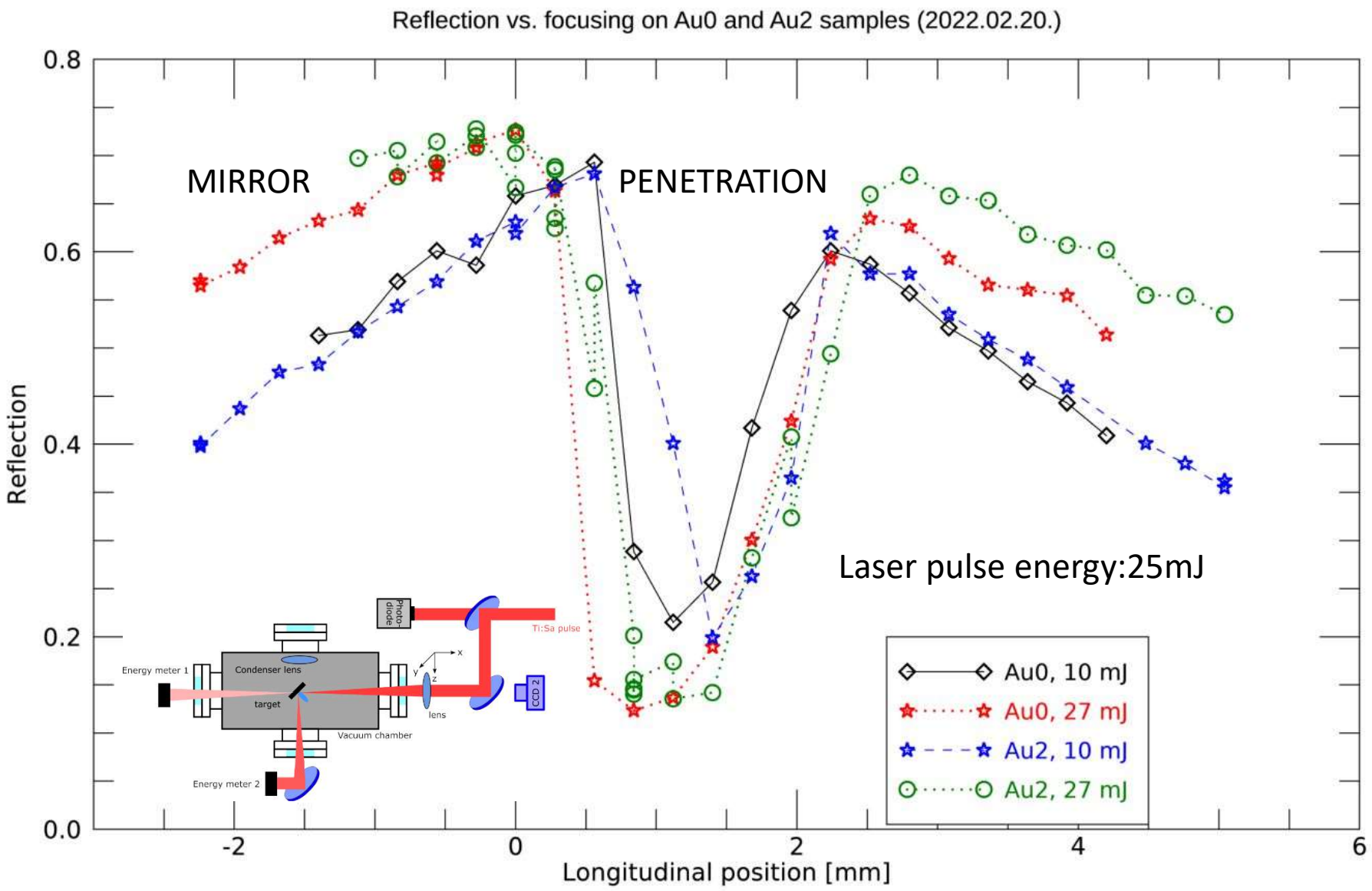
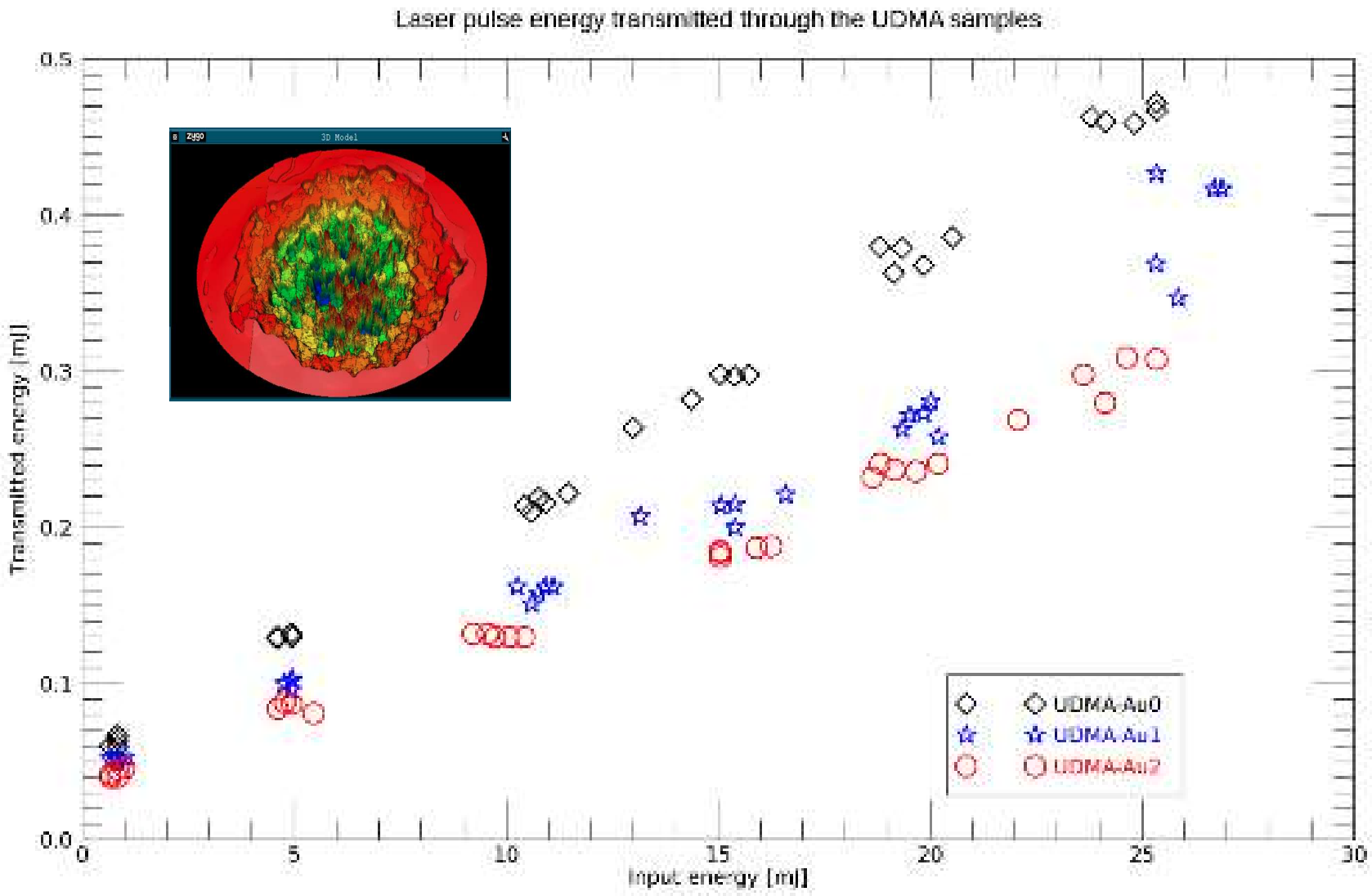


Figure 2. Measured reflectivity from (*a*) gold and (*b*) boron targets. The red circles (solid line) correspond to the case of low and the green squares (dotted line) the high-contrast case.

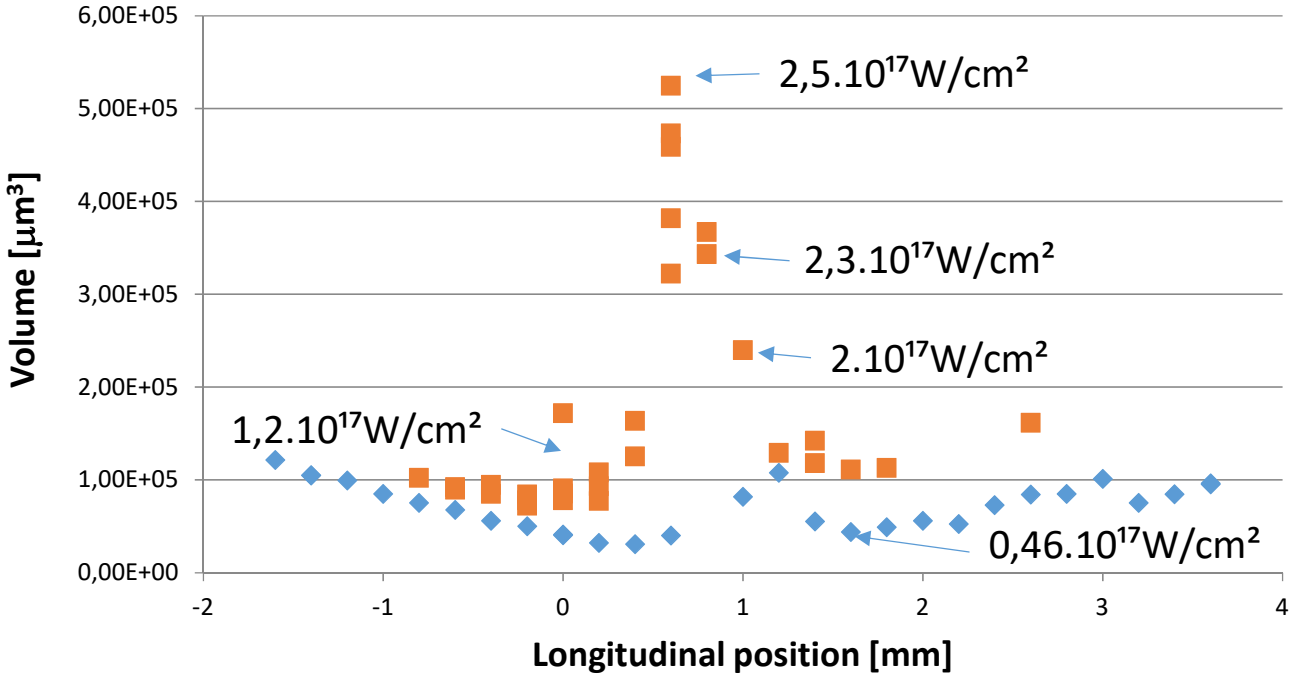
Zs.Kovács, I.B.Földes: Phyl.Trans.R.Soc A378 20200043 (2020)

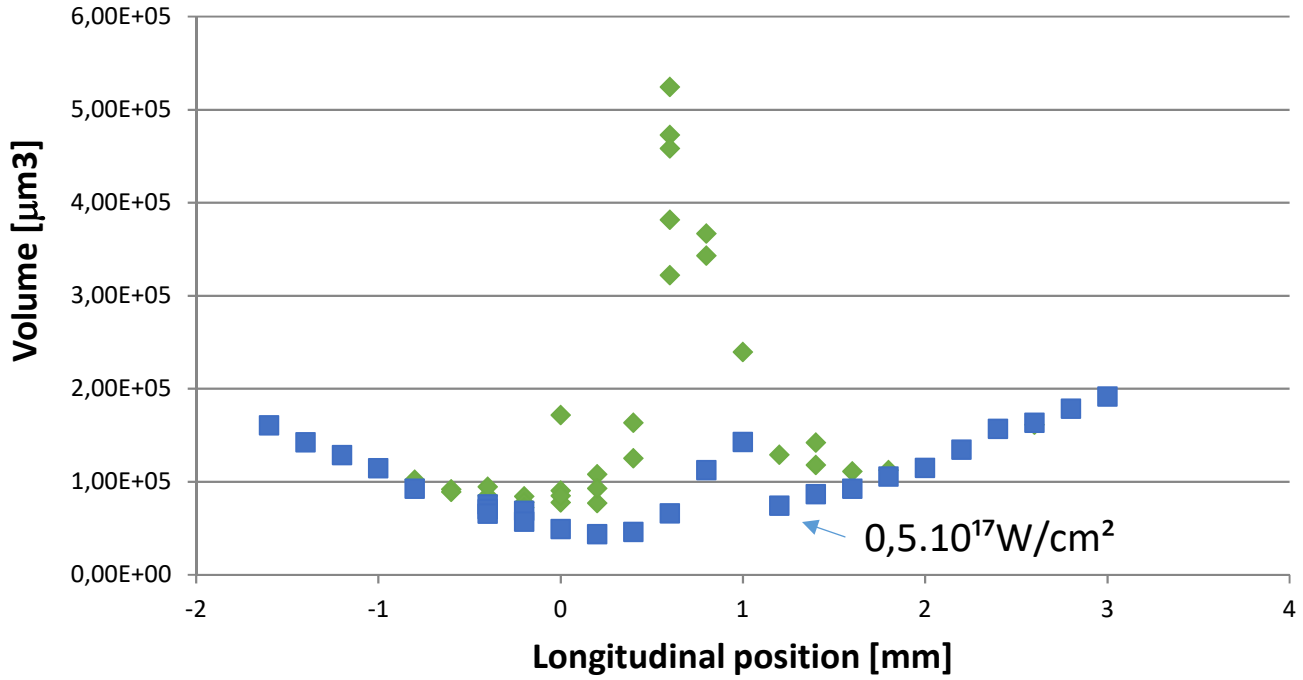


Sample: 160µm thick transparent polymer (UDMA).


Laser pulse energy transmitted through the UDMA samples
Transmitted energy [mJ]
Input energy [mJ]
0.0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
20
25
30
UDMA Au0
UDMA Au1
UDMA Au2
Zygo
3D Model

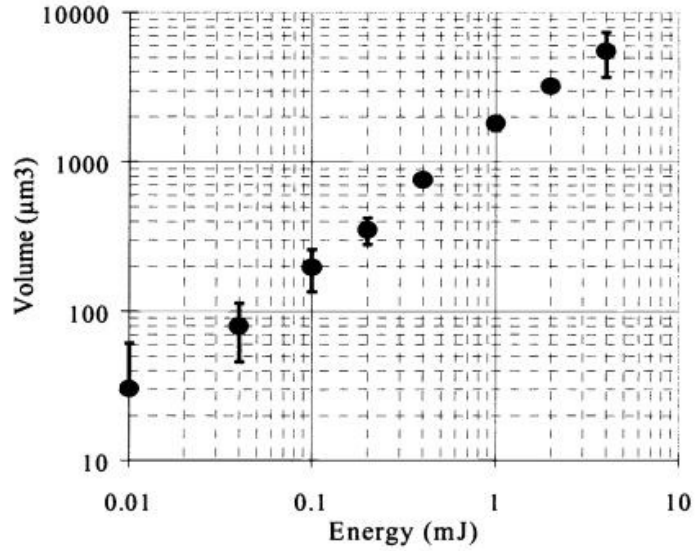
CRATER VOLUMES





HIGH FIELD PLASMONICS WORKS!

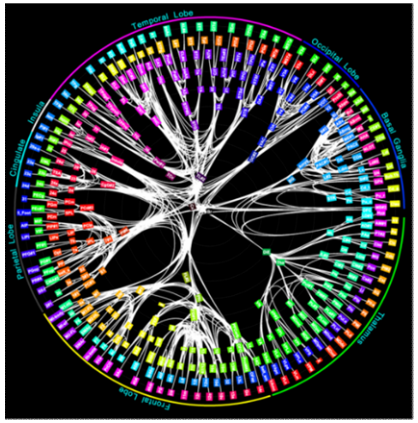
Laser pulse energy:25mJ

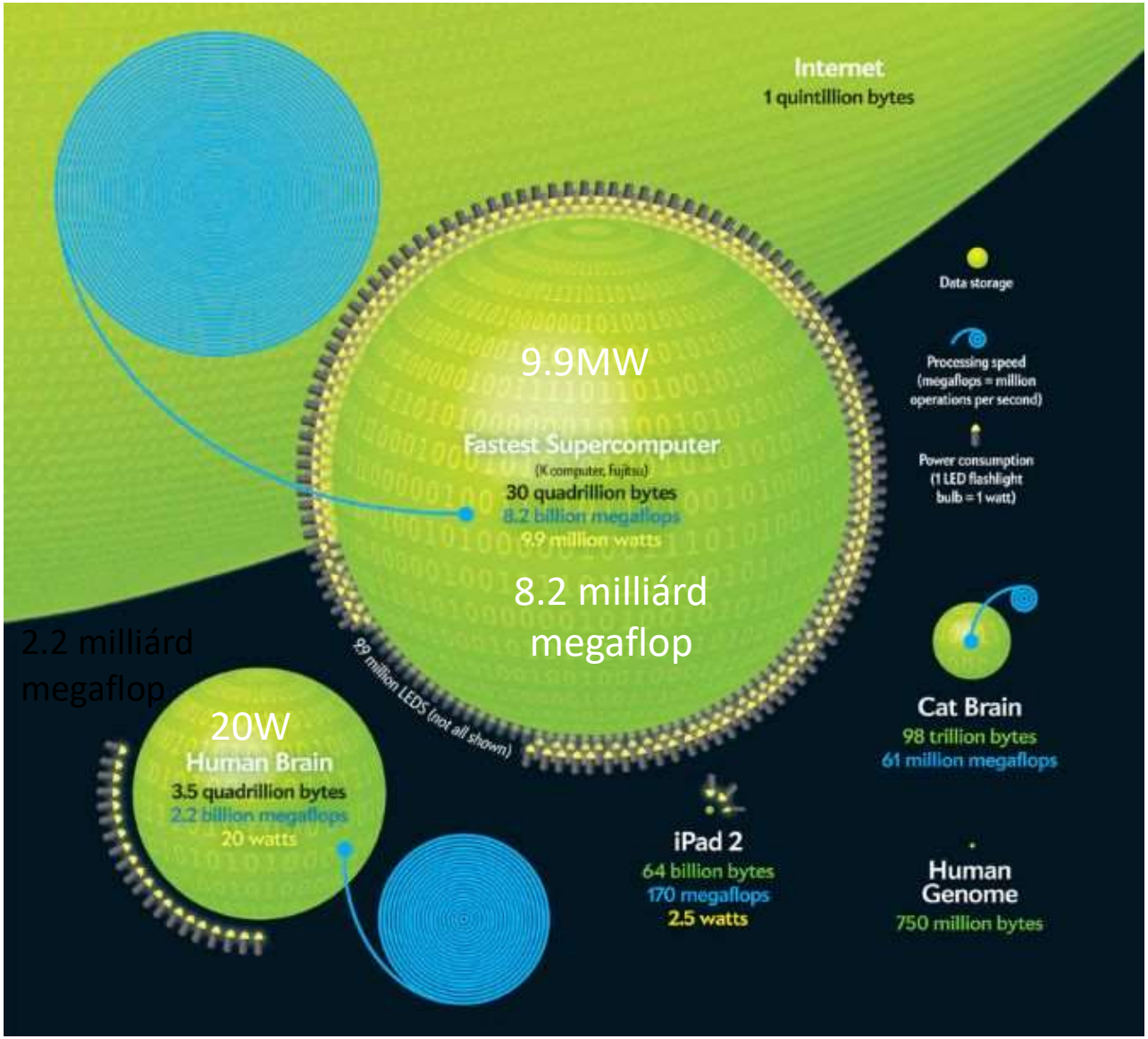


Dependence of crater volume on laser energy for copper. (532 nm, 6 ns)

COPYING NATURE!

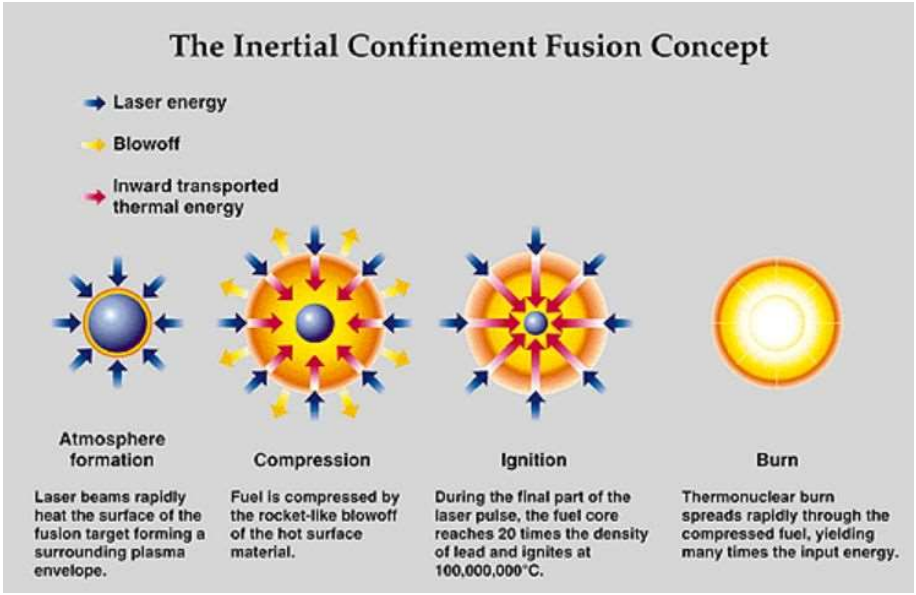
HUMAN BRAIN VS SUPER COMPUTER





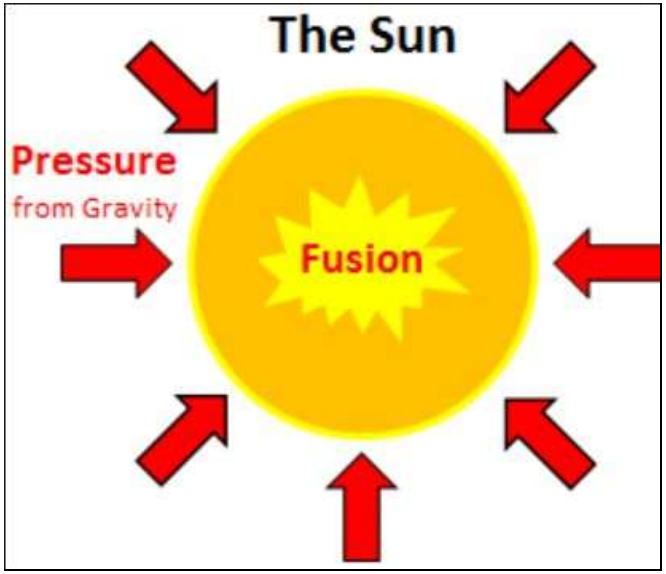
(IBM TrueNorth chip simulation of 1million neurons and 256 million synapses , 10 thousand times less energy) Memristors(nanorods)

No2 application (LSPP)

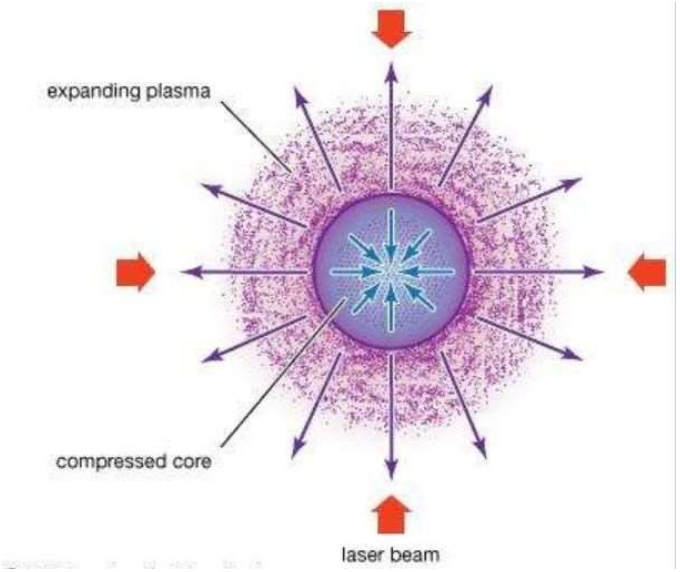


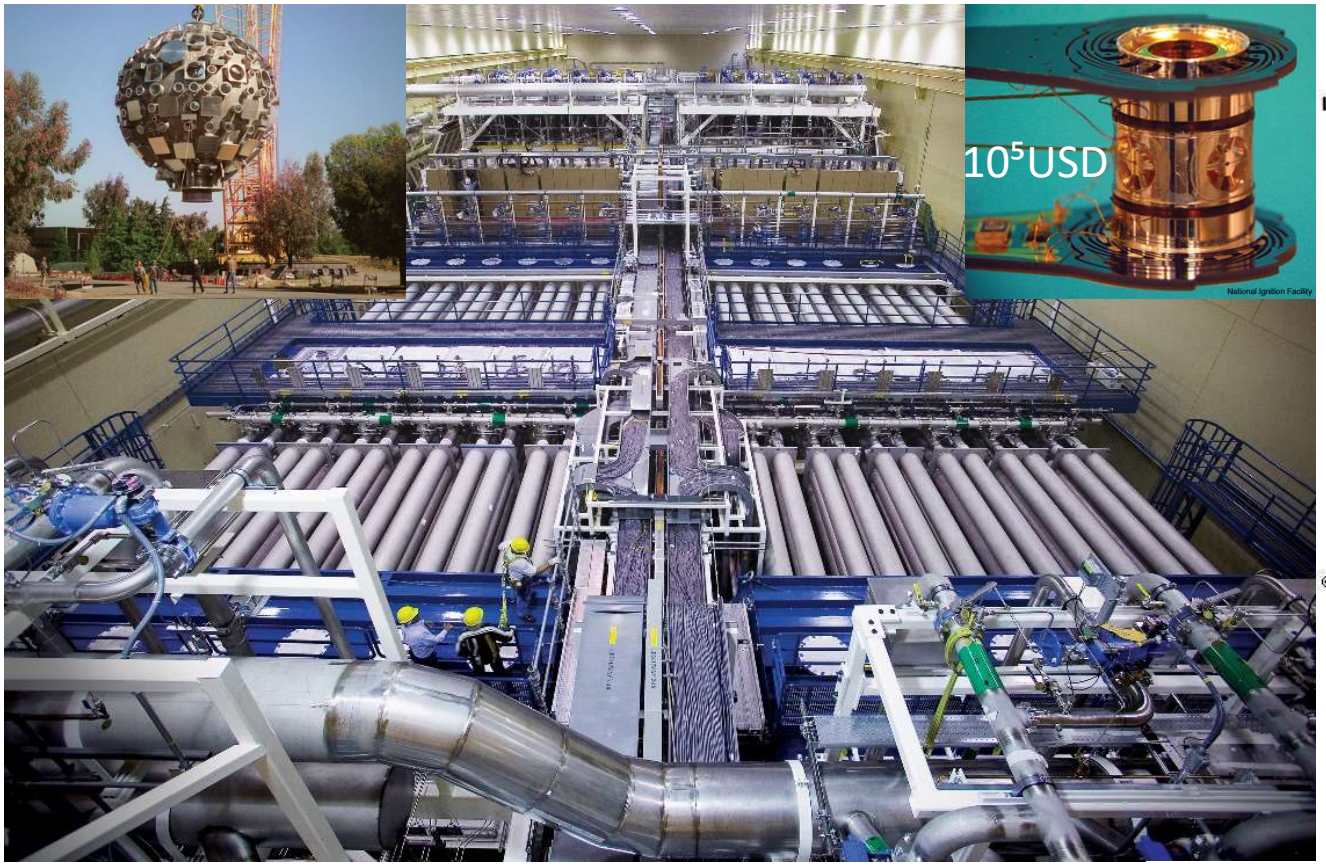
The most succesful technologies imitate nature

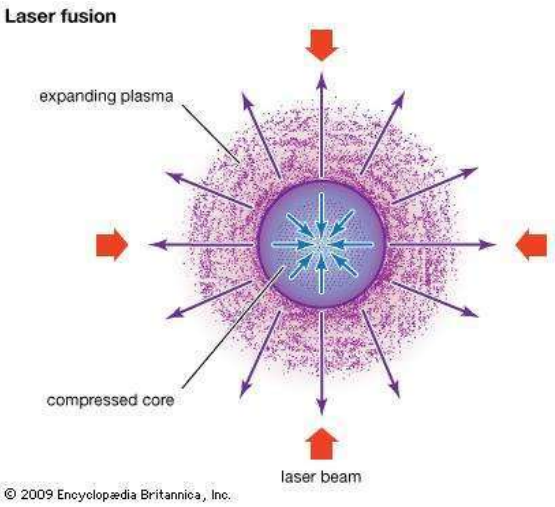
$E = mc^2$



Laserbeams







Long laser pulses (~50ns)
Raileigh-Taylor instability
Complicated target construction
Enormous laser energy (400/1.8MJ)

Problems of inertial fusion

- High requirements on irradiation symmetry
- Insufficient laser repetition rate
- Very precise injection system is needed
- The target position has to be tracked in order to ensure required irradiation precition

TO COMBINE 2 DIFFERENT (e.g. fusion and nano-) TECHNOLOGIES TO REACH FUSION AT THESE ULTRAHIGH EM FIELDS?

OUR PROPOSAL: COMBINE PLASMONICS WITH NUCLEAR FUSION TECHNOLOGY

SOME POTENTIALLY EXPLOITABLE HIGH FIELD PLASMONIC EFFECTS:

1.Go for localized surface plasmon polaritons (LSPP)

2.Lifetime of LSPP-s is in the few ten femtosecond range. We may get high intensity laser pulses in this time-domain and the plasma instabilities disappear.

3.High electron densities and EM fields can be obtained in small (nanosized) volumes on resonant plasmonic nanoparticles (hot spots).

4.The near field of plasmons screen the repulsive field of positively charged (e.g. protons) particles and so they may fuse more easily. So do the ponderomotive forces.

5.The large number of conduction electrons move in the plasmonic excitations in correlated way and their momentum may be in sum transfered in high exciting fields to positive particles, moving together with them, further increasing the probability of nuclear fusion.

6.With these short pulses we do not need many beams, like in the NIF, the target can be a thin film, illuminated only by 2 beams from opposite directions, and the same energy density may be achieved in the whole thicknes of the target sample, and this may

Ti:Sa LASER PULSE SPECTRA AT DIFFERENT INTENSITIES

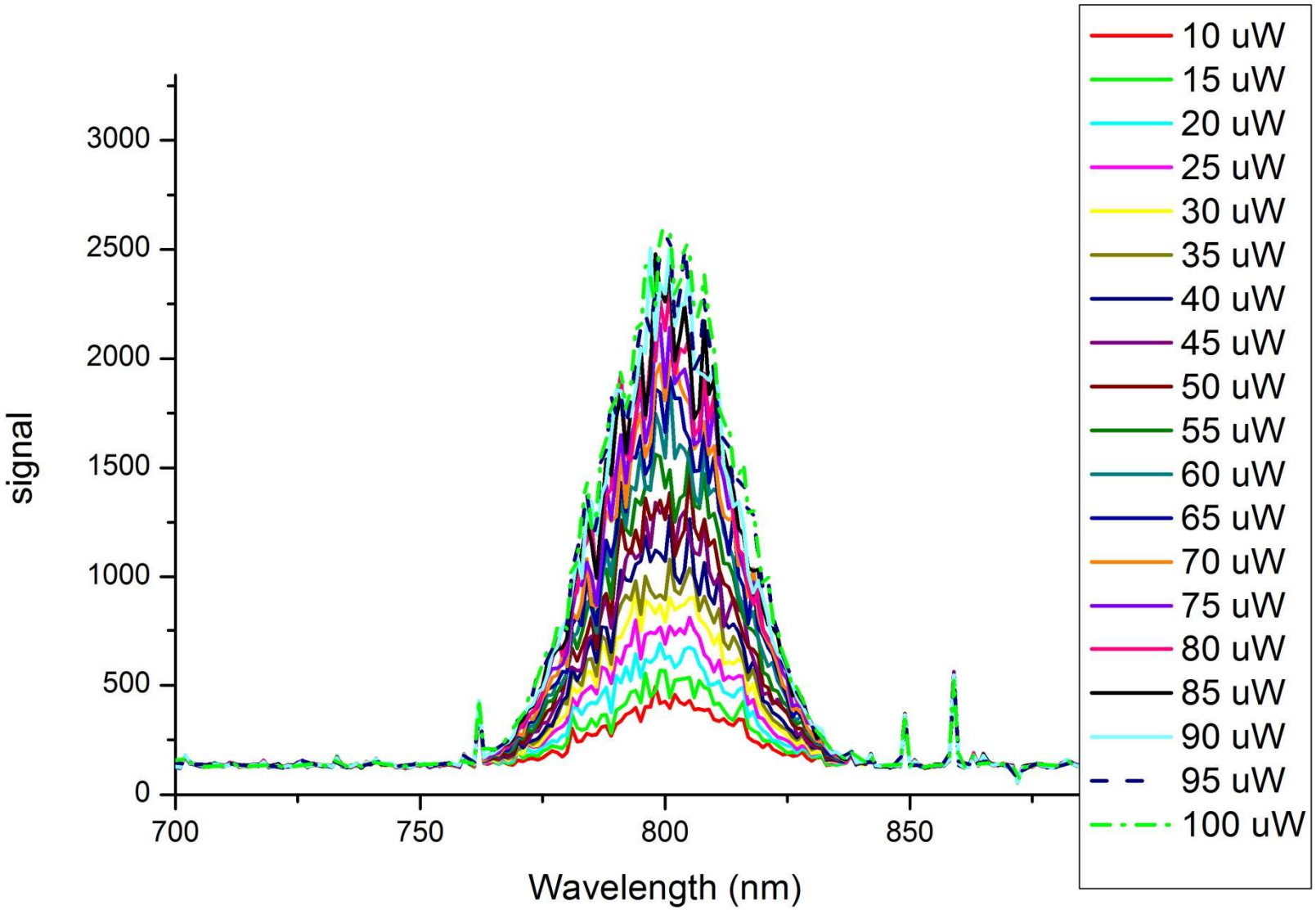
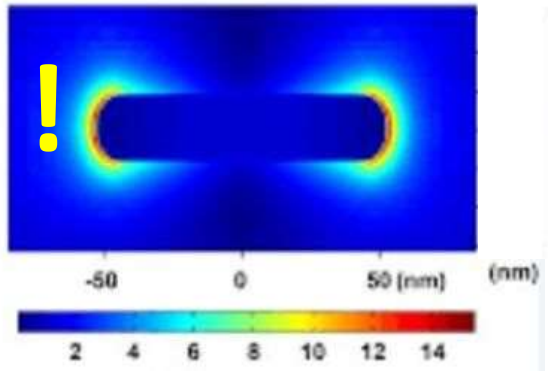
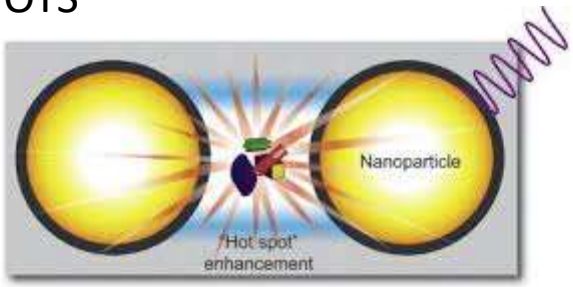


ILLUSTRATION OF THE RESULT OF THE SCREENING EFFECT

HOT SPOTS





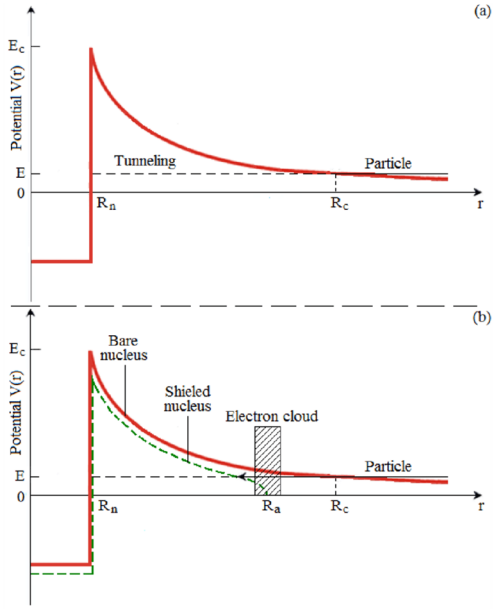
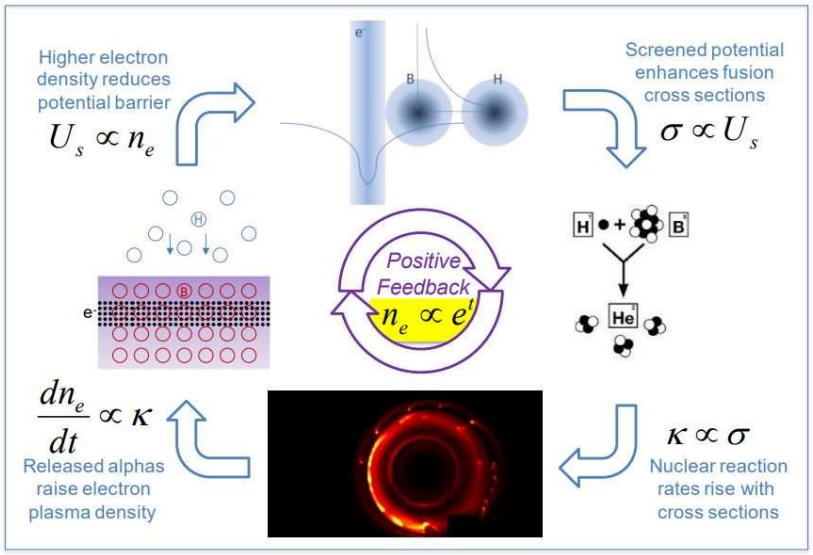


Illustration with the H+B ⟶ 3He reaction

Ponderomotive screening

$F_p = (e^2/4m_e\omega^2).\text{grad}\,(E^2)$



A.Y.Wong and C-C.Shinh:UCLA 2019

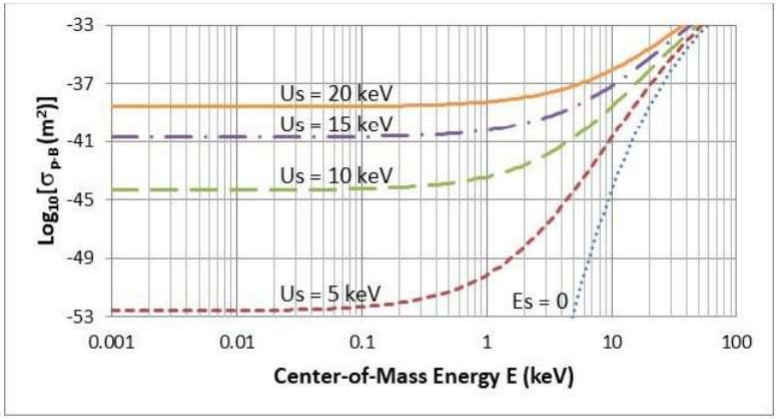
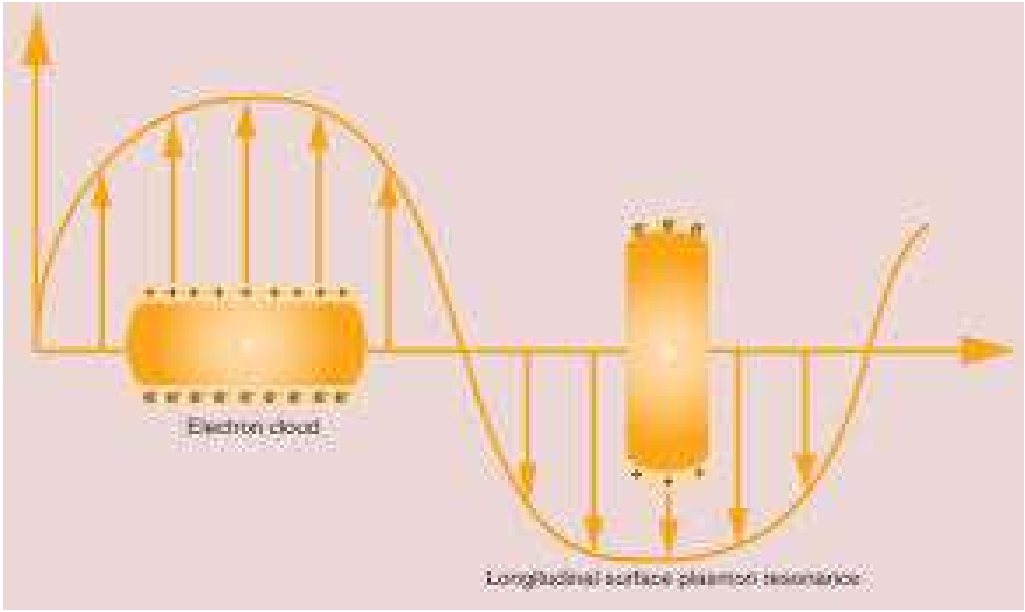
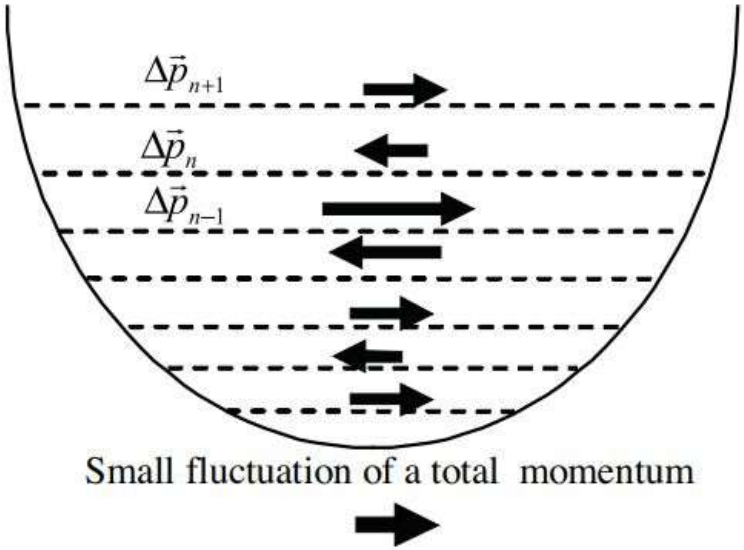


Figure 1: p-^{11}B cross section as function of particle energy for the screening electron densities up to E_s = 20keV. The cross section near E = 10eV grows over 14 orders of magnitude (from 10^{-53} to 10^{-39}m^2) over the range of 5 to 20keV.

Demonstration of the correlated state

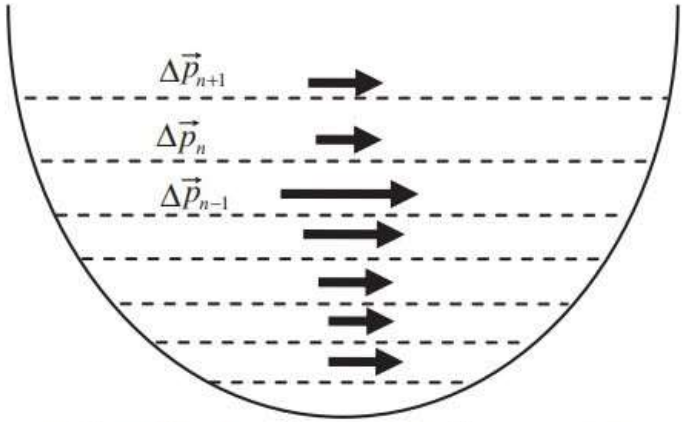


Uncorrelated state



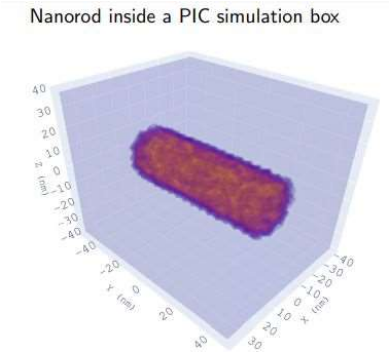
Small fluctuation of a total momentum

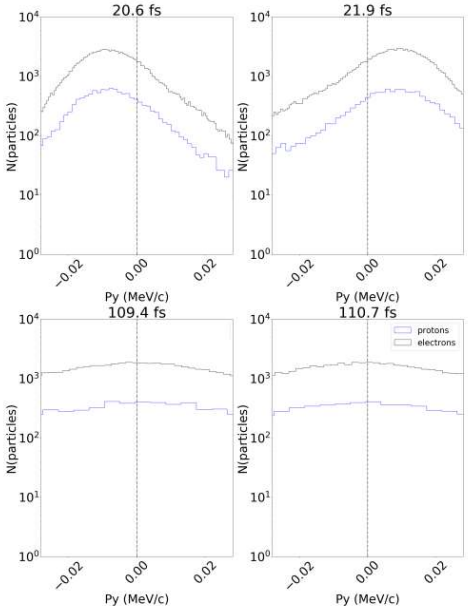
Correlated state

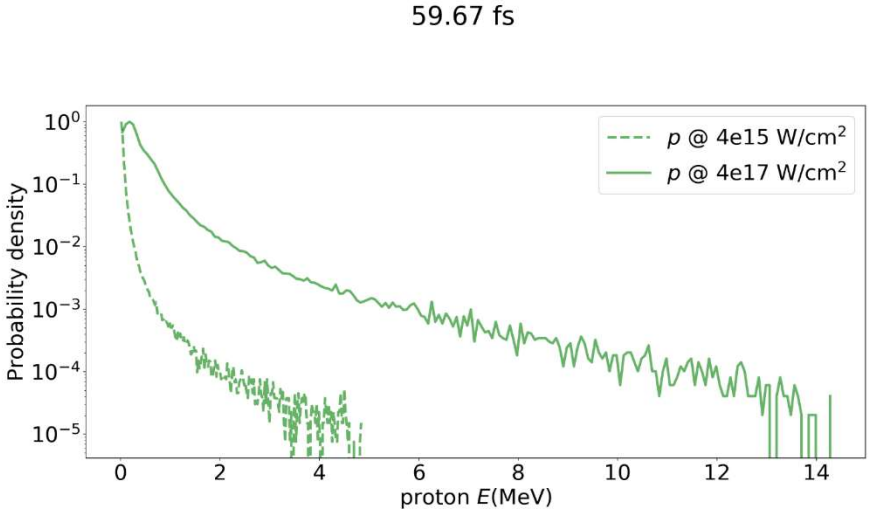


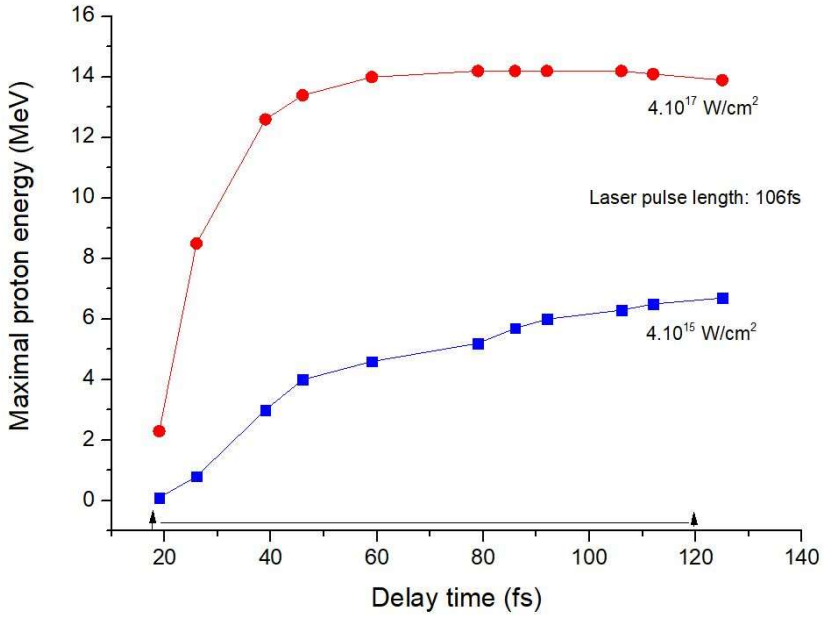
Giant fluctuation of a total momentum

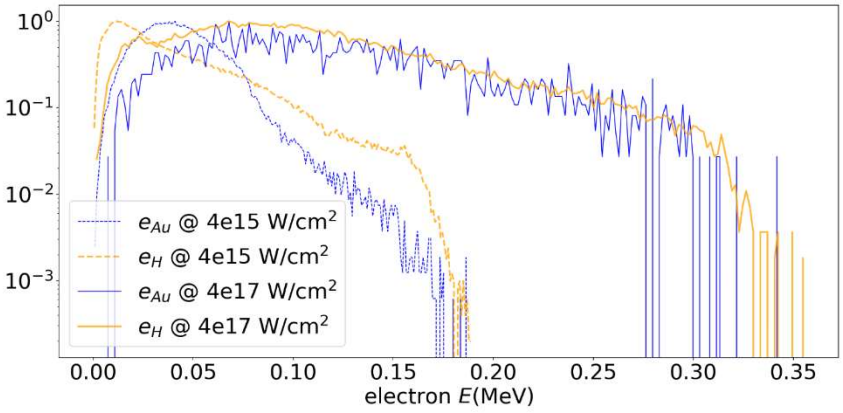
SIMULATION OF PROTON AND ELECTRON ENERGIES AT A SINGLE NANOROD



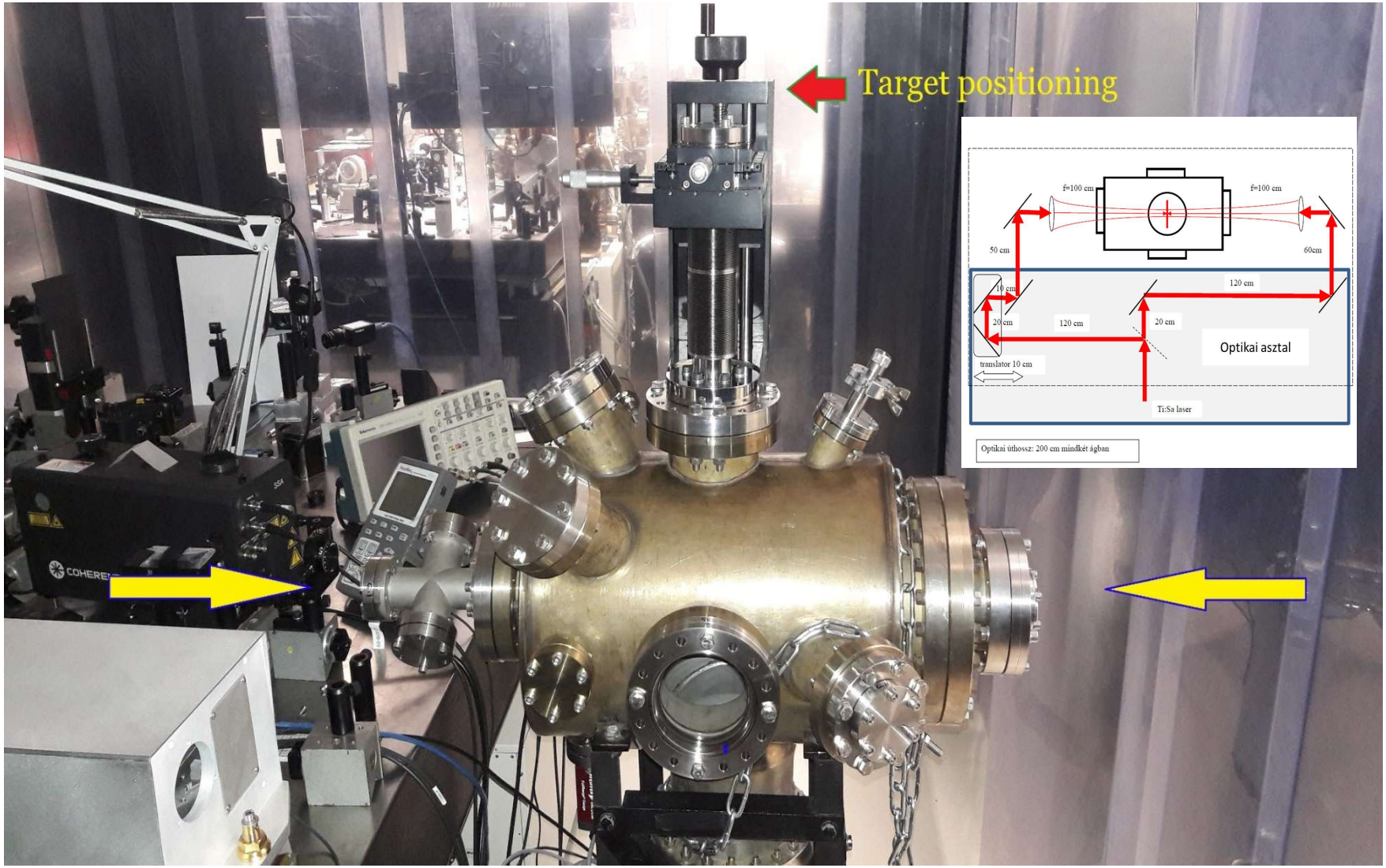


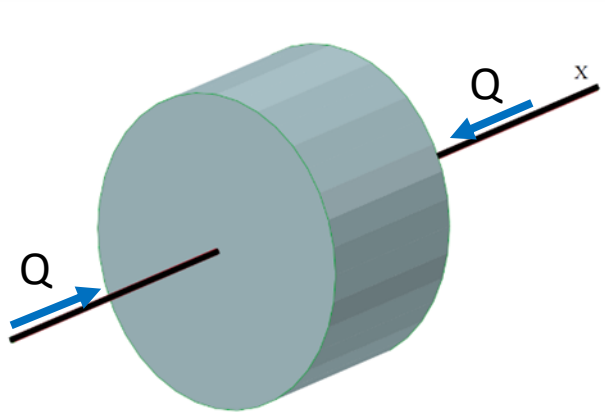


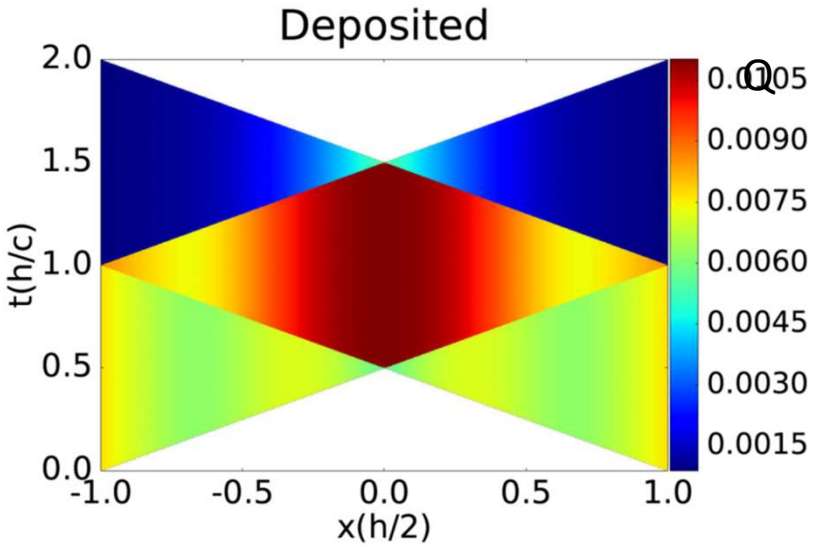




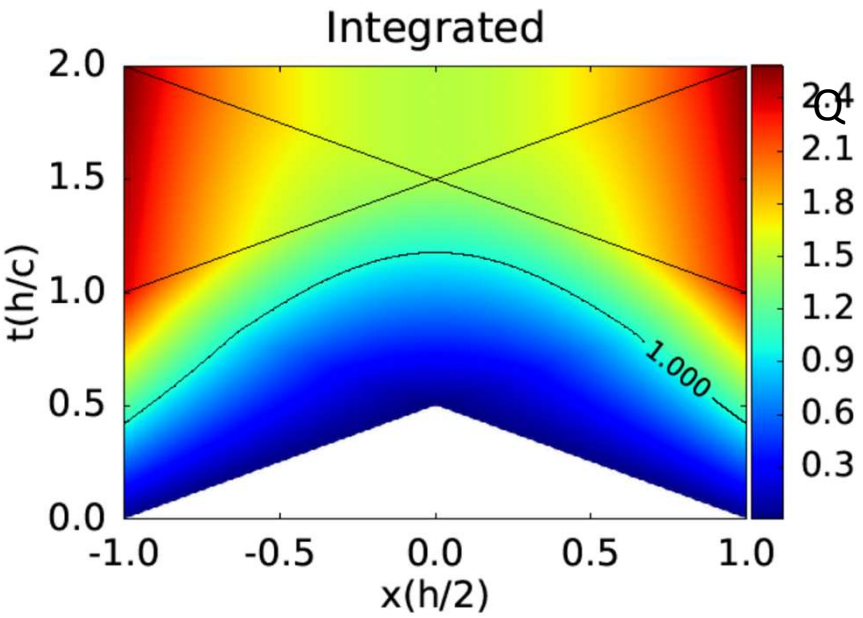
The future:Two-sided irradiation



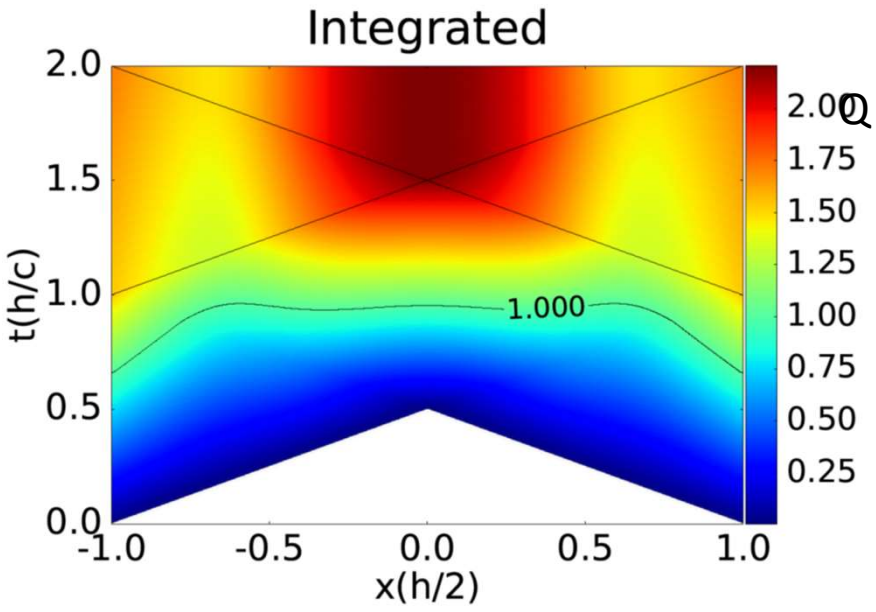




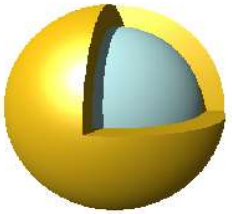
without nanoparticles



with nanoparticles

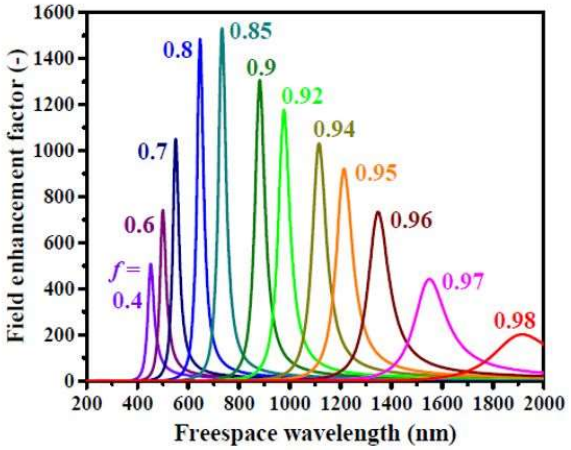


Some preliminary results with one side illumination

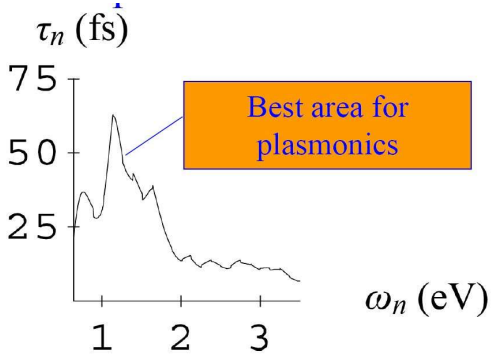


NANOSHELL
(nx10nm)

NANOROD (~85x25nm)

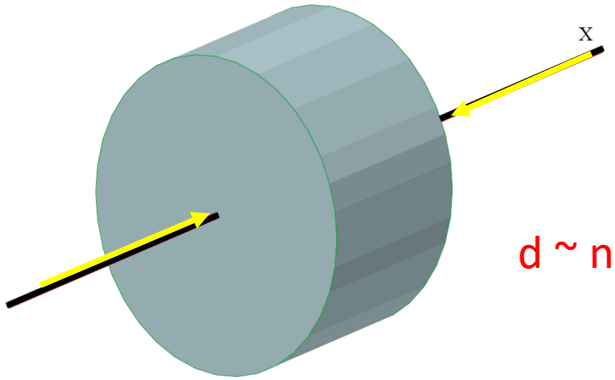


λ = 800nm



n.10μ

NANOPARTICLES IN
THE FUSION MATERIAL

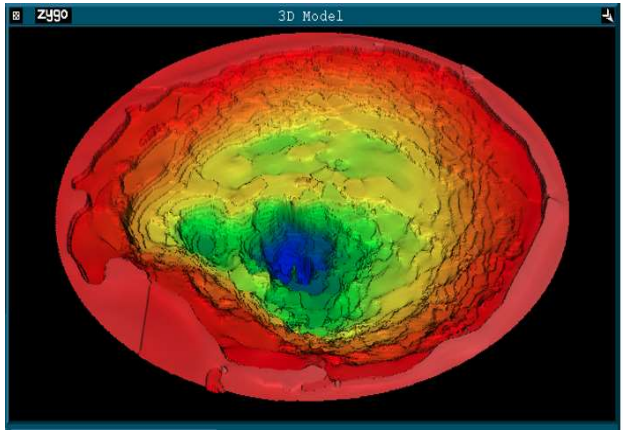


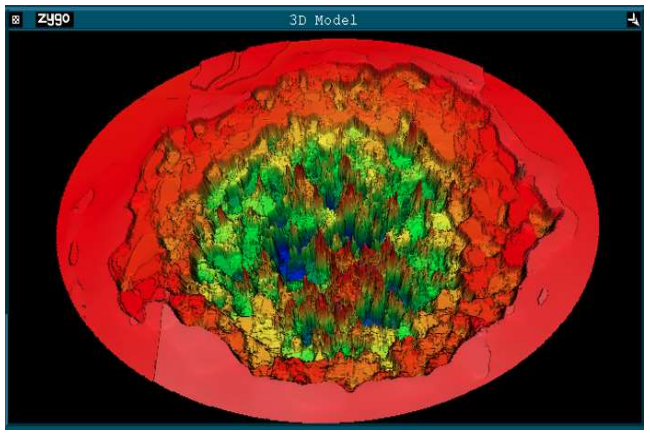
d ~ n.10μ

FEMTOSECOND LASER PULSES;
HIGH REPETITION FREQUENCY;
LIGHT SPEED: NO TIME FOR INSTABILITIES;
ONLY TWO BEAMS;
TIMELIKE VOLUME IGNITION

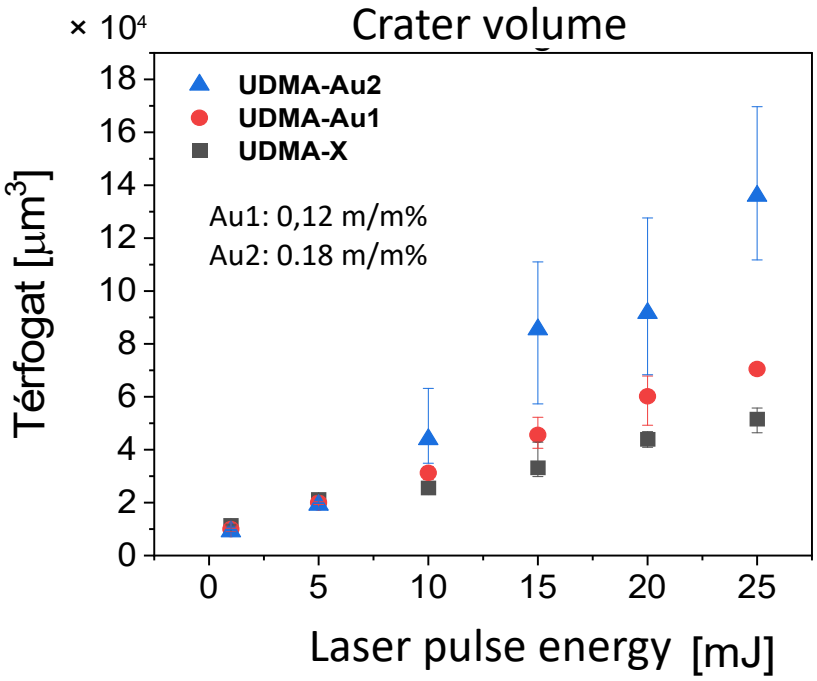
1. DIAGNOZIS (crater volume)

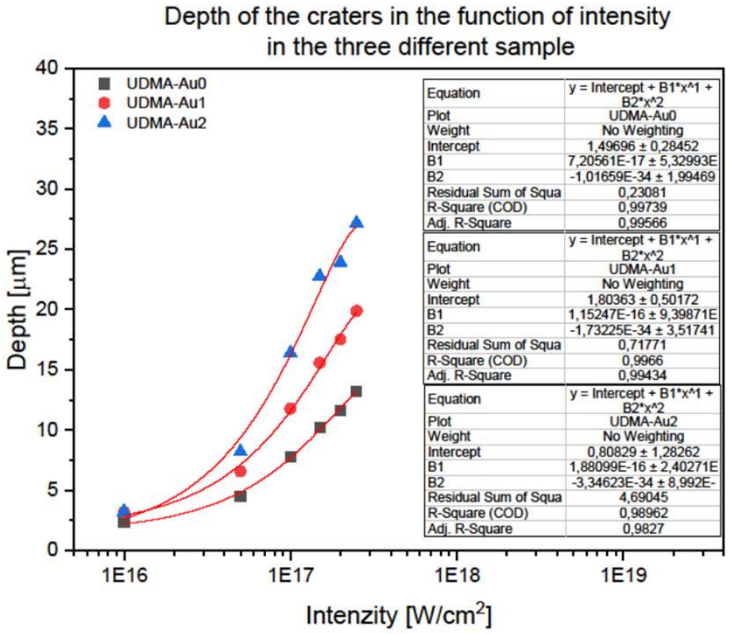
Volume:V_o

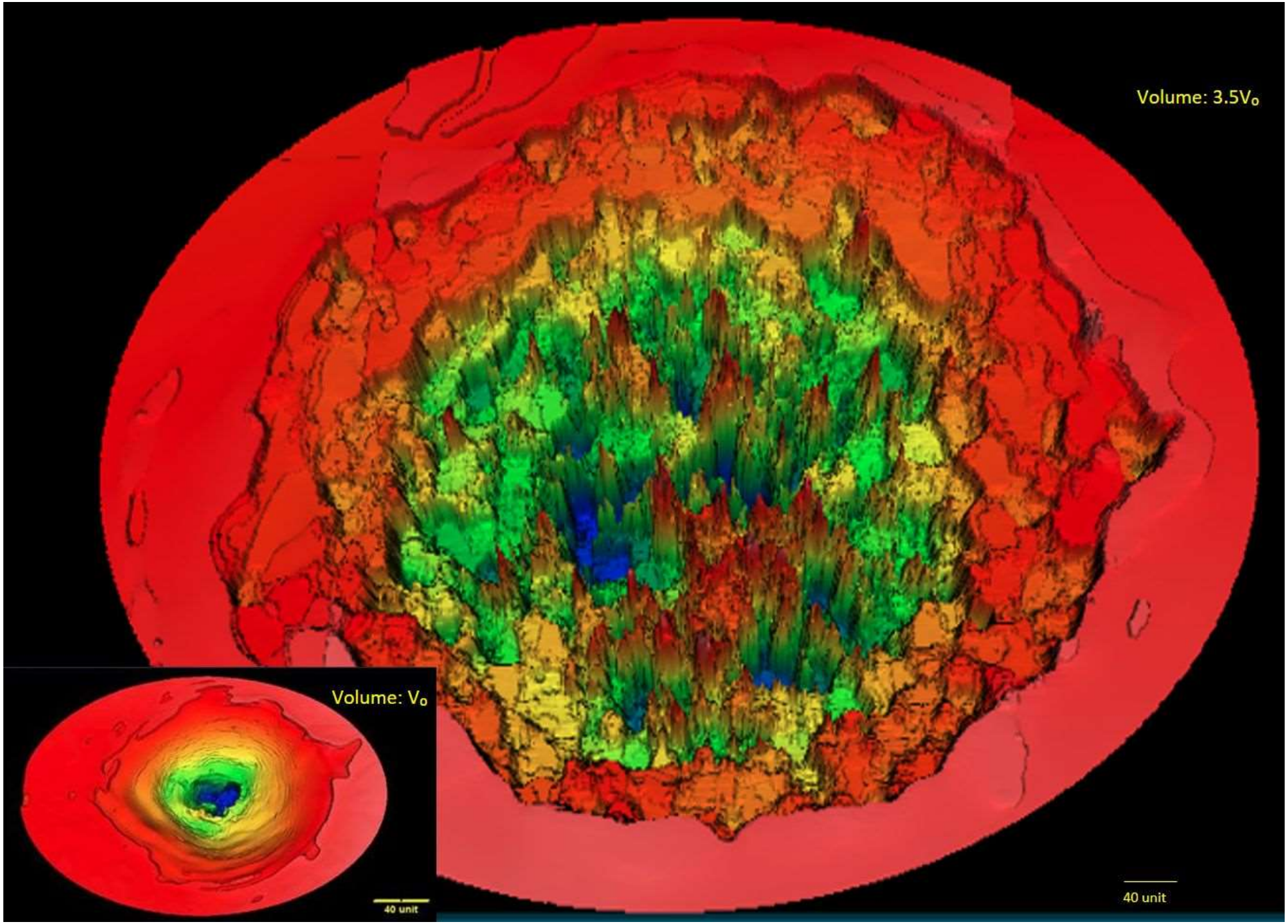




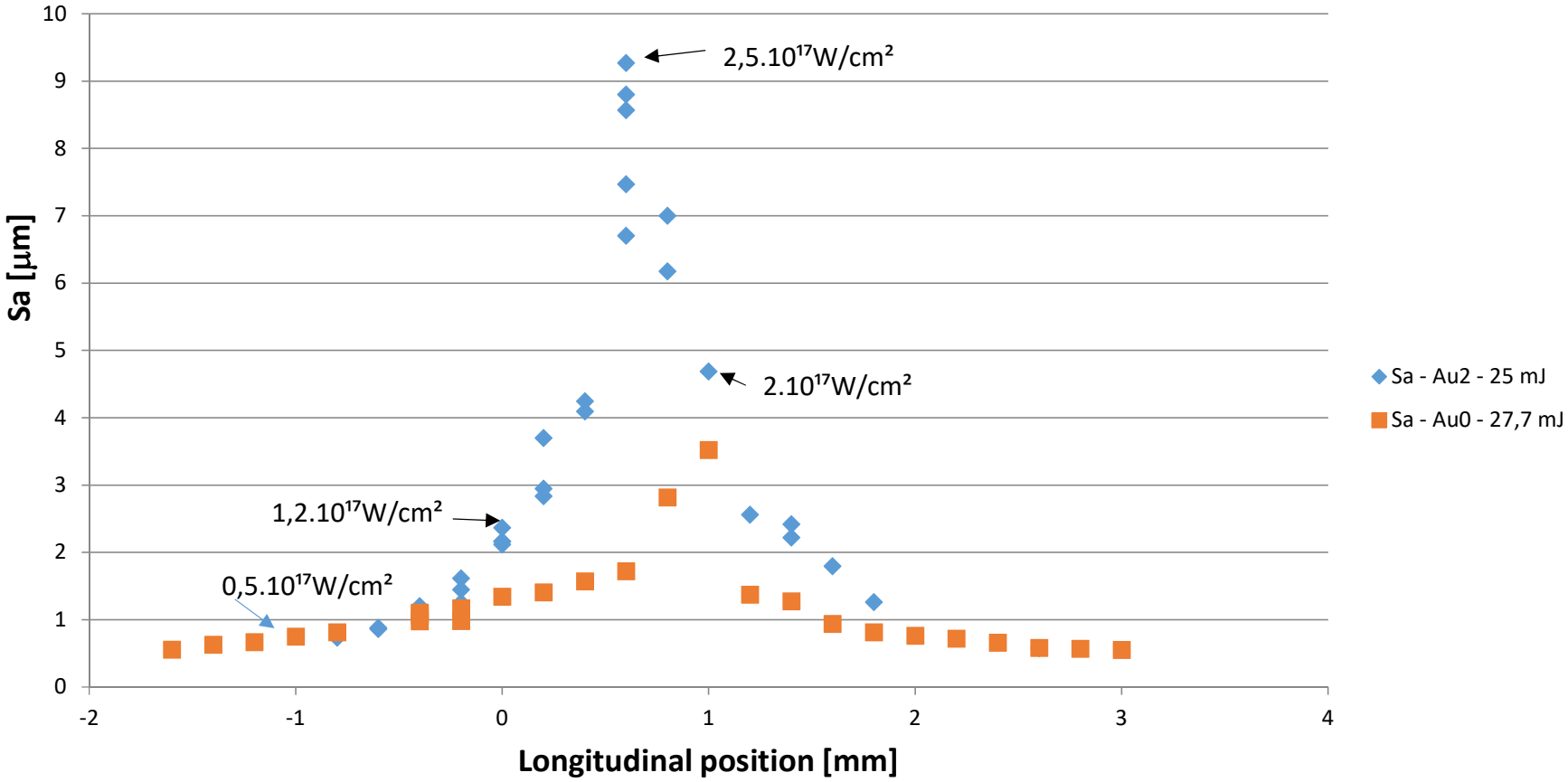
Volume
max. 3.5V_o





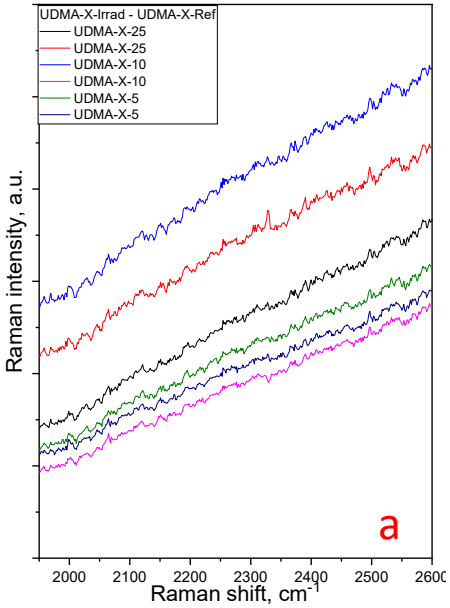

Volume: 3.5Vo
40 unit
Volume: Vo
40 unit

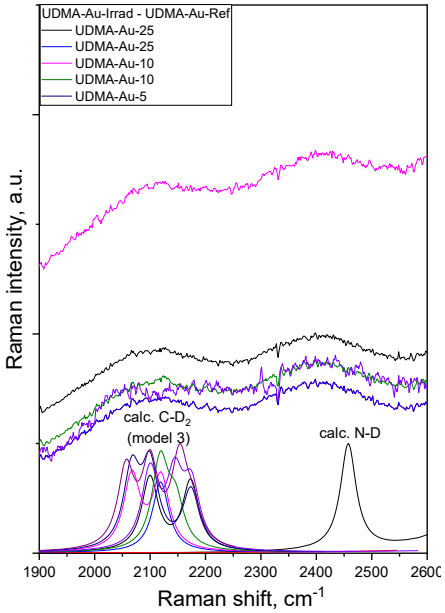
Surface roughness as function of the longitudinal position of the Au2 vs. Au0 samples
Energy of the impulse: 27,7 mJ (Au0) and 25 mJ (Au2)

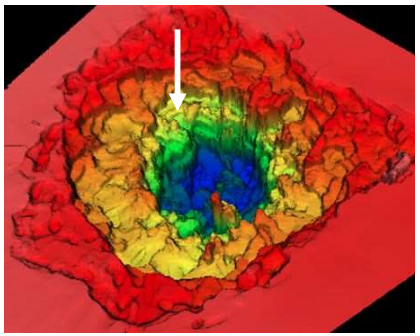


2.Diagnozis :Raman scattering from the crater surface

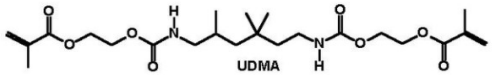
arXiv2210.00619(2022),submitted to Advanced Optical Materials

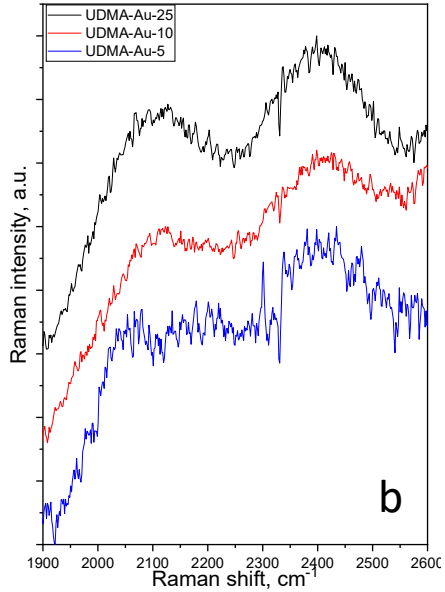


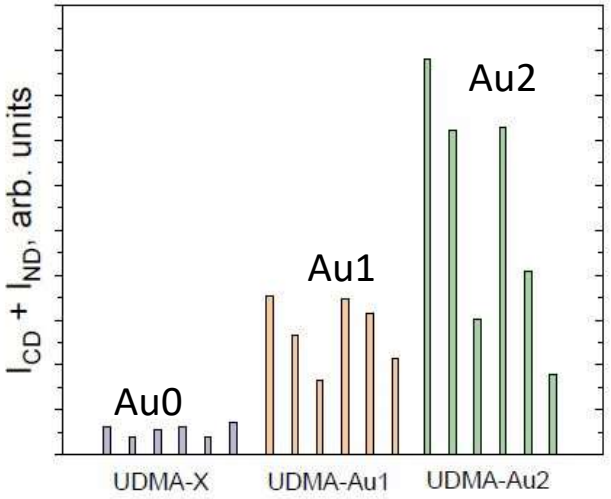


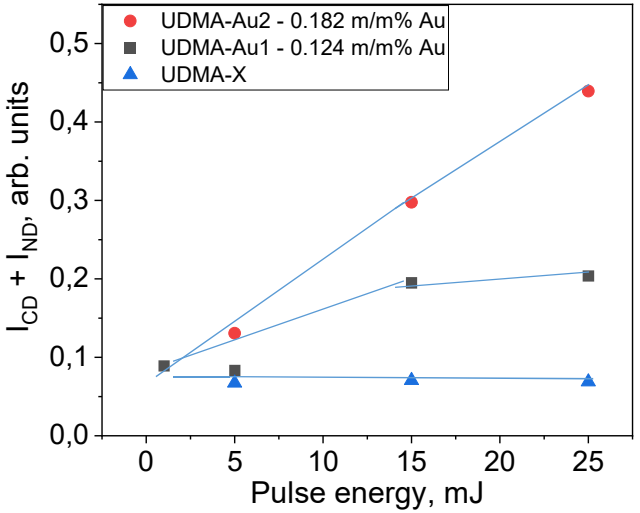


$I_{laser} > 10^{16}$ W/cm²

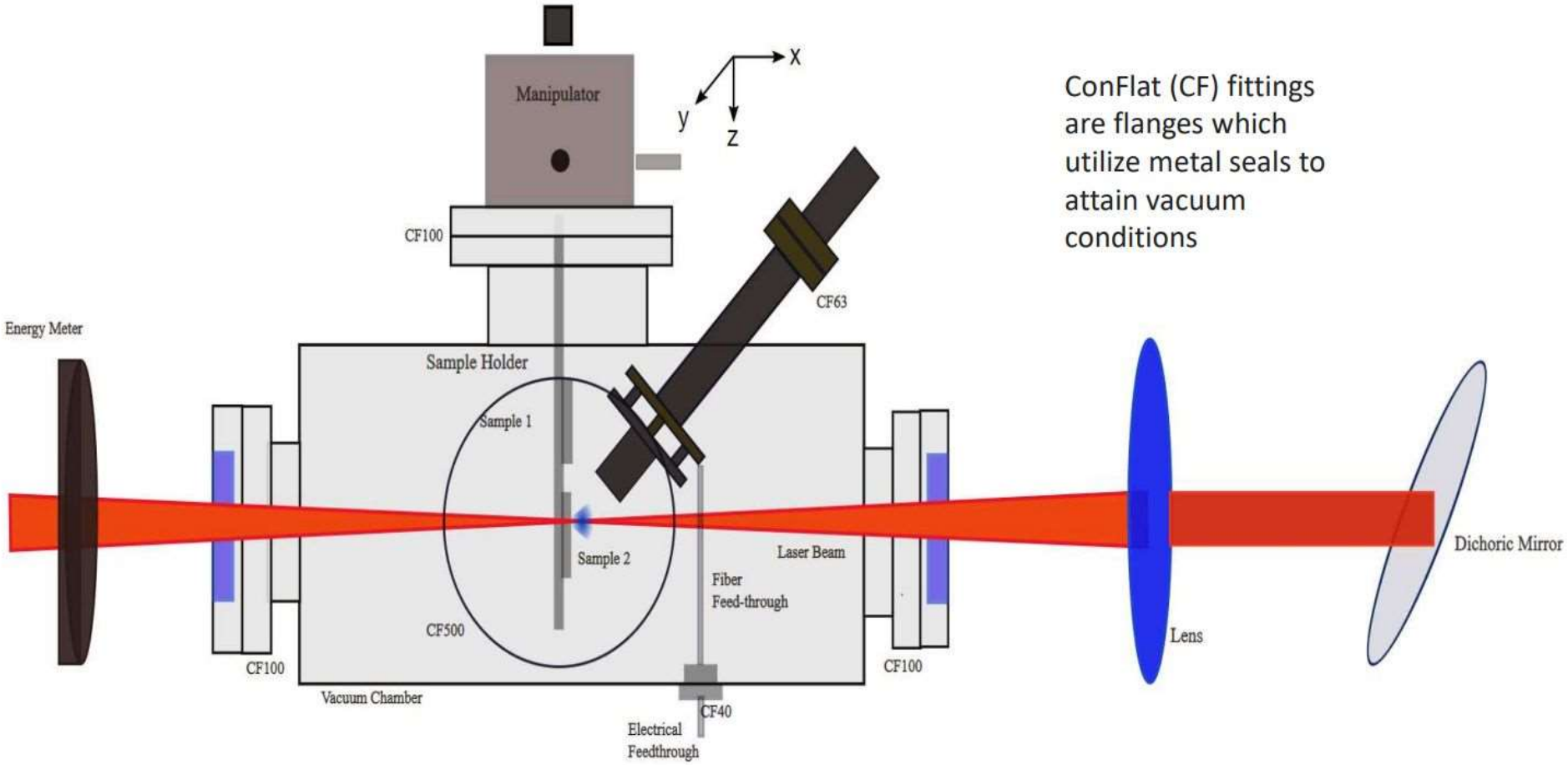


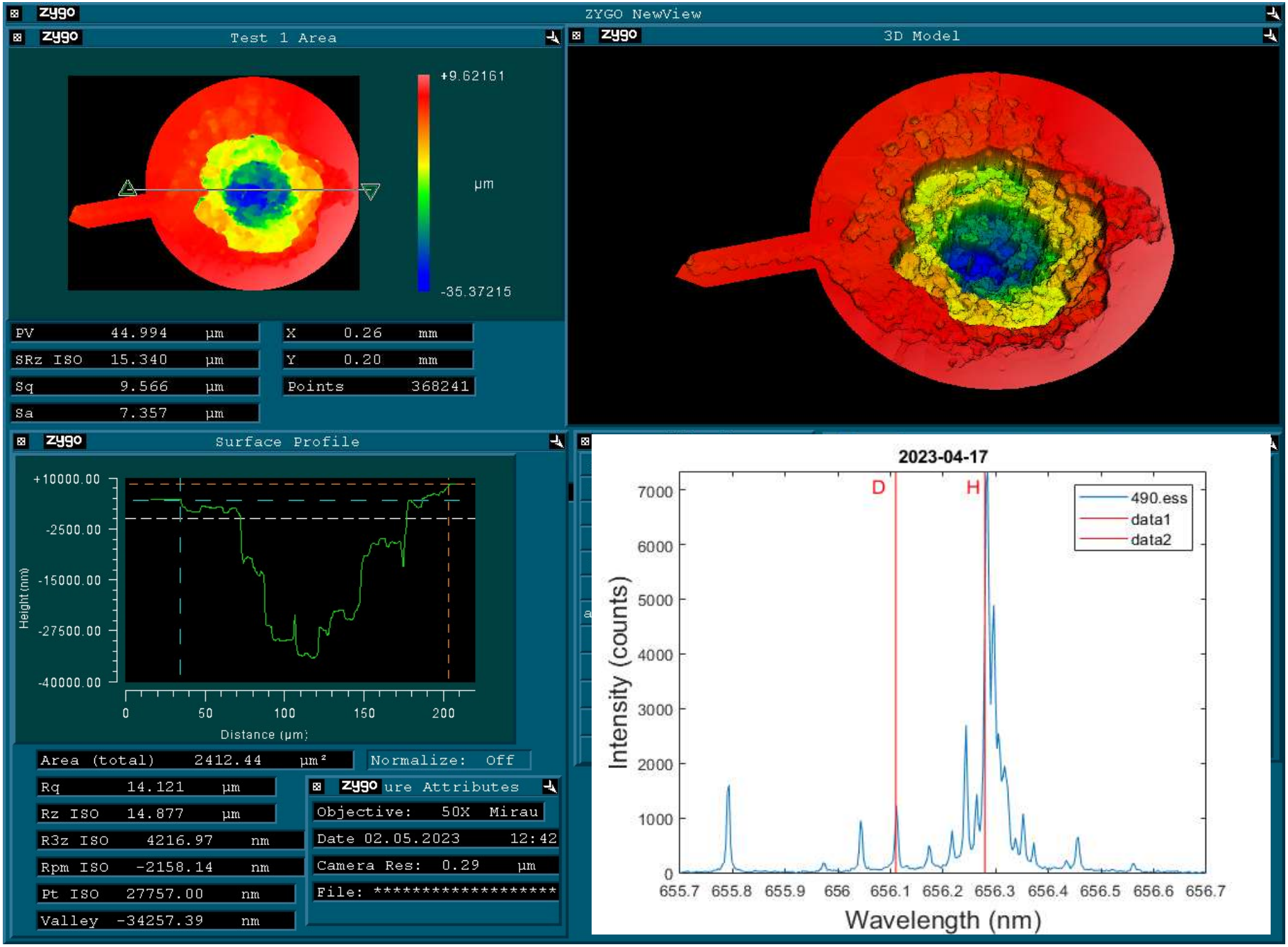




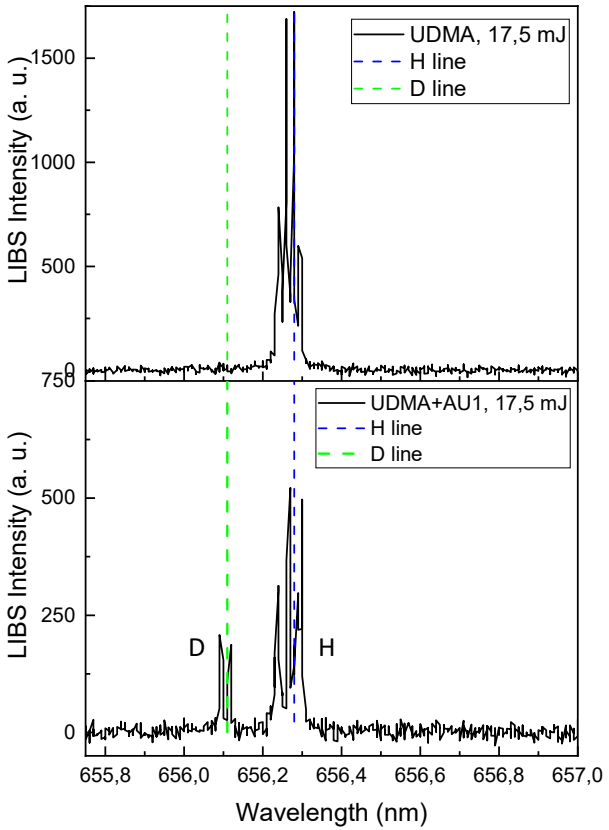


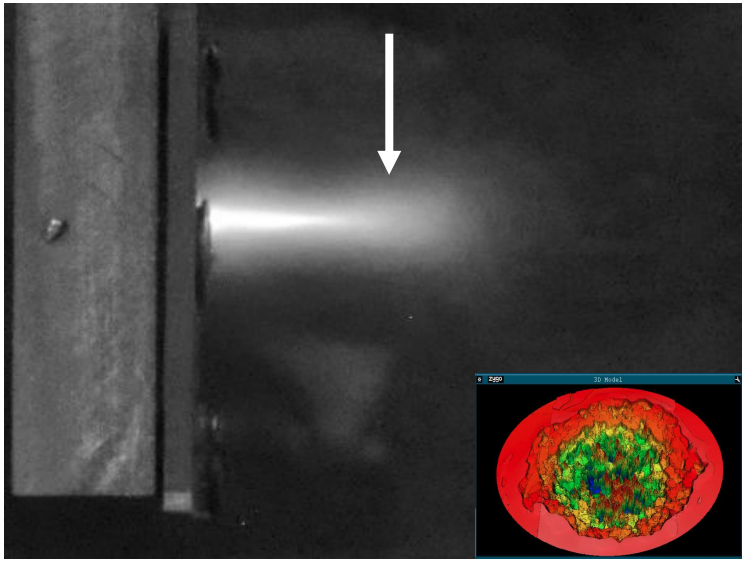
3.DIAGNOZIS: LIBS SPECTRUM OF Hᵅ AND Dᵅ SPECTRAL LINES

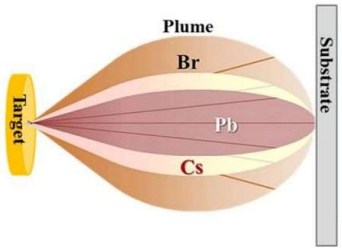


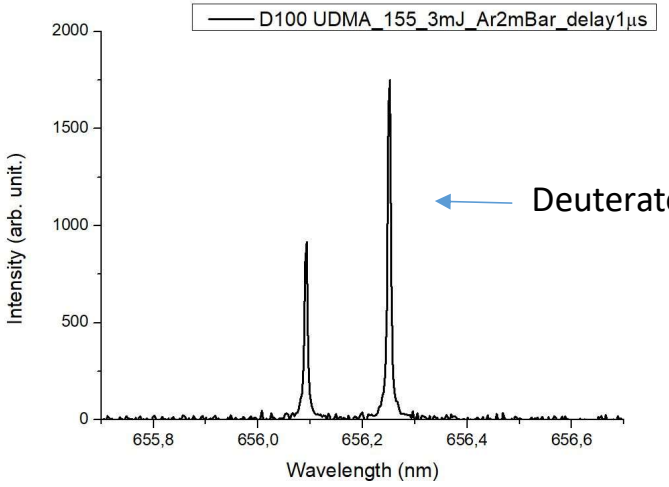

ZYGO NewView
Test 1 Area
+9.62161
µm
-35.37215
PV 44.994 µm
SRz ISO 15.340 µm
Sq 9.566 µm
Sa 7.357 µm
X 0.26 mm
Y 0.20 mm
Points 368241
3D Model
Surface Profile
+10000.00
-2500.00
-15000.00
-27500.00
-40000.00
Height (mm)
0
50
100
150
200
Distance (µm)
Area (total) 2412.44 µm²
Normalize: Off
Rq 14.121 µm
Rz ISO 14.877 µm
R3z ISO 4216.97 nm
Rpm ISO -2158.14 nm
Pt ISO 27757.00 nm
Valley -34257.39 nm
ure Attributes
Objective: 50X Mirau
Date 02.05.2023 12:42
Camera Res: 0.29 µm
File: ********************
2023-04-17
D
H
490.ess
data1
data2
Intensity (counts)
7000
6000
5000
4000
3000
2000
1000
0
655.7 655.8 655.9 656 656.1 656.2 656.3 656.4 656.5 656.6 656.7
Wavelength (nm)

SOME RESULTS OF THE Hᵅ AND Dᵅ SPECTRAL LINES

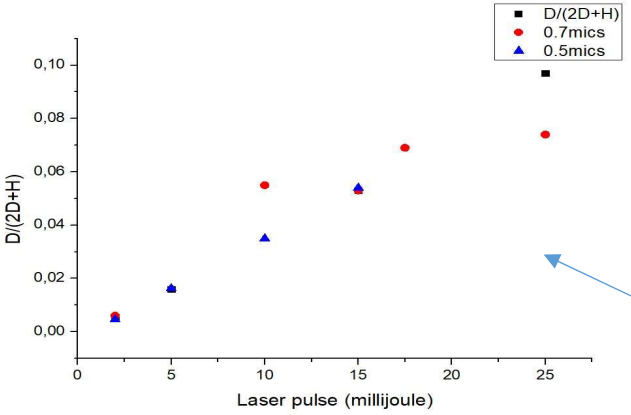








Deuterated (30%) sample



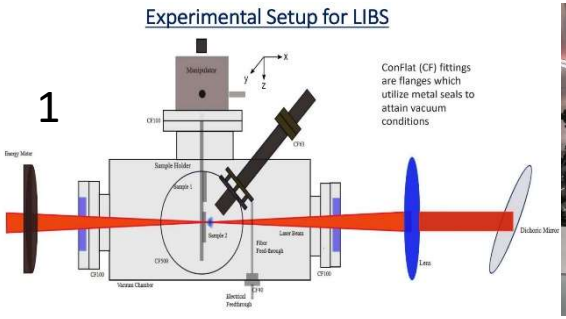
2D+H The total number of H atoms before the transmutation process

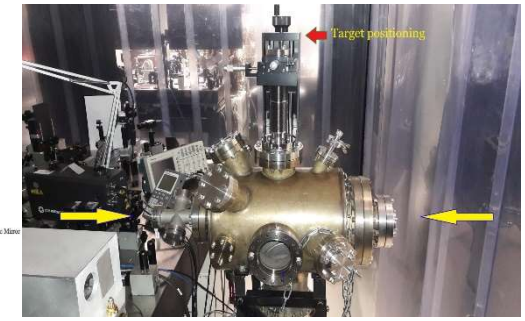
Number of D atoms in the case of 17.5mJ laser pulses : ~1.76×10^{15}

IN WORK BUT NOT YET CONCLUDING TECHNIQUES:

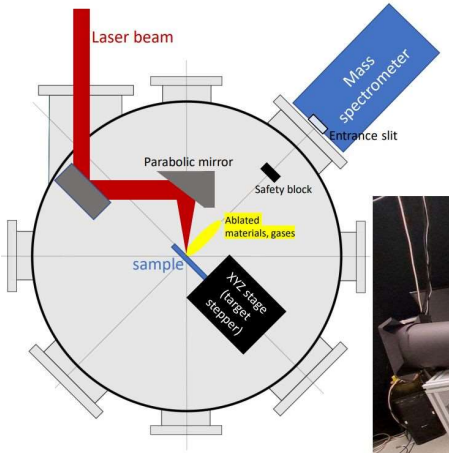
1. Atomic optical spectroscopy,
2. Mass spectrometry.
3. Nuclear detection techniques.

1

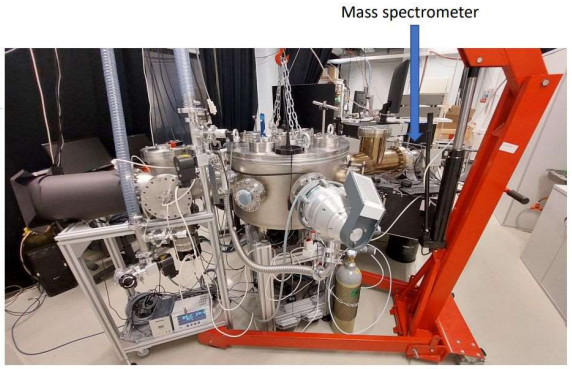




2

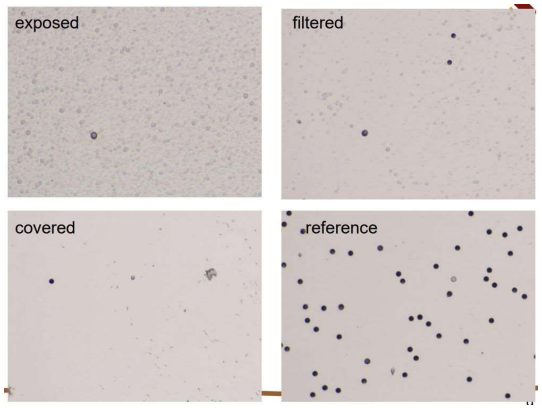


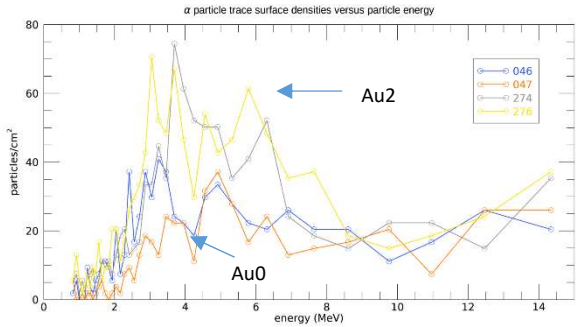
Experimental arrangement

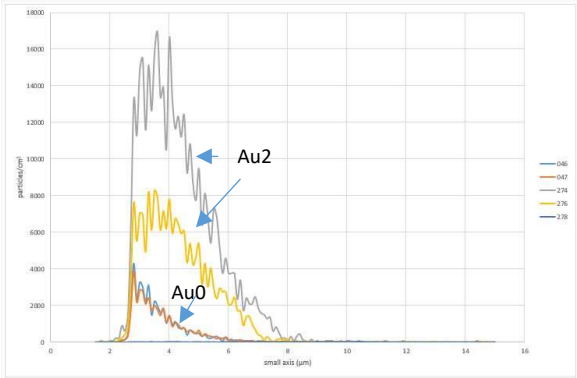


Boron nitride seeded samples

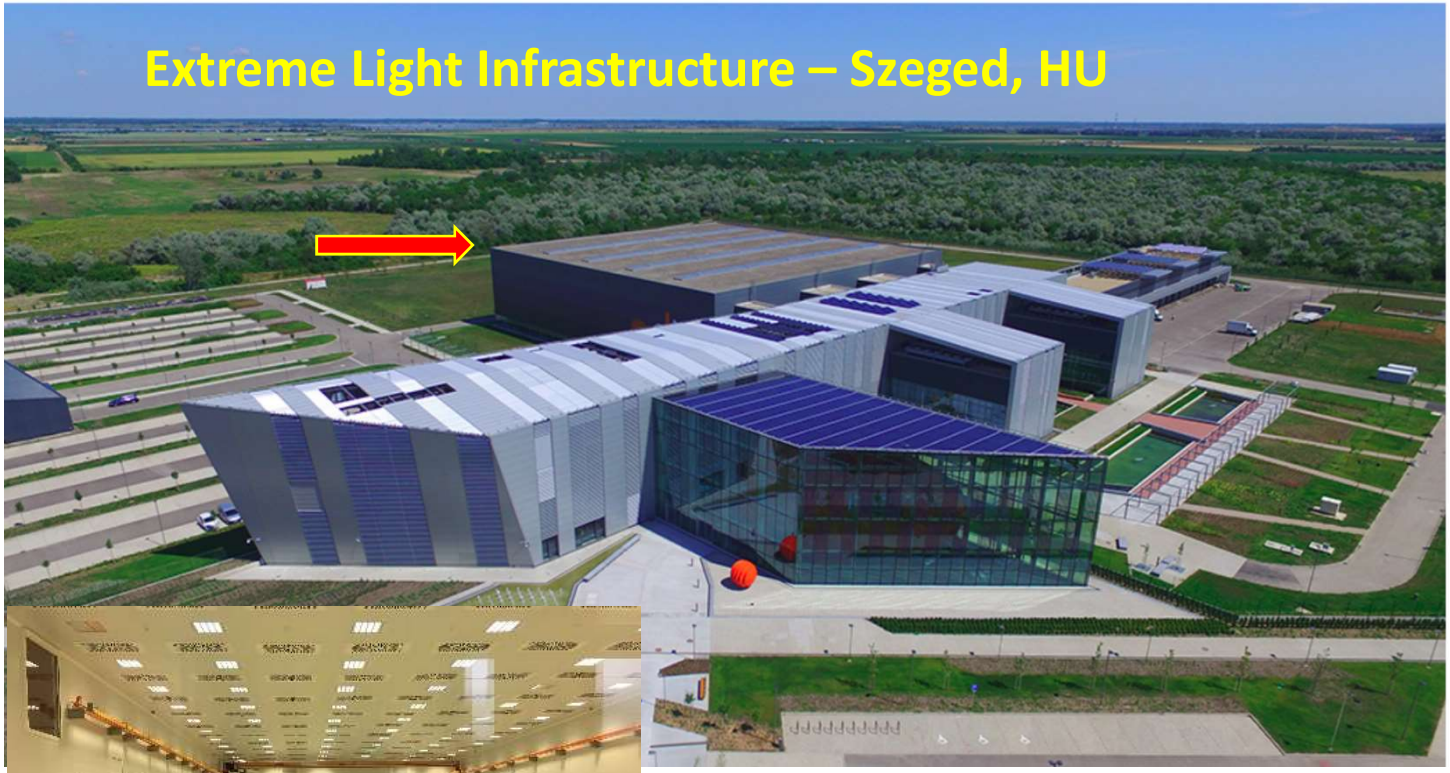
3: CR39 film, 1 laser shot







Extreme Light Infrastructure – Szeged, HU



ELI-ALPS Szeged:
EU Extreme Light Infrastructure
Also attosec laser pulses

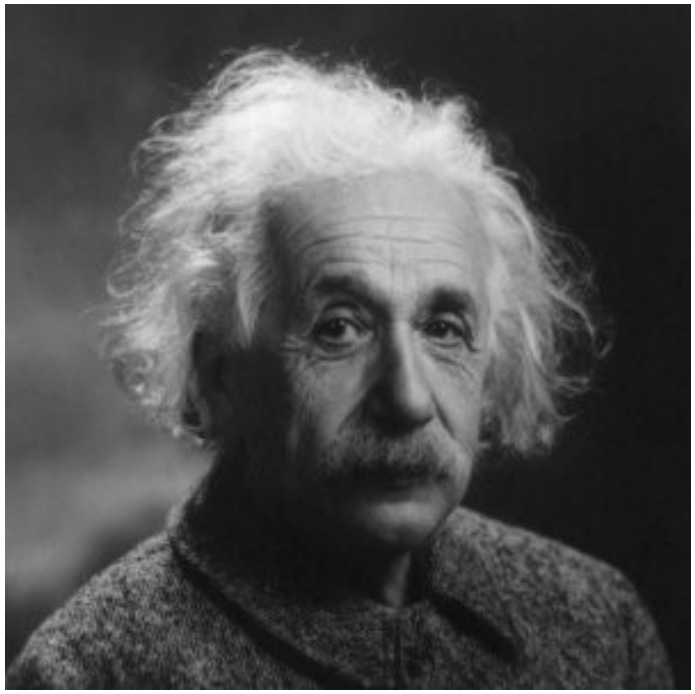
2PW extreme energies;
10Hz/1Hz, <10fs, 30 J, 10^{12} contrast

SUMMARY:

-Localized plasmons (LSPP) differ from the propagating ones with positive consequences.
-Properties are shape and material dependent (Au and Ag resonances in the visible spectrum)
-At high laser intensities no plasma mirror effect.
-Nanoparticles are effective at high laser intensities. Field amplification (hot spots).
Optimal lifetime for femtosecond lasers (e.g. Ti:Sa, 800nm)
Simplified geometry.
Screening (near field and ponderomotive effect)
Correlated momentum transfer
-Energy production (crater volume up to 8 times larger with Au nanorods) and H $\longrightarrow$ D transmutation (fusion) as the explanation, indicated by Raman scattering on the C-D and N-D vibrations
-Supportive modelling results.
-Still several open questions.

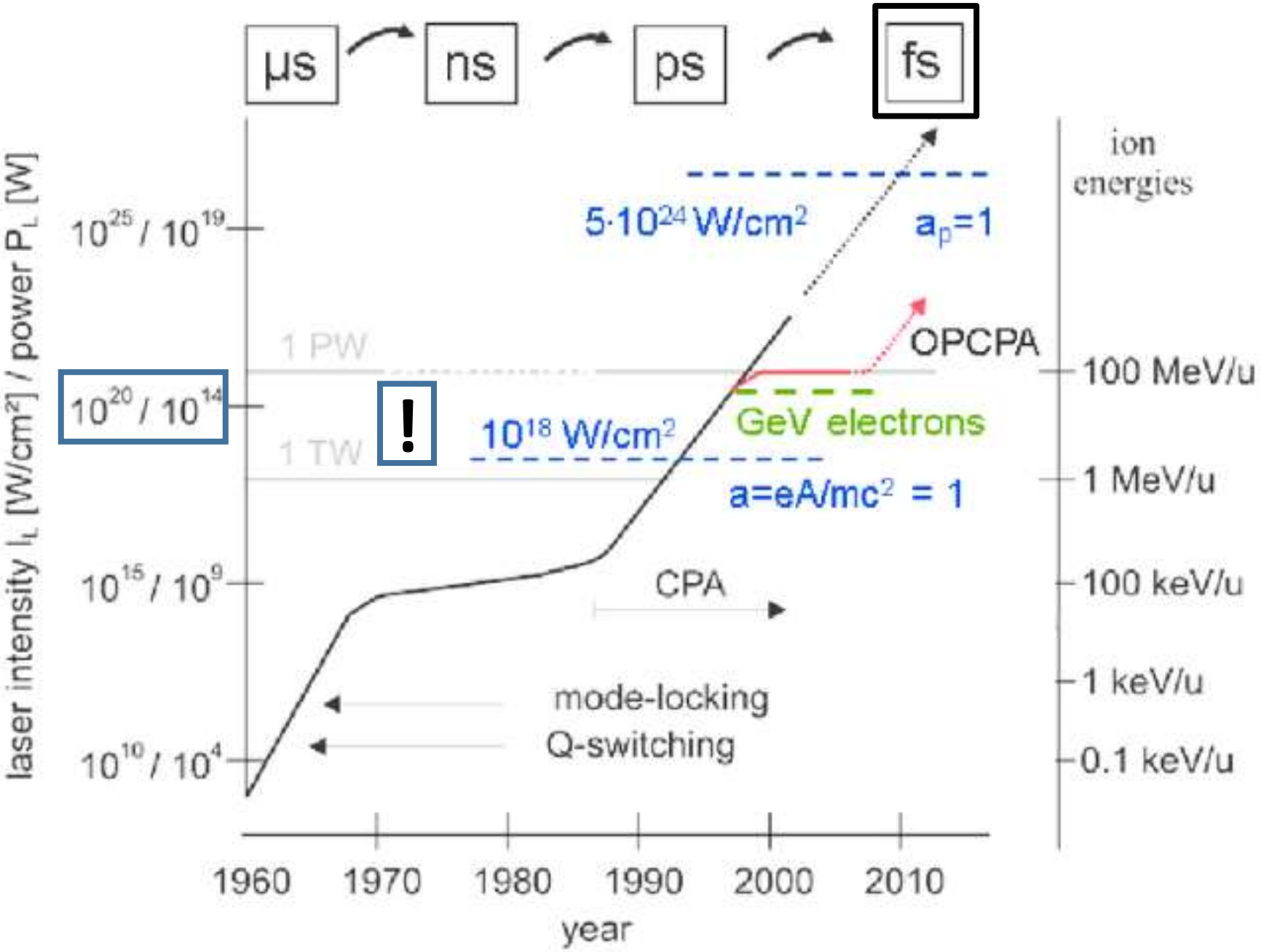
THE ADVICE OF ALBERT EINSTEIN FOR THE FUTURE:

THE PROBLEMS WE ARE FACING TODAY CAN NOT BE SOLVED WITH THE SAME WAY OF THINKING BY WHICH WE CREATED THEM.

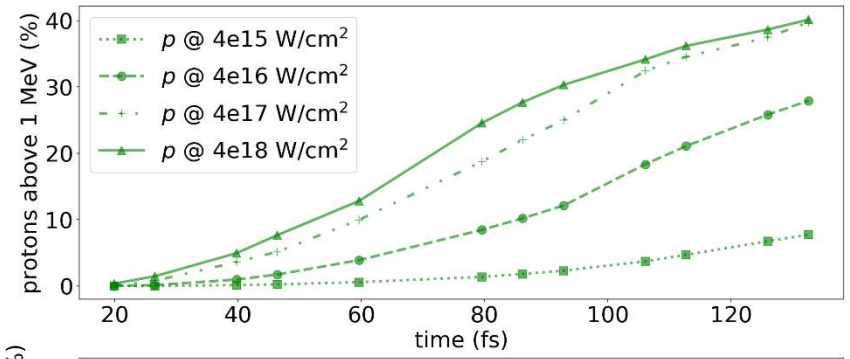


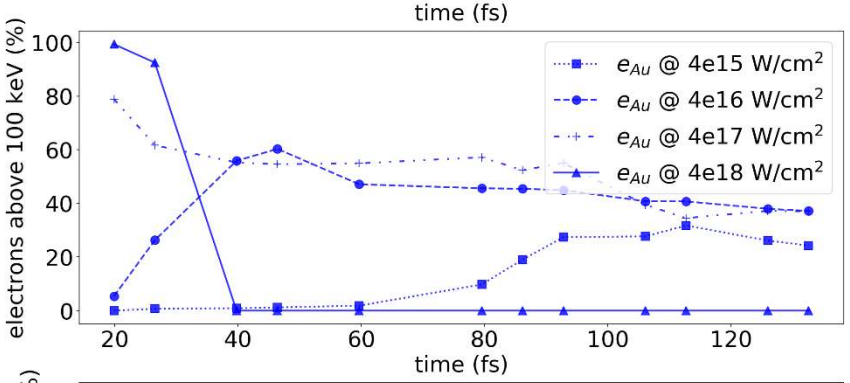
THIS IS WHY CREATIVE SCIENTIFIC THINKING IS THE KEY TO OUR FUTURE

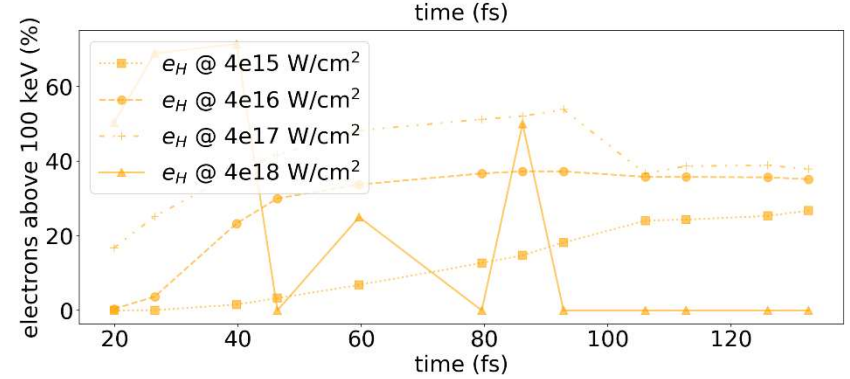
THANKS FOR YOUR ATTENTION


µs
ns
ps
fs
ion energies
$5 \cdot 10^{24}$ W/cm²
a_p=1
OPCPA
1 PW
100 MeV/u
10^{20} / 10^{14}
!
10^{18} W/cm²
GeV electrons
1 TW
a=eA/mc² = 1
1 MeV/u
10^{15} / 10^{9}
CPA
100 keV/u
mode-locking
1 keV/u
Q-switching
10^{10} / 10^{4}
0.1 keV/u
laser intensity I_L [W/cm²] / power P_L [W]
10^{25} / 10^{19}
1960
1970
1980
1990
2000
2010
year

Fraction of particles at energies







Fraction of particles at energies