EJC2021

école Joliot-Curie school

THE INTERPLAY BETWEEN ATOMIC ELECTRONS AND THE NUCLEUS

TRAPS, LASERS, SPECTROSCOPY

OCTOBER 3-8, 2021

SAINT-PIERRE D'OLERON, FRANCE

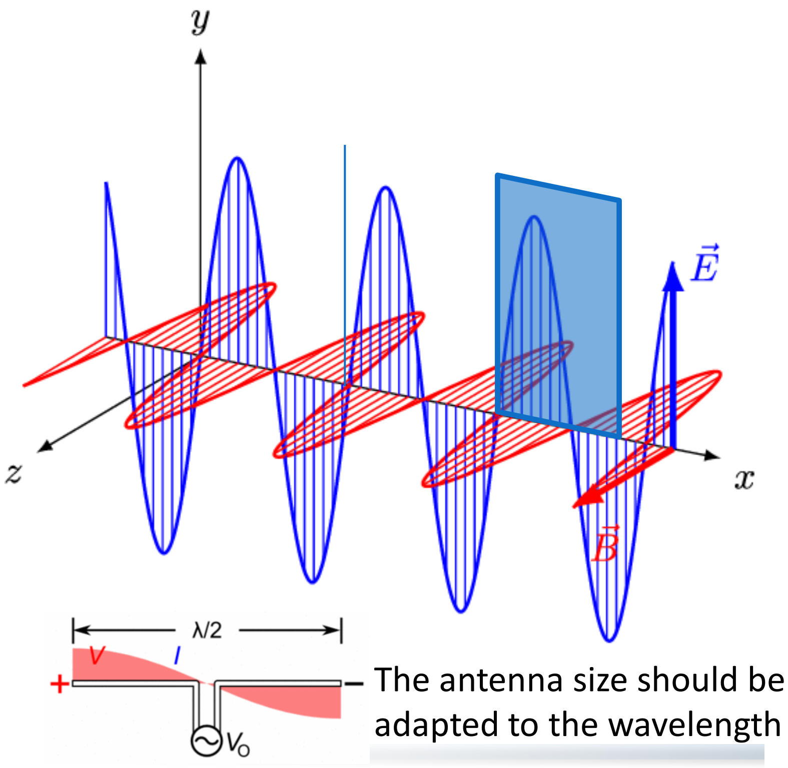
Introduction to Nuclear physics with high-power lasers

Medhi Tarisien

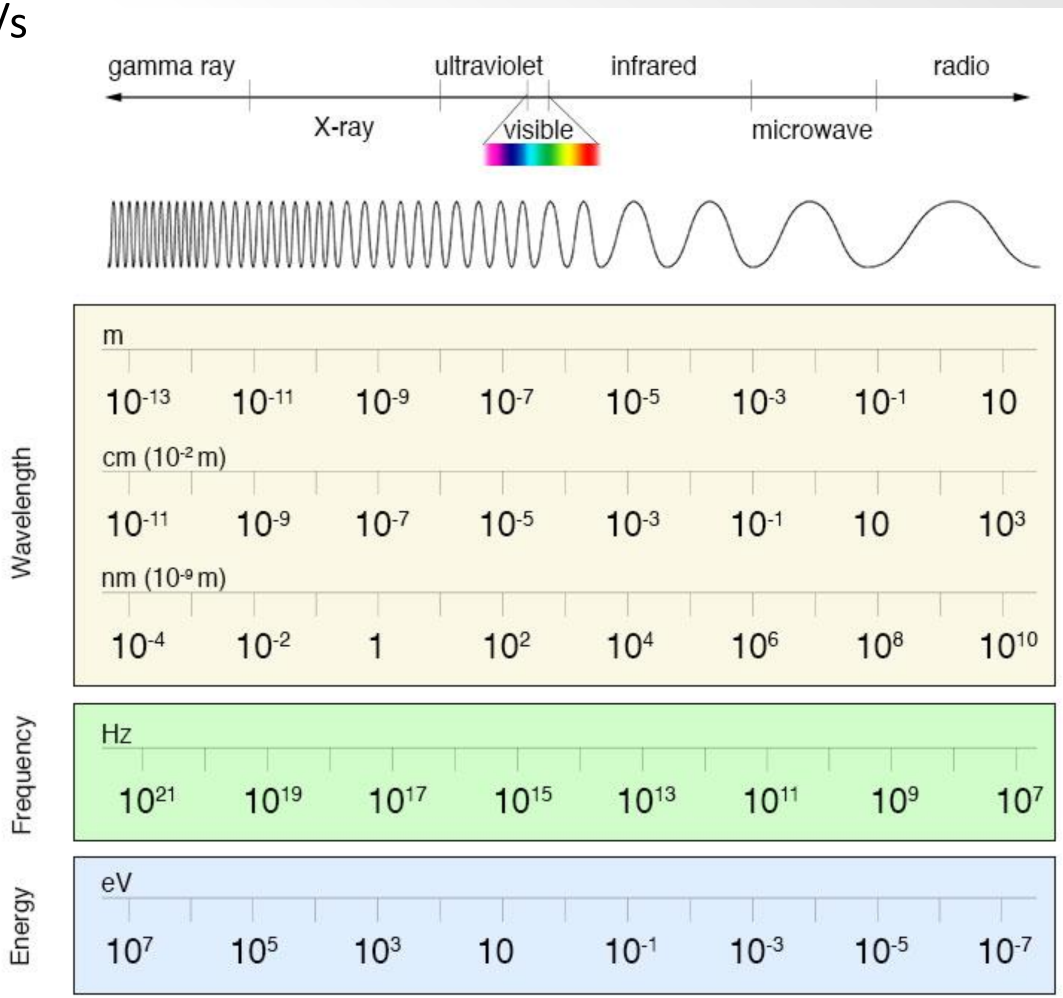
How a laser can have an effect on a nucleus?

Electromagnetic radiation

λ_0 : Wavelength (m)
c = 299 792 458 m/s
ν : frequency (s^{-1})
T : period (s)



The antenna size should be adapted to the wavelength

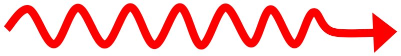


How a laser can have an effect on a nucleus?

λ_0 : Wavelength (m)
c = 299 792 458 m/s
ν : frequency (s^{-1})
T : period (s)

One photon

$$\lambda_0 = cT = \frac{c}{\nu}$$

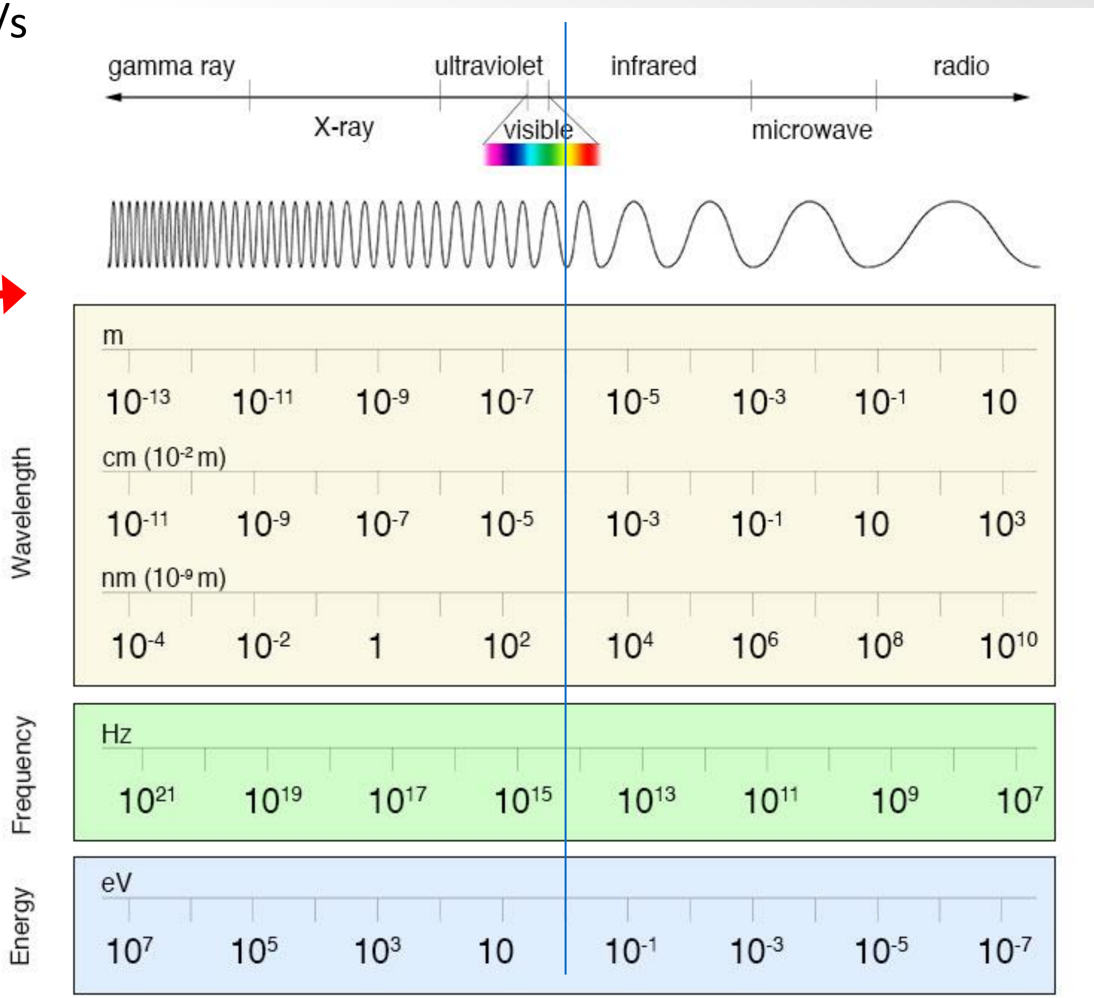


The light we use : $\lambda_0 \approx 1\mu m$
$T \approx 3$ fs

$E = h\,\nu$
$h = 4.135667696 \times 10^{-15}$ eV.s
Planck constant

⇔ 1.3 eV

No direct effect of IR photon on the nucleus !



How a laser can have an effect on a nucleus?

The laser

Light Amplification by Stimulated Emission of Radiation

Théodore Maiman : 1960 LASER rubis

How a laser can have an effect on a nucleus?

The High power Laser

LULI
2000

How a laser can have an effect on a nucleus?

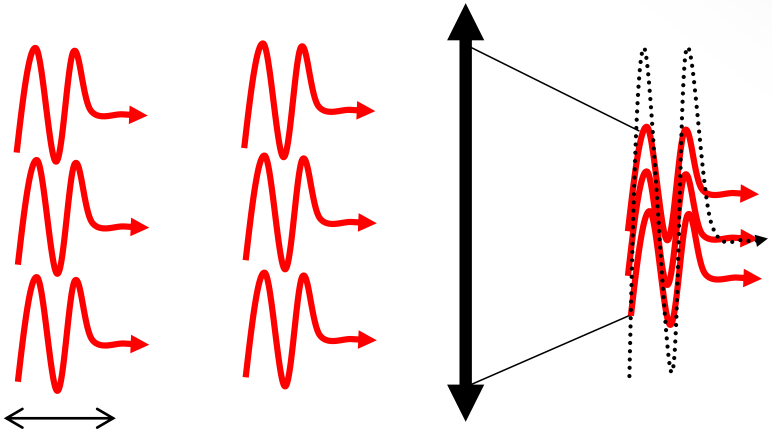
Plenty of photons

$\lambda \approx 1 \mu m$

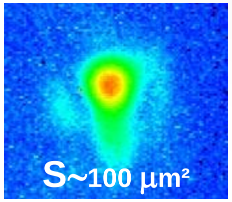
$T \approx 3$ fs

⇔ 1.3 eV

$E_L = N_{ph} \times 1.3 \text{ eV} \times 1.602 .10^{-19} \text{J/eV}$



Δt FWHM of a gaussian pulse



Focal spot

The intensity

$$I = \frac{E_L}{\Delta t . S}$$

Equivalent electric field :

$$E(V/cm) = 27{,}446 \sqrt{I(W/cm^2)}$$

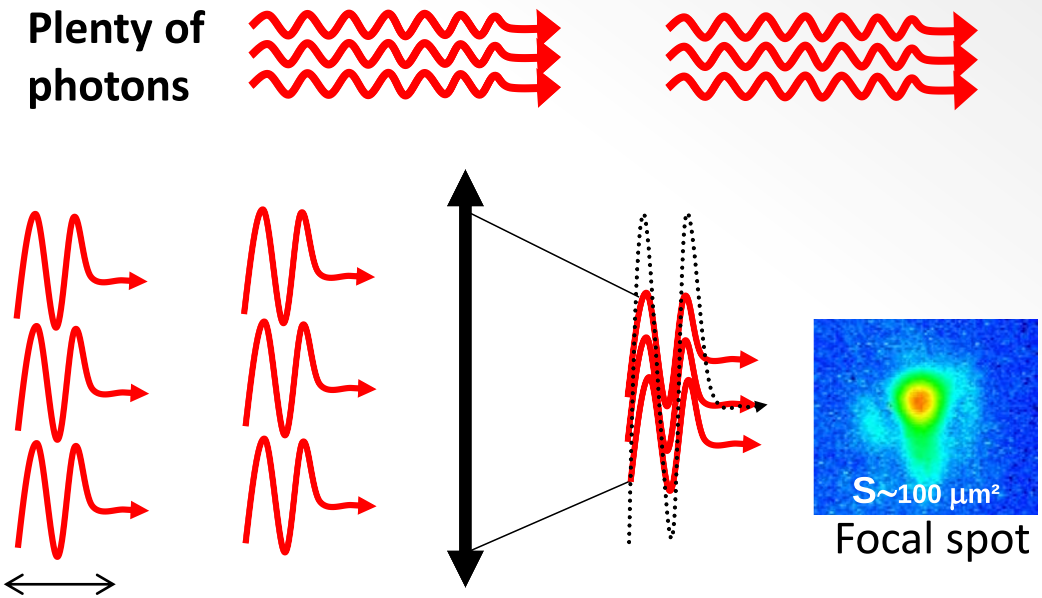
$$E_{atom} \approx 9.10^9 \frac{1{,}6.10^{-19}}{(10^{-10})^2} \approx 10^9 \, V/cm$$

$$E_{nucl} \approx 9.10^9 \frac{1{,}6.10^{-19}}{(10^{-15})^2} \approx 10^{19} \, V/cm$$

Which Intensities are requiered to have an effect on the atom? The nucleus?

How a laser can have an effect on a nucleus?

Plenty of photons



Focal spot

Δt FWHM of a gaussian pulse

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⇔ 1.3 eV

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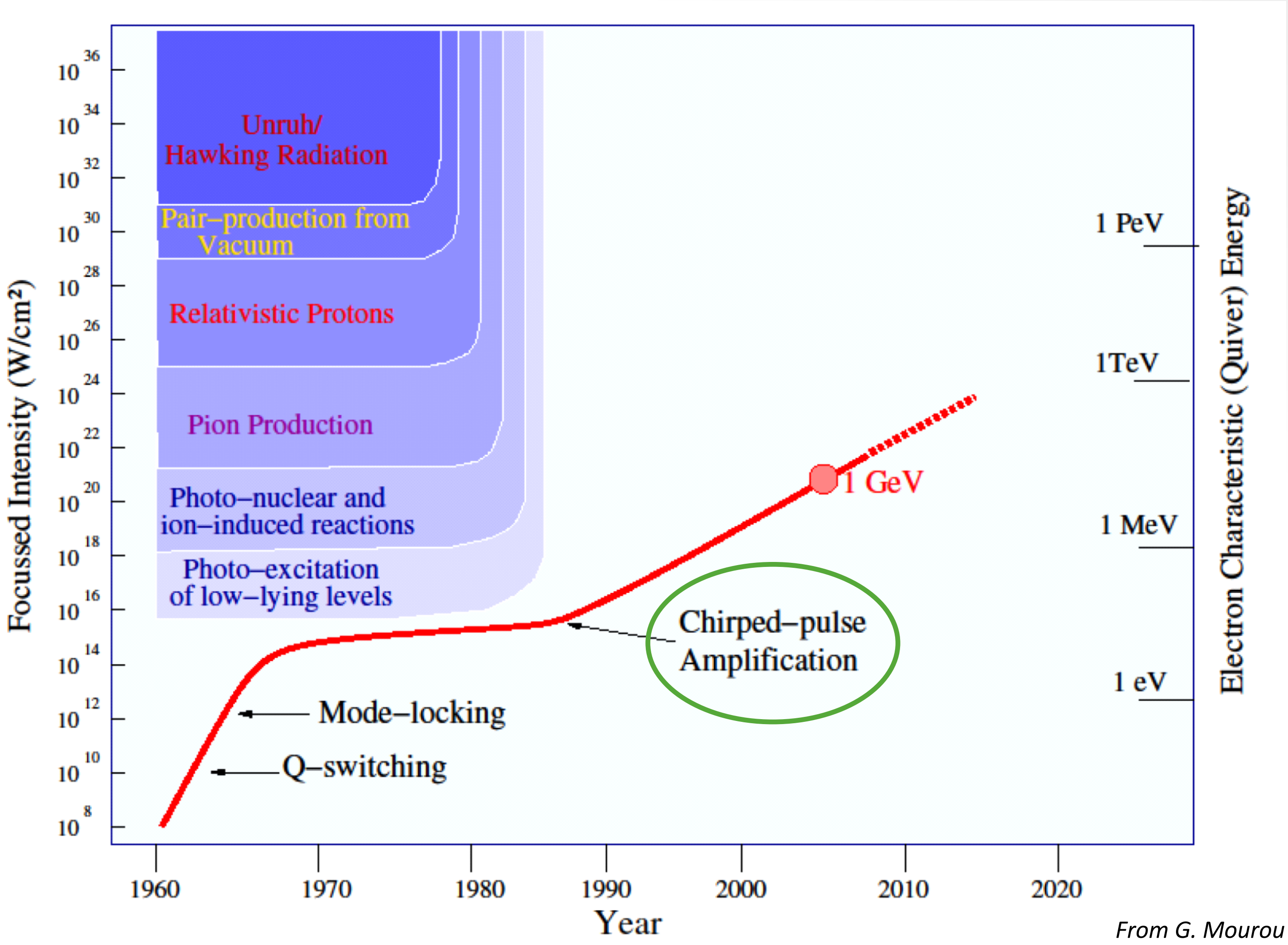
Atom : $I \approx 1.3 \times 10^{15}$ W/cm²
Nucleus : $I \approx 1.3 \times 10^{35}$ W/cm²

High power lasers



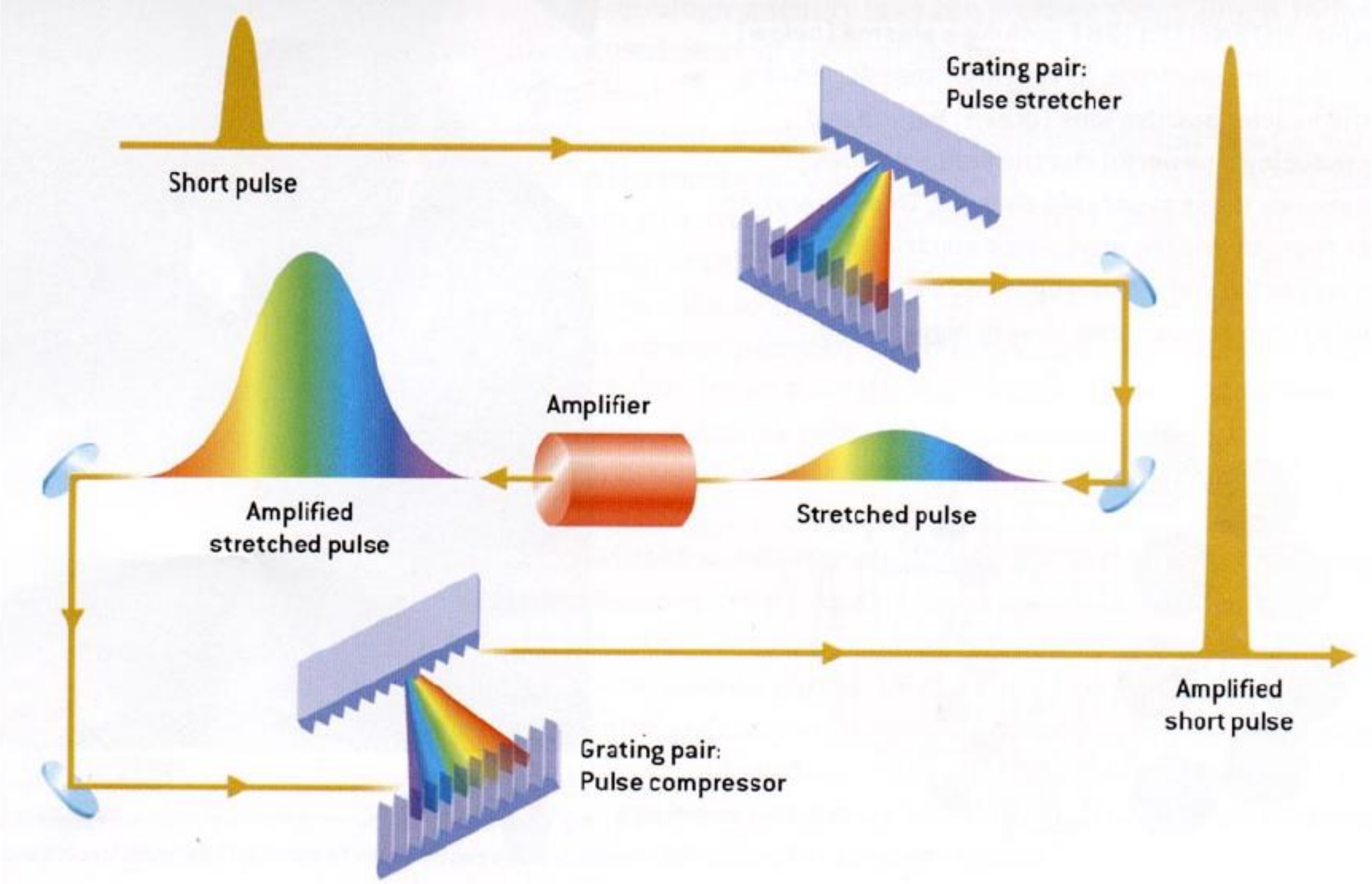
From G. Mourou

High power lasers

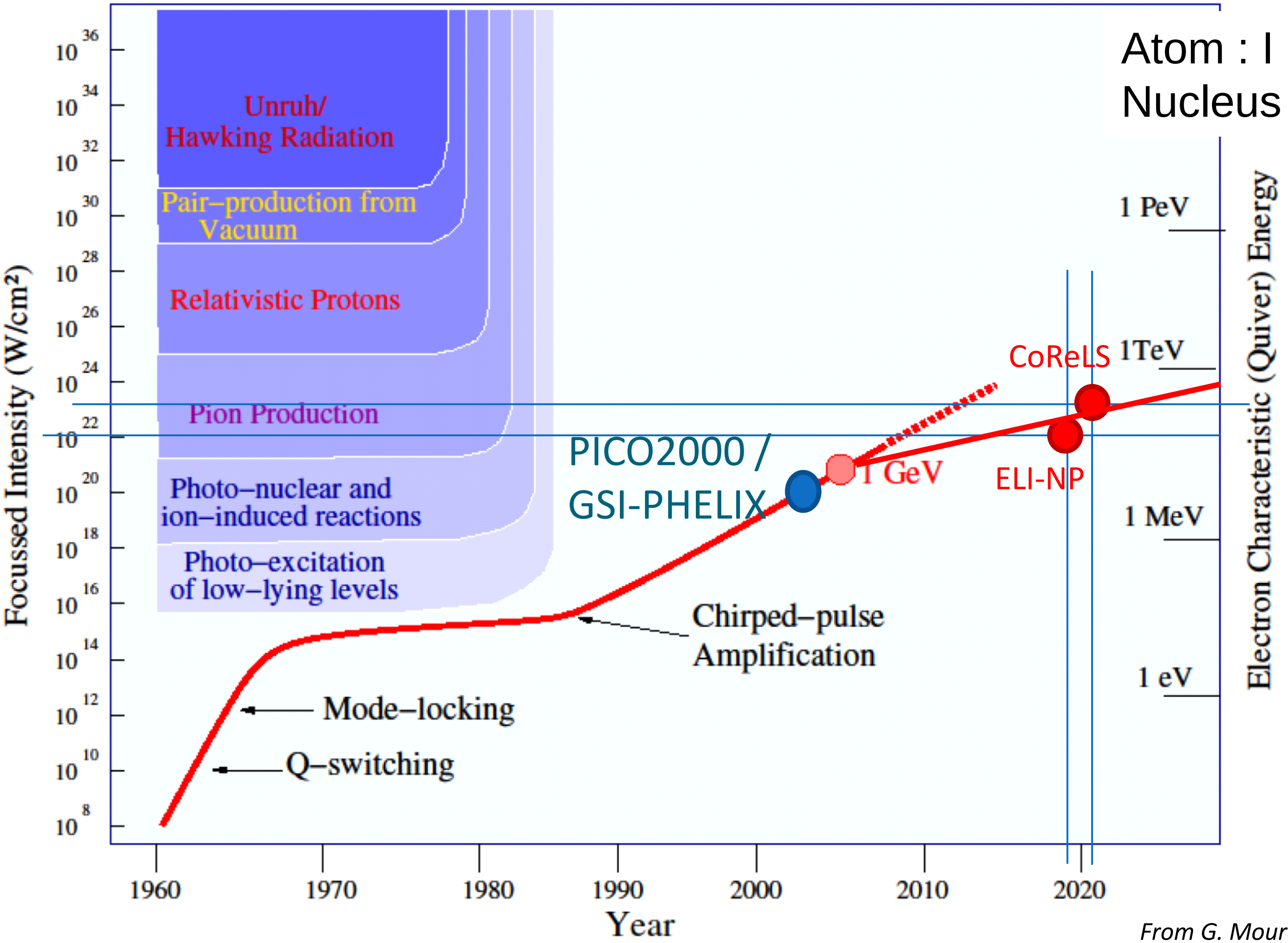
Chirped Pulse Amplification (CPA)

D. Strickland & G. Mourou

Nobel prize in Physics 2018



High power lasers

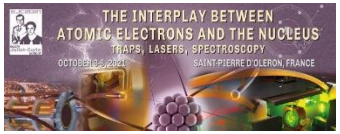


From G. Mourou

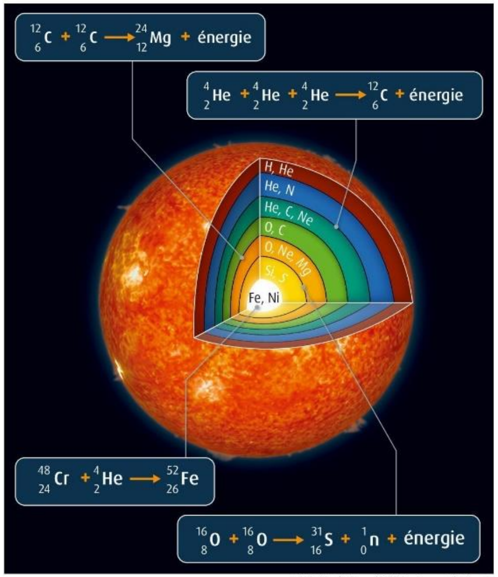
Atom : $I \approx 1.3 \times 10^{15}$ W/cm²
Nucleus : $I \approx 1.3 \times 10^{35}$ W/cm²

No direct effect of the electric field on the nucleus before a century !!!

BUT we can use the **interplay between atomic electrons and nucleus**



A contribution in Nucleosynthesis studies



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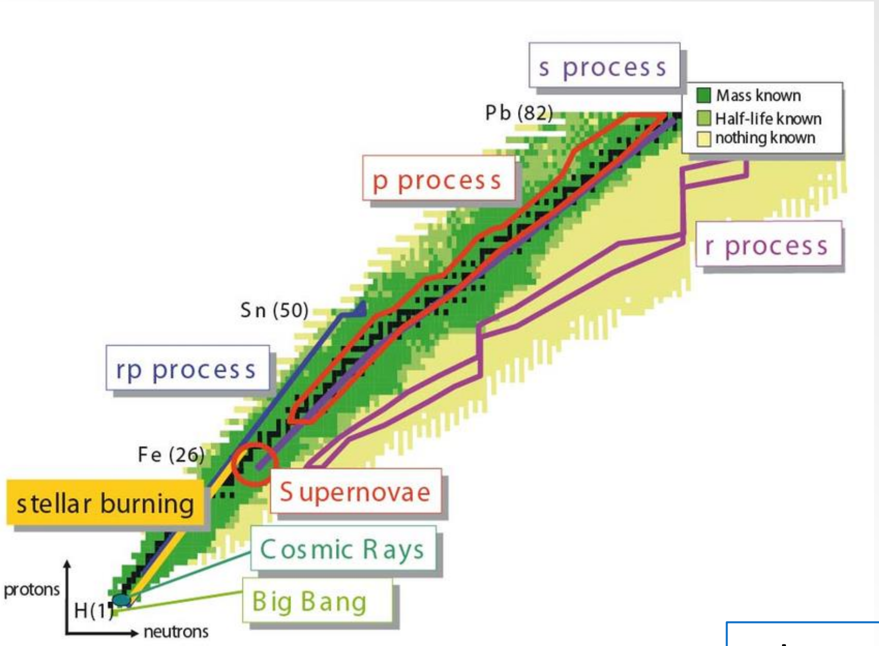


Nuclear Physics : cross-sections, resonance parameters, β-decays, …

Astrophysics modeling

Abundances

Abundances

Observations meteorites, stars, …

On earth, in laboratories

In stellar and interstellar environments

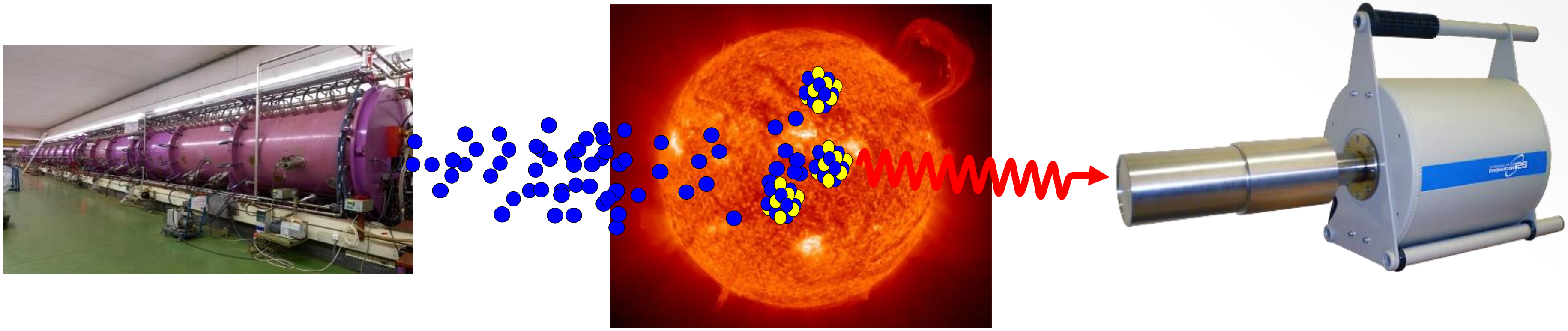
Are nuclear reactions the same in a star as in a solid?

Nuclear physics in stellar medium

Take a star in a laboratory as a target

Take an accelerator and send some particle projectiles on the star

Detect the nuclear reaction signatures



Are nuclear reactions the same in a star as in a solid?

Nuclear physics in stellar medium

High power lasers

Take a star in a laboratory as a target :

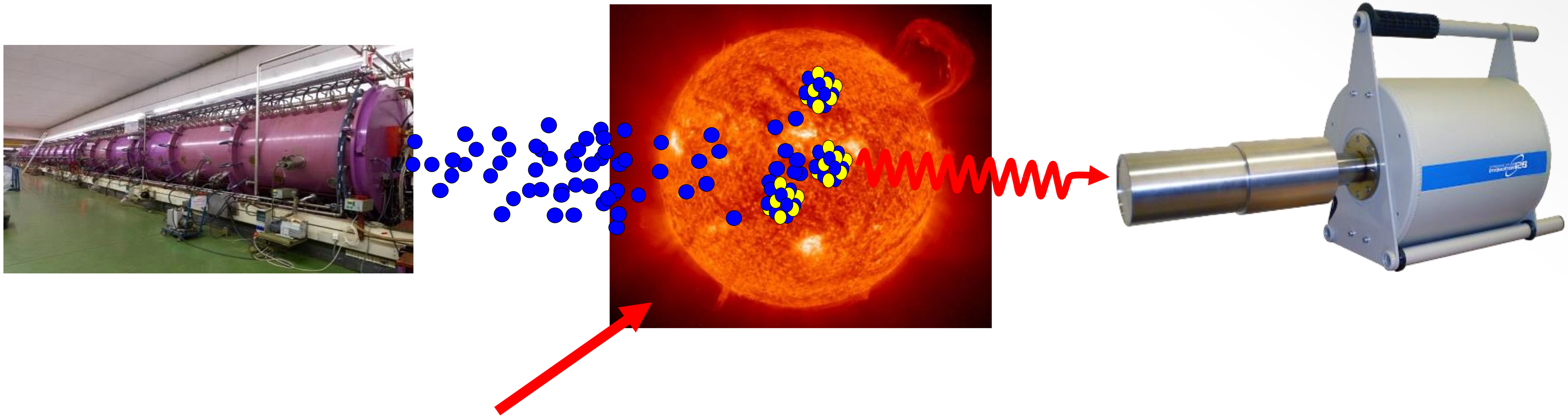
you can have one during ~**1 ns** only

Take an accelerator and send some particle projectiles on the star :

What should be the intensity of a proton beam for 10^{13} protons passing through the plasma target? ($e = 1.6\ 10^{-19}$ C)

$I = ?$

Detect the nuclear reaction signatures



High power lasers

Are nuclear reactions the same in a star as in a solid?

Nuclear physics in stellar medium

High power lasers

Take a star in a laboratory as a target :

you can have one during 1 ns only

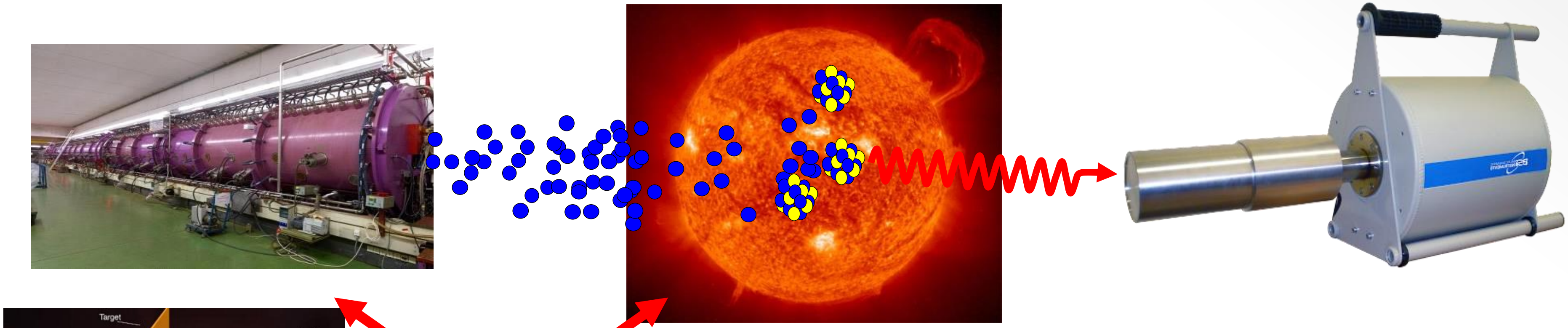
Take an accelerator and send some particle projectiles on the star :

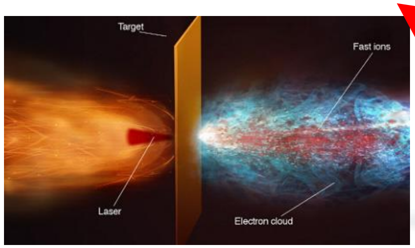
What should be the intensity of a proton beam for 10^{13} protons passing through the plasma target? (e = $1.6\ 10^{-19}$ C)

$$I = 10^{13} \times 1.6\ 10^{-19}\ \mathrm{C} / 10^{-9}\mathrm{s} = 1{,}6\ \mathrm{kA}$$

accelerators Ultra-High Intensity : ~100 mA

Detect the nuclear reaction signatures





L. Gremillet seminar

High power lasers

Are nuclear reactions the same in a star as in a solid?

Nuclear physics with high-power lasers

- High power lasers and their interaction with matter
- Laser-Plasma Acceleration
- Nuclear Physics in plasmas
- Challenges to take up

Part 1

HIGH POWER LASERS AND THEIR INTERACTION WITH MATTER

- High power laser characteristics
- What is a Plasma ?
- Laser/plasma interaction

High power laser characteristics

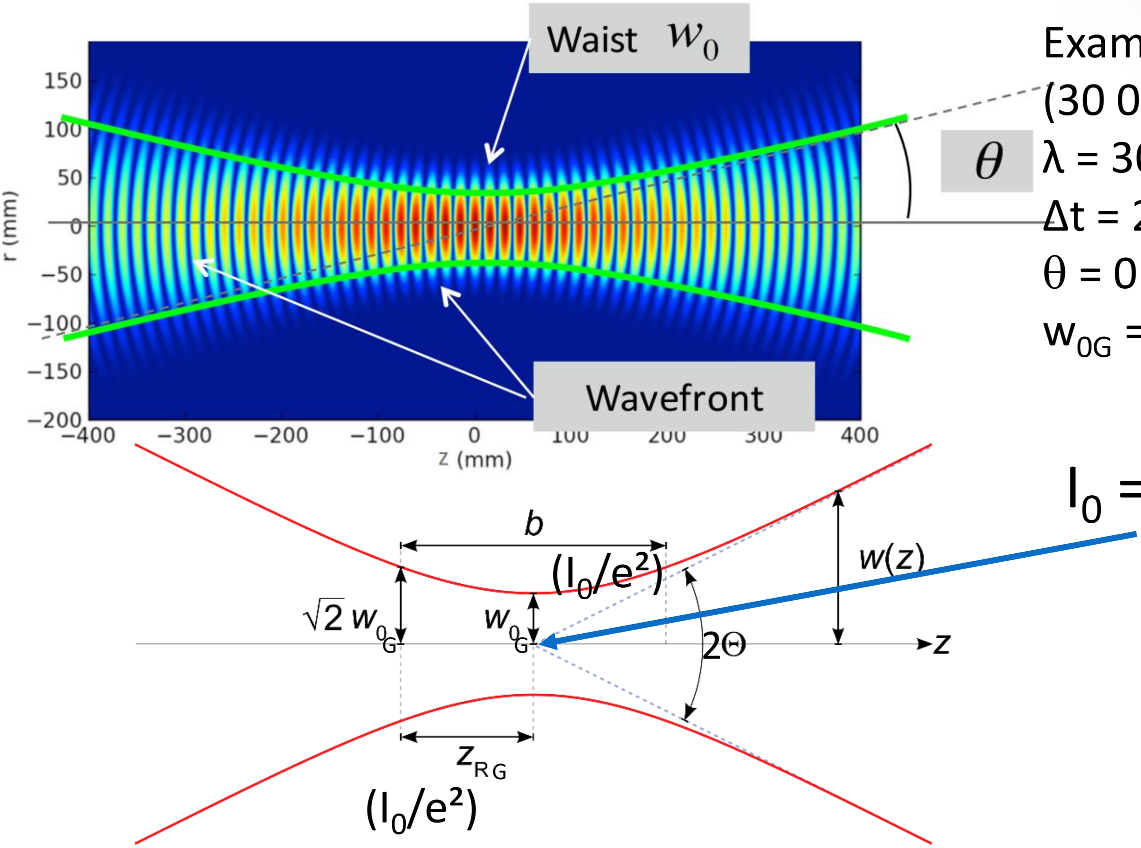
$$\mathrm{I} = \frac{\mathrm{E_L}}{\Delta \mathrm{t.\,S}}$$

Is it possible to decrease S→ 0 cm² to increase I→ ∞ ?

High power laser characteristics

$$I = \frac{E_L}{\Delta t . S}$$

Is it possible to decrease S→ 0 cm² to increase I→ ∞ ?



Example of a focused **Gaussian** pulse
(30 000 times a laser size)
λ = 30 mm
Δt = 2.6 ns ↔ 780 mm
θ = 0.24 rad = 13.7°
w_{0G} = 40 mm

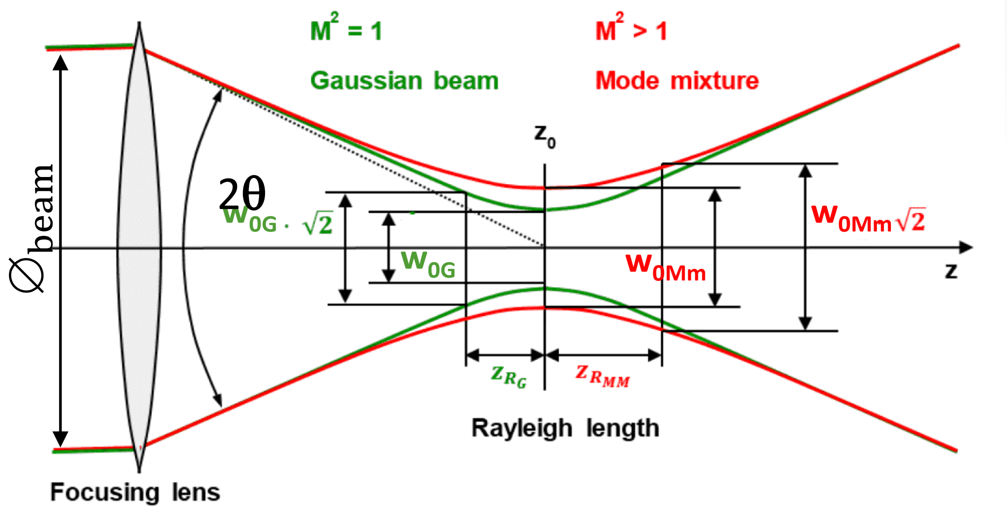
$$I_0 = \frac{2E_L}{\Delta t \times \pi w_0^2}$$

Field depth b ↔ Rayleigh length

$$b = 2\times Z_{RG} = 2\times\pi\frac{{w_{0G}}^2}{\lambda_L}$$

Here b = 334 mm

High power laser characteristics



$$\tan\theta = \frac{\varnothing_{\mathrm{beam}}/2}{f}$$

$$w_{0MM} = \frac{M^2\lambda_L}{\pi\theta}$$

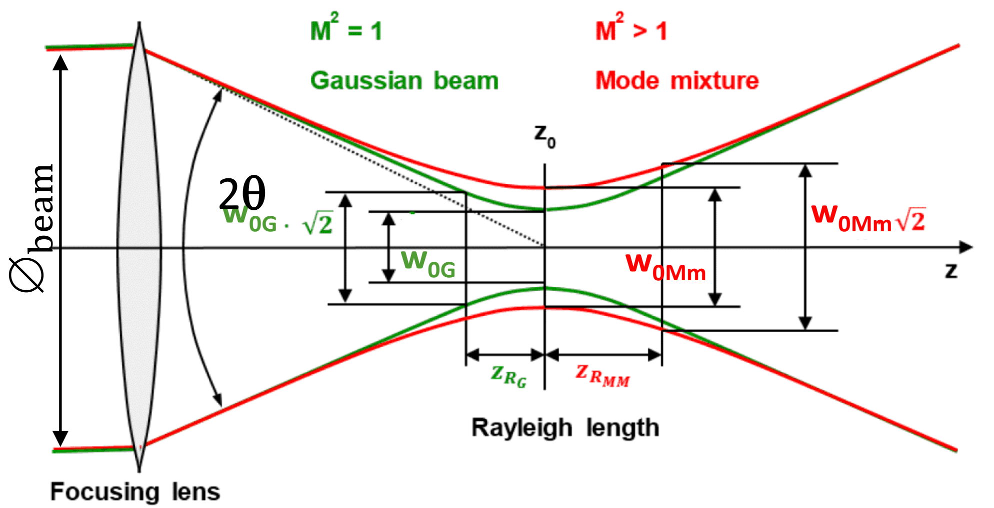
$$Z_{RMM} = \pi\frac{{w_0}^2}{M^2\lambda_L}$$

$$I_0 = \frac{2E_L}{\Delta t\times\pi w_0^2}$$

- LULI-PICO2000 has the following characteristics :
  λ_L=1.053 µm , M^2 = ~2, $\varnothing_{\mathrm{beam}}$ = 18 cm, E_L = 90 J, Δt = 1 ps
- It is focused with a parabola mirror of 800 mm focal distance

What is the ultimate focal spot diameter we can obtain? Which focal depth sensitivity? Which maximum intensity?

High power laser characteristics



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$$\tan\theta = \frac{180/2}{800} \quad \rightarrow \theta = 0.112 \text{ rad}$$

$$\pm Z_{RMM} \approx \pi \frac{(6\mu m)^2}{2 \times 1.053\mu m} \approx \pm 54\ \mu m$$

$$w_{0MM} = \frac{2}{\pi \times 0.122} \times 1.053\ \mu\text{m} \approx 6\ \mu\text{m}$$

$$\varnothing_{\text{beam}} \approx\ 12\ \mu\text{m}$$

$$I_0 \approx \frac{2 \times 90\ J}{10^{-12} \times \pi \times (6.10^{-4} cm)^2} \approx 1.6\ \ 10^{20}\ \text{W/cm}^2$$

High power laser characteristics

a0 : the normalized laser vector potential

Is the ratio of classical speed of electron accelerated by the electric field of the laser in the middle of the waist over light celerity

$$a_0 = \frac{v}{c}$$

$0 \leq a_0 < 1$ classical electron, linear regime
$a_0 >> 1$ relativistic electron, non linear regime
$a_0 \approx 1$: quasi-linear regime

$$a_0 = \sqrt{\frac{e^2 I \lambda_L^2}{2\pi^2 \varepsilon_0 \, m_e^2 c^5}} \approx 0.85 \left(\frac{I \lambda_{L\mu m}^2}{10^{18} \mathrm{Wcm}^{-2} \mu m^2} \right)^{1/2}$$

→L. Gremillet presentation

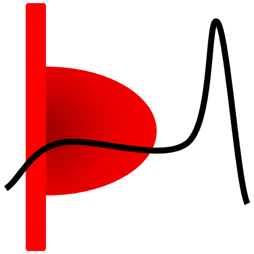
High power laser characteristics

$$I_0 = \frac{2E_L}{\Delta t \times \pi w_0^2}$$

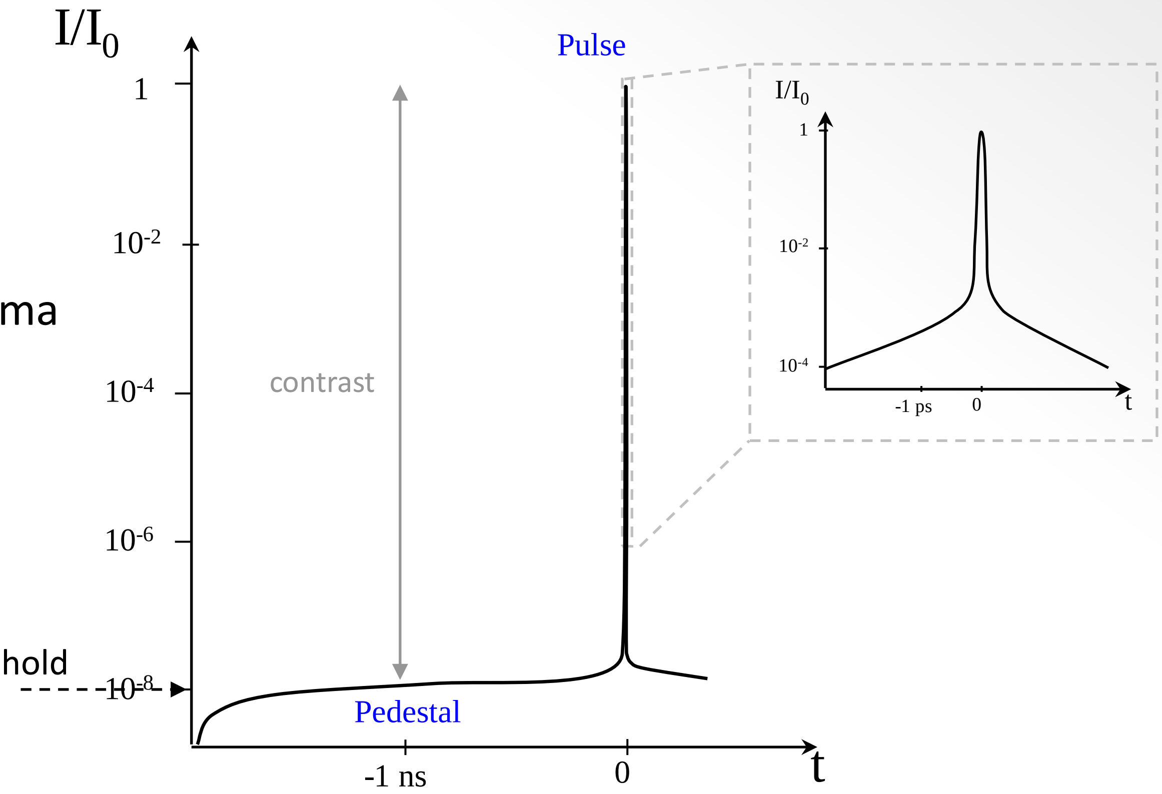
$I_0 \sim 10^{20}$ W/cm²

- A laser pulse is preceded by a pedestal : Amplified Spontaneous Emission (ASE)
- The ration between the pre-pulse intensity and the main pulse one is called Contrast

The pedestal create a pre-plasma

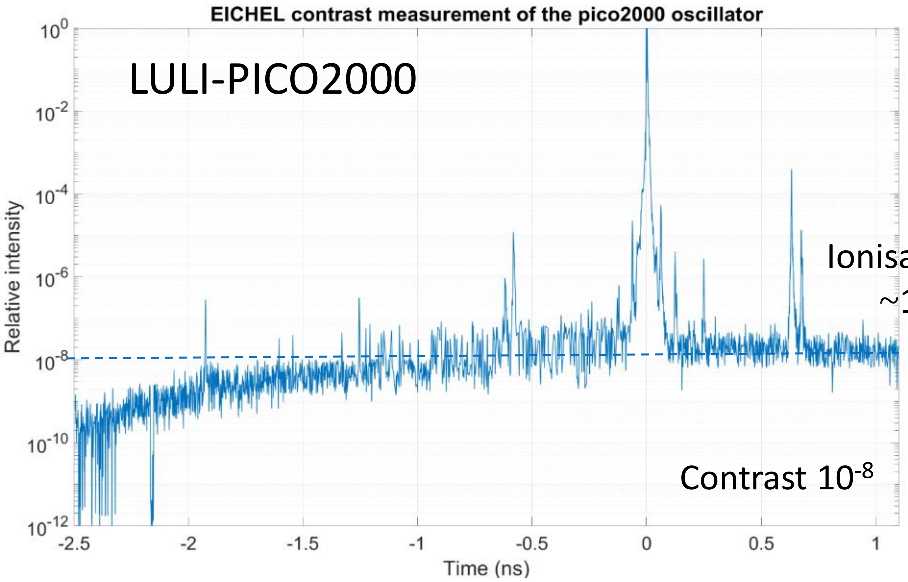


Ionisation threshold
$\sim 10^{12}$ W.cm^{-2}



High power laser characteristics

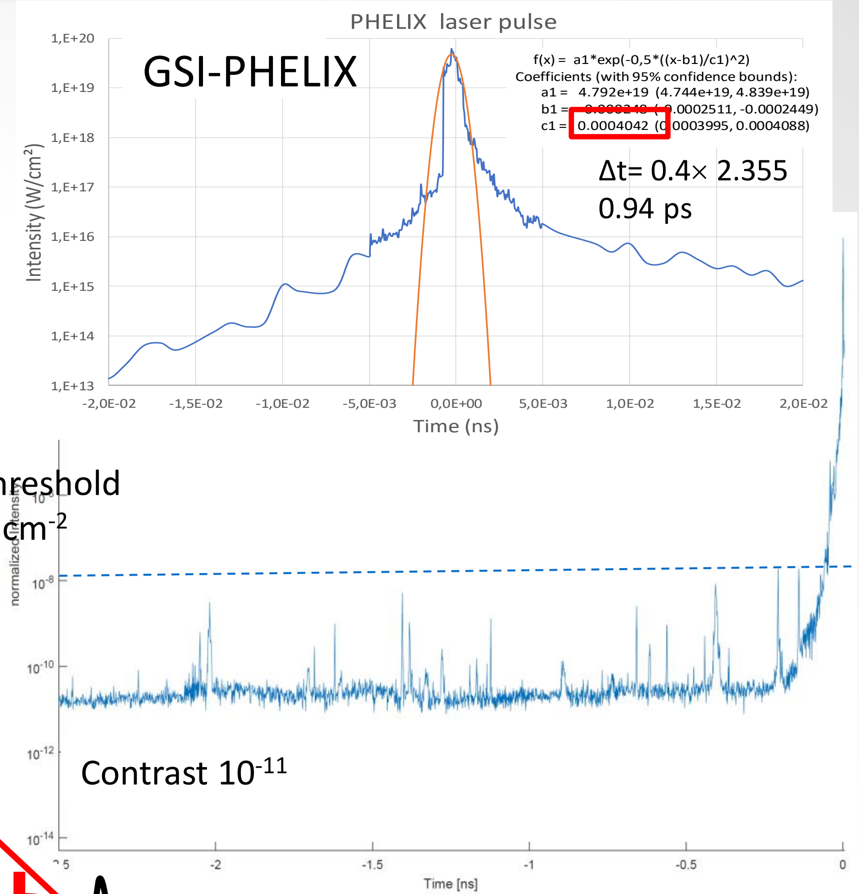
$I_{max} = 10^{20}$ W/cm² ; E~50 J ; Δt = 1 ps



LULI-PICO2000

Contrast 10^{-8}

Ionisation threshold $\sim 10^{12}$ W.cm^{-2}



GSI-PHELIX

Δt= 0.4× 2.355
0.94 ps

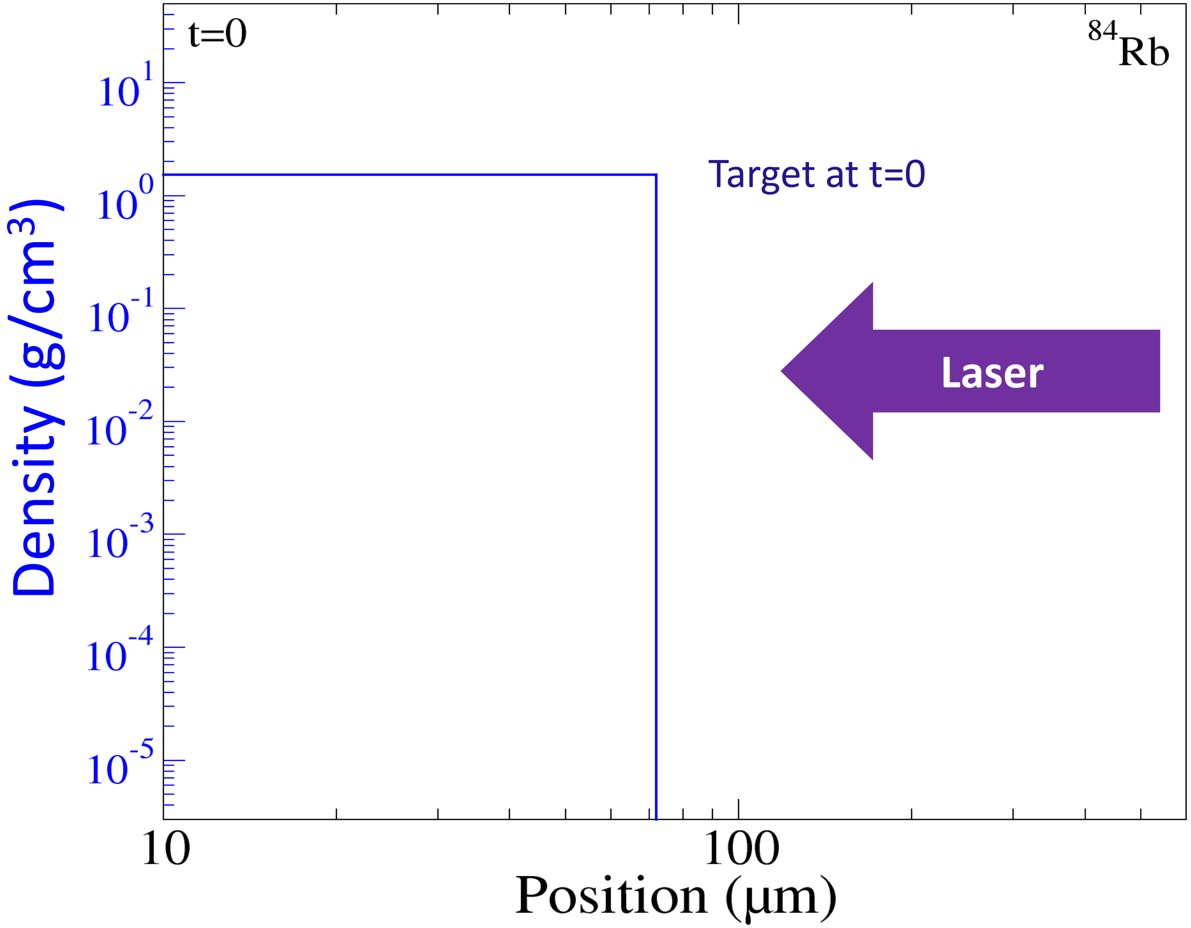
Contrast 10^{-11}

Pre-plasma >1 ns before the pusle

No pre-plasma >1 ns before the pusle

Every research laser facility is unique and has is own characteristics

Laser / solid target Interaction



$I=10^{14}$ W/cm^2

$a_0 = 9.\ 10^{-3}$

Laser / solid target Interaction

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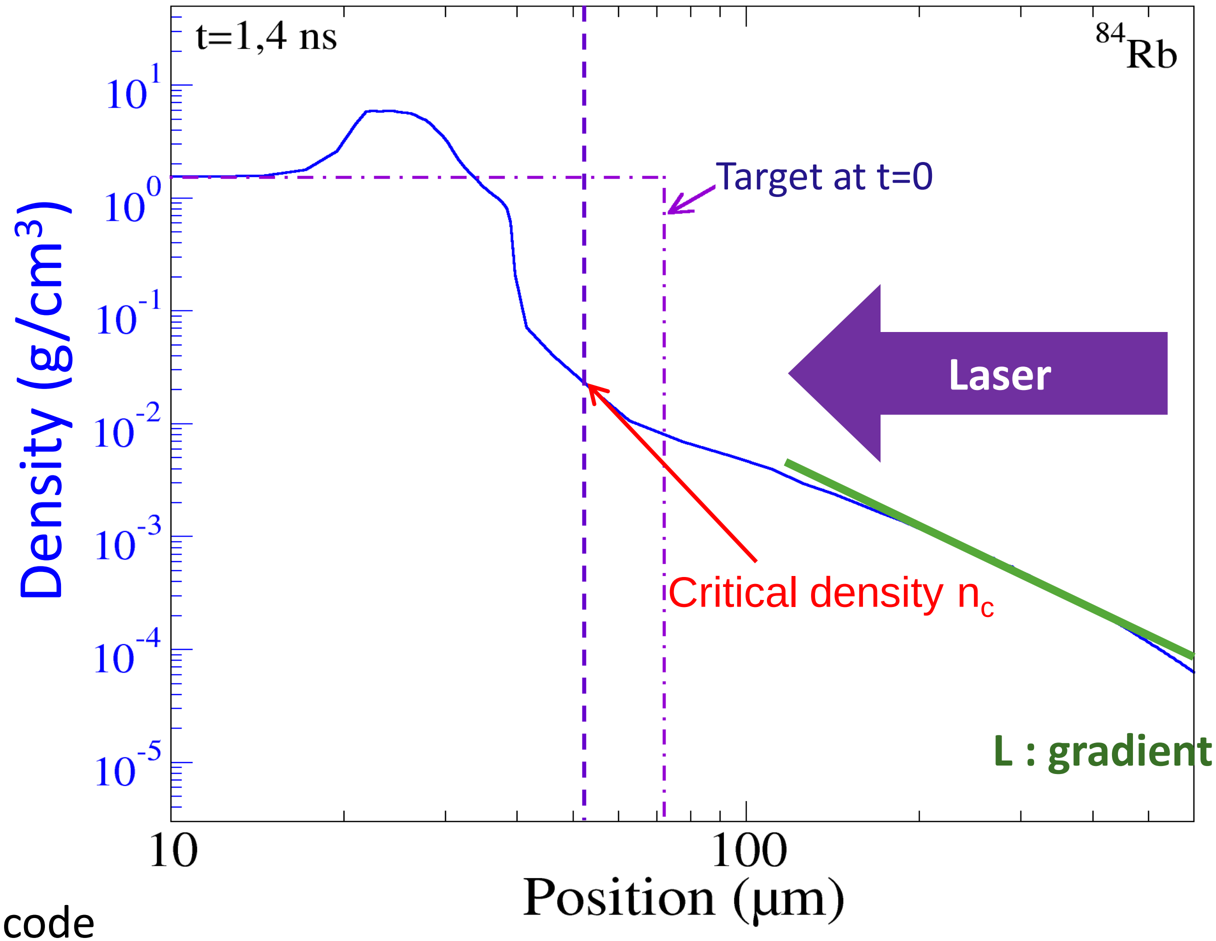
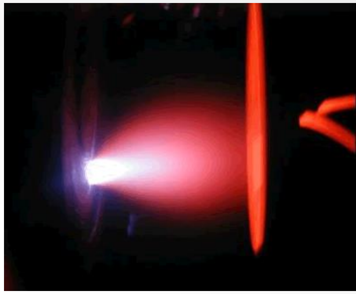


L : gradient length of pre-plasma

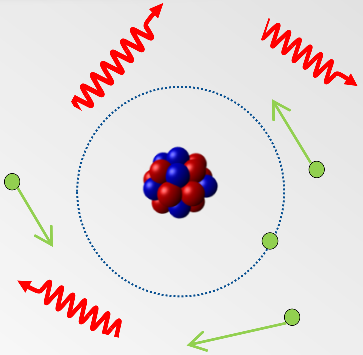


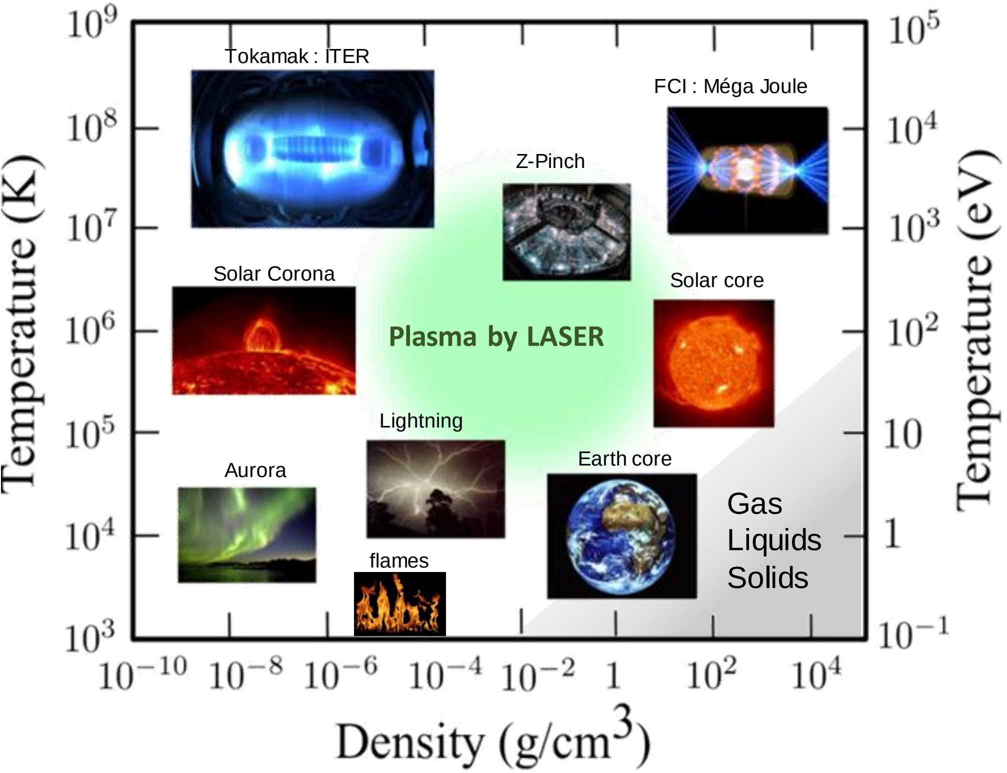
Chivas code

The high power laser pulses always interact with a plasma!

What is a plasma?

The 4th state of matter (99.9% of the visible matter)





- Multicharged ions
- Free electrons
- Photons

3 temperatures $T_é$;T_{ion} ; T_{ph}

Different models to describe the plasma :

- **Thermodynamic Equilibrium**:

$T_é = T_{ion} = T_{ph}$ (never reached)

- **Local Thermodynamic Equilibrium** :

$T_é = T_{ion} \neq T_{ph}$ (Locally reached in dense plasmas)

- **Non Local Thermodynamic Equilibrium**

$T_é \neq T_{ion} \neq T_{ph}$

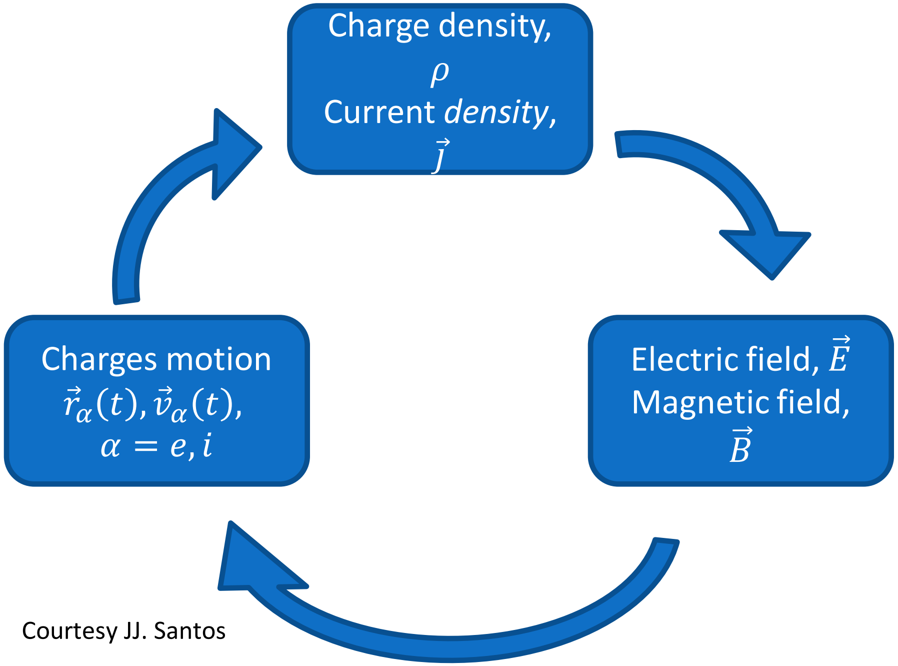
Ionization Temperature T_Z

$$\overline{Q_{NETL}}(\rho, T_e) = \overline{Q_{ETL}}(\rho, T_Z)$$

What is a plasma?

General behavior of a plasma

Plasma: a **quasi-neutral** gas of charged (electrons + ions, $n_i \approx n_e$) and neutral particles (atom less than 1% + photons) which exhibit <u>collective</u> behavior



Charge density, ρ
Current *density*, $\vec{j}$

Electric field, $\vec{E}$
Magnetic field, $\vec{B}$

Charges motion
$\vec{r}_\alpha(t), \vec{v}_\alpha(t)$,
$\alpha = e, i$

Courtesy JJ. Santos

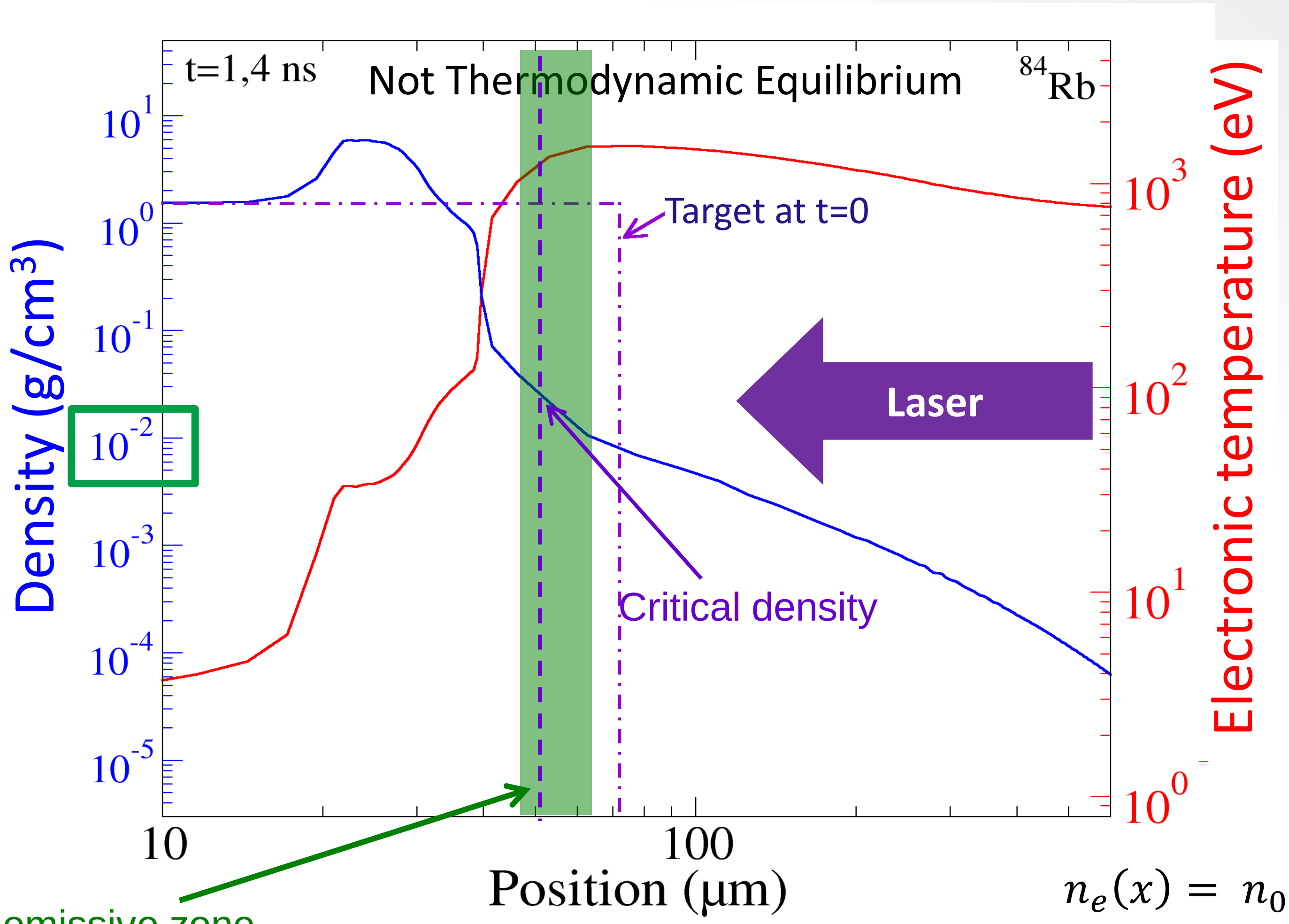
E>10^9 V/cm

B>> 100 T

- Charges move and generate local concentration of + or – charges → **E-fields**.
  Also, motion of charges generates currents → **B-fields**.
- Fields affect motion of other particles far away
  → **collective behavior**
- Particles (charges) exchange momentum and energy through collisions. System tends to converge to equilibrium (**Maxwell distributions**, thermalisation).
- $m_e \ll m_i$ → much shorter time-scale for electron dynamics. **Ions follow** by electrostatic effect on **slower time scale**.
- According to temperature, density and the time-scale, plasma dynamics are described **kinetically** (Particles-In-Cell - PIC) or as **fluids** (MagnetoHydroDynamics).

What is a plasma?

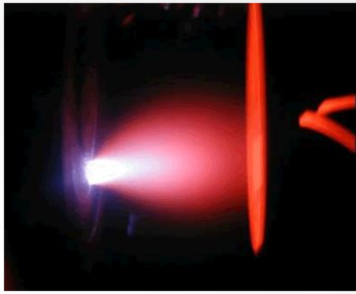
Fluid (MagnetoHydroDynamics).



Most emissive zone

$I = 10^{14}$ W/cm^2

$a_0 = 9.\,10^{-3}$

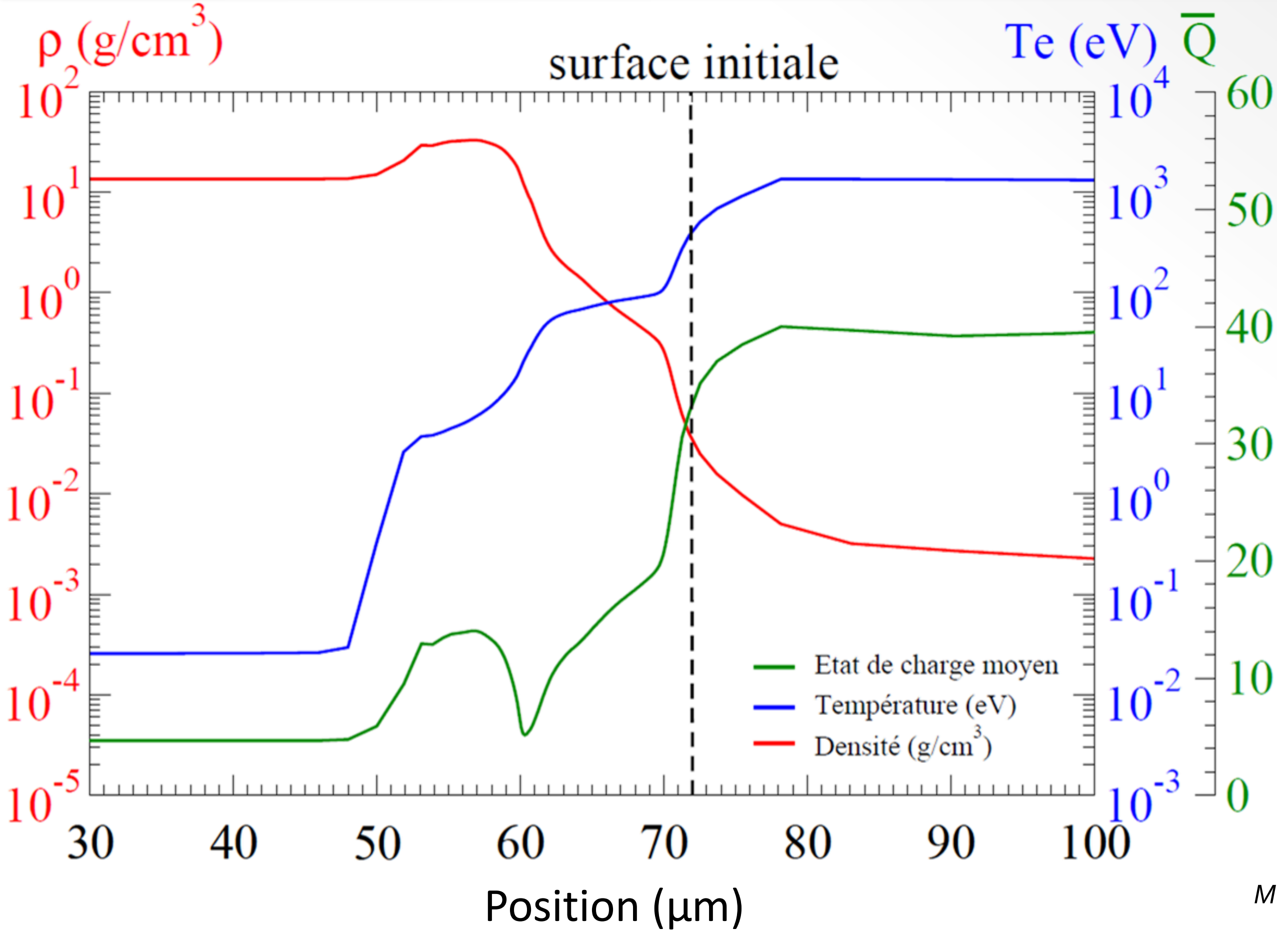


$$n_e(x) = n_0 \exp\left(-\frac{x - x_0}{L}\right)$$

Requires ns to create a dense and hot plasma

What is a plasma?

Fluid (MagnetoHydroDynamics).



$I=10^{14}$ W/cm^2

$a_0 = 9.\ 10^{-3}$

E=35J,

τ=4 ns

ϕ=100 µm

λ=1.06 µm

Target : $_{80}$Hg

Profils at the end of the laser pulse

M. Comet, thèse université de Bordeaux, 2014

- Highly mean charge states reached → lot of atomic transitions
- Multiple collisions $\Delta t \Delta E \geq h/4\pi$ → resonant phenomena are enhanced

What is a plasma?

Particles

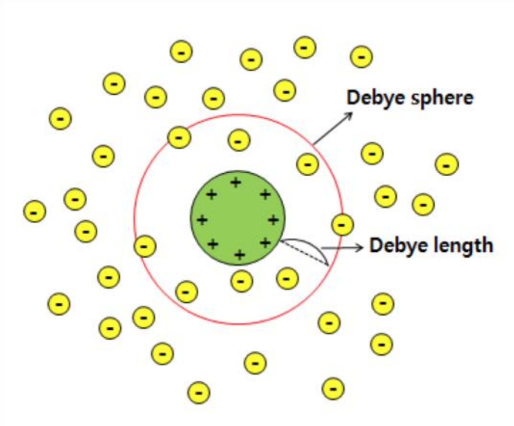
Spatial and time scales

➜ Debye length:

Spatial-scale of deviation from electric neutrality around a multicharged ion

Coulomb potential

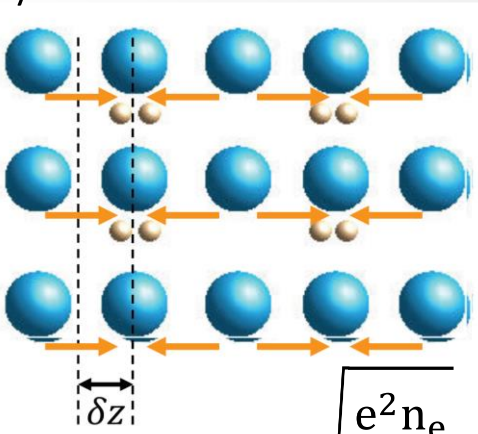
$$V(r) = \frac{Qe}{4\pi\varepsilon_0}\underbrace{e^{-\frac{r}{\lambda_D}}}_{\text{Plasma screening}}$$



$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{e^2 n_e}}$$

➜ Plasma pulsation frequency:

(inverse of) time-scale of deviation from electric neutrality



$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}}$$

➜ Critical density n_c :

If electrons oscillate faster than the laser, it can not propagate inside : $\omega p_e > \omega_L$

$$n_c = \varepsilon_0\, me\, \frac{\omega_L^2}{e^2}$$

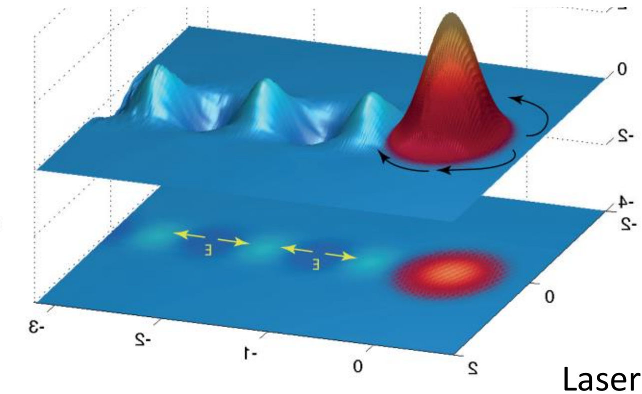
In relativist regime : $n_{c\text{-rel}} = \gamma\, n_c$

For PICO2000 λ_L = 1052 nm ,
$n_c = \gamma\, 10^{21}$ e/cm^3

Laser / plasma interaction

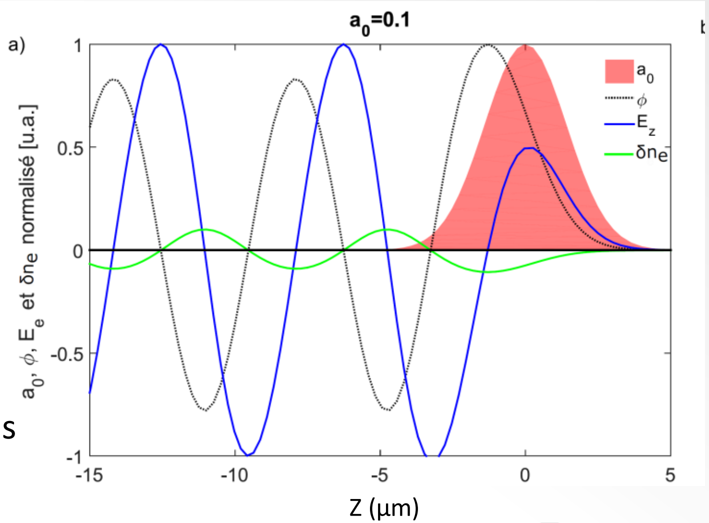
Particles In Cell

Lasers do not move ions significantly, but they move electrons (ions too heavy)



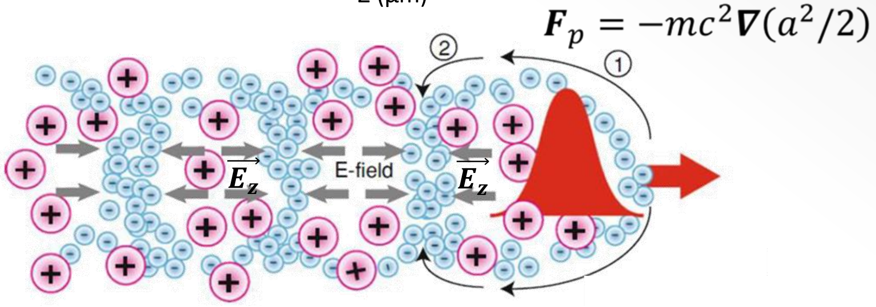
$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}}$$

Laser-induced plasma waves



Phase velocity : $v_{pe} = \sqrt{1 - \frac{\omega_{pe}^2}{\omega_L^2}}\, c$

Plasma waelength: $\lambda_{pe} = v_{pe} \frac{2\pi}{\omega_{pe}}$



PICO2000 : λ_L = 1052 nm in a plasma density of 10^{19} e^-/cm^3.
→ v_{pe} = 99.5% ×c
→ $\lambda_{pe} \approx$ 10.50 µm

Part 2

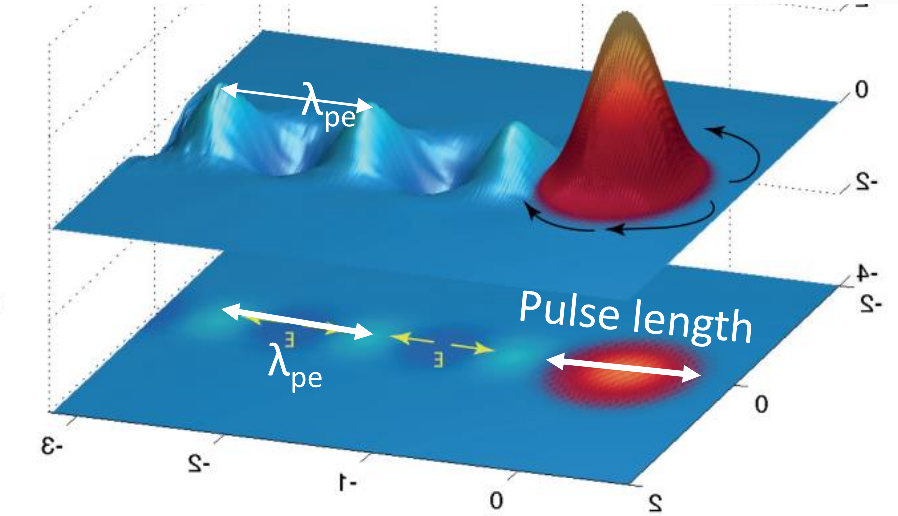
LASER-PLASMA ACCELERATION

- Electrons
- Photons
- Ions
- Neutrons

Electron source

Particles In Cell

Lasers do not move ions significantly, but they move electrons (ions too heavy)



$$\omega_{\mathrm{pe}} = \sqrt{\frac{\mathrm{e}^2 \mathrm{n_e}}{\epsilon_0 \mathrm{m_e}}}$$

$$v_{pe} = \sqrt{1 - \frac{\omega_{pe}^2}{\omega_L^2}}\, c$$

$$\lambda_{pe} = v_{pe} \frac{2\pi}{\omega_{pe}}$$

LULI-PICO2000 : λ_L = 1052 nm ; Δt = 1ps in a plasma density of 10^{19} e^-/cm^3.

→ v_{pe} = 99.50% ×c

→ λ_{pe} ≈ 10.5 µm → Pulse length = 298 µm

LULI-APOLLON : λ_L = 840 nm ; Δt = 30 fs in a plasma density of 10^{19} e^-/cm^3.

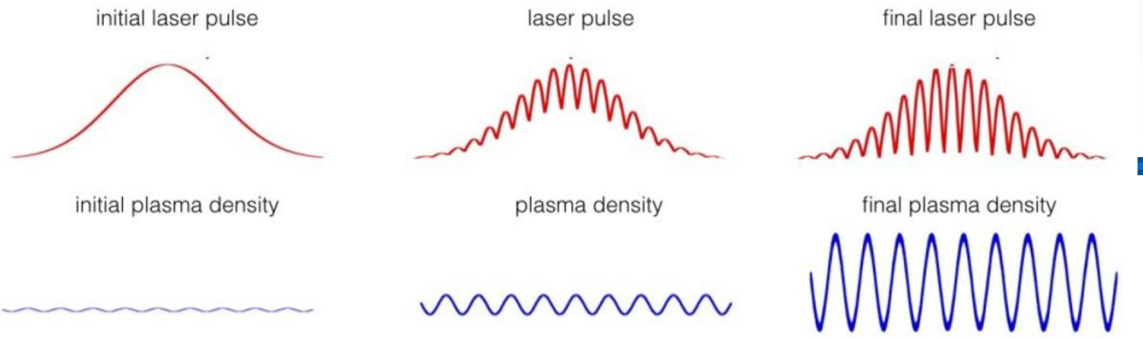
→ v_{pe} = 99.68% ×c

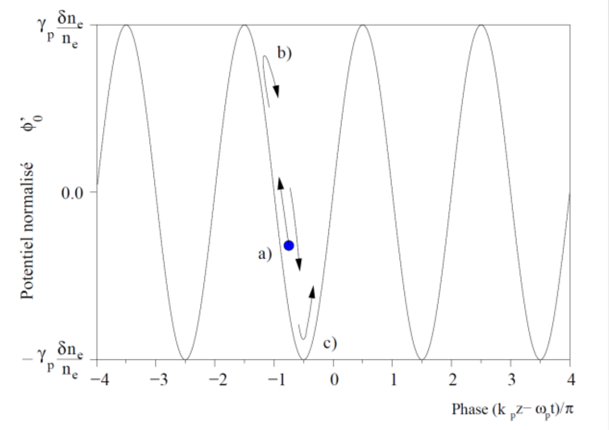
→ λ_{pe} ≈ 11 µm → Pulse length = 9 µm

Electron source

Long pulse compared to λ_{pe}

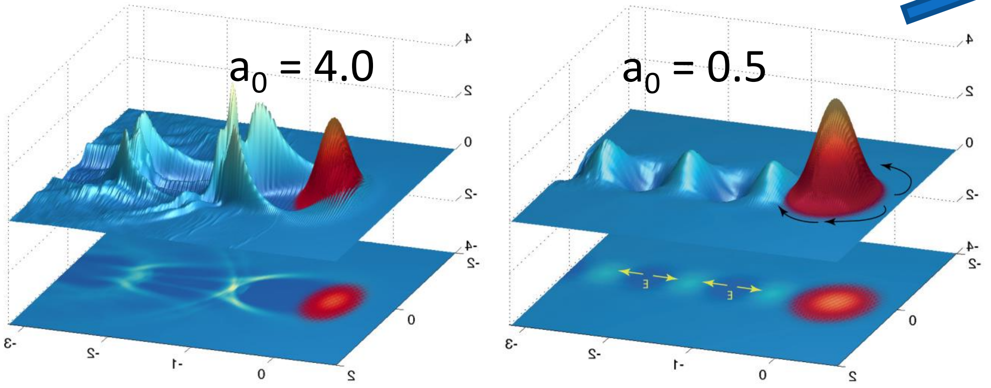
Self Modulated Laser Wake Field Acceleration process – SMLWFA



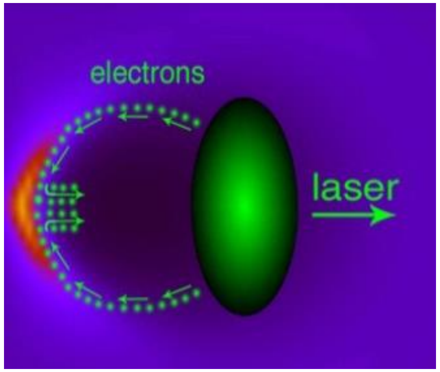


Maxwellian energy distribution

short pulse compared to λ_{pe}

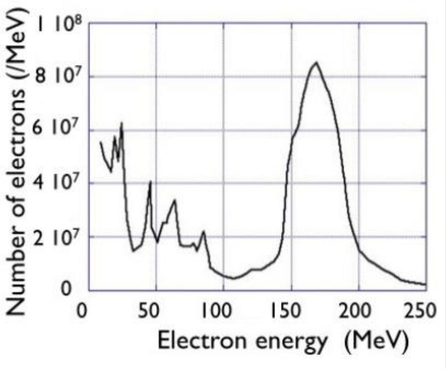


Bubble regime



peaked energy distribution

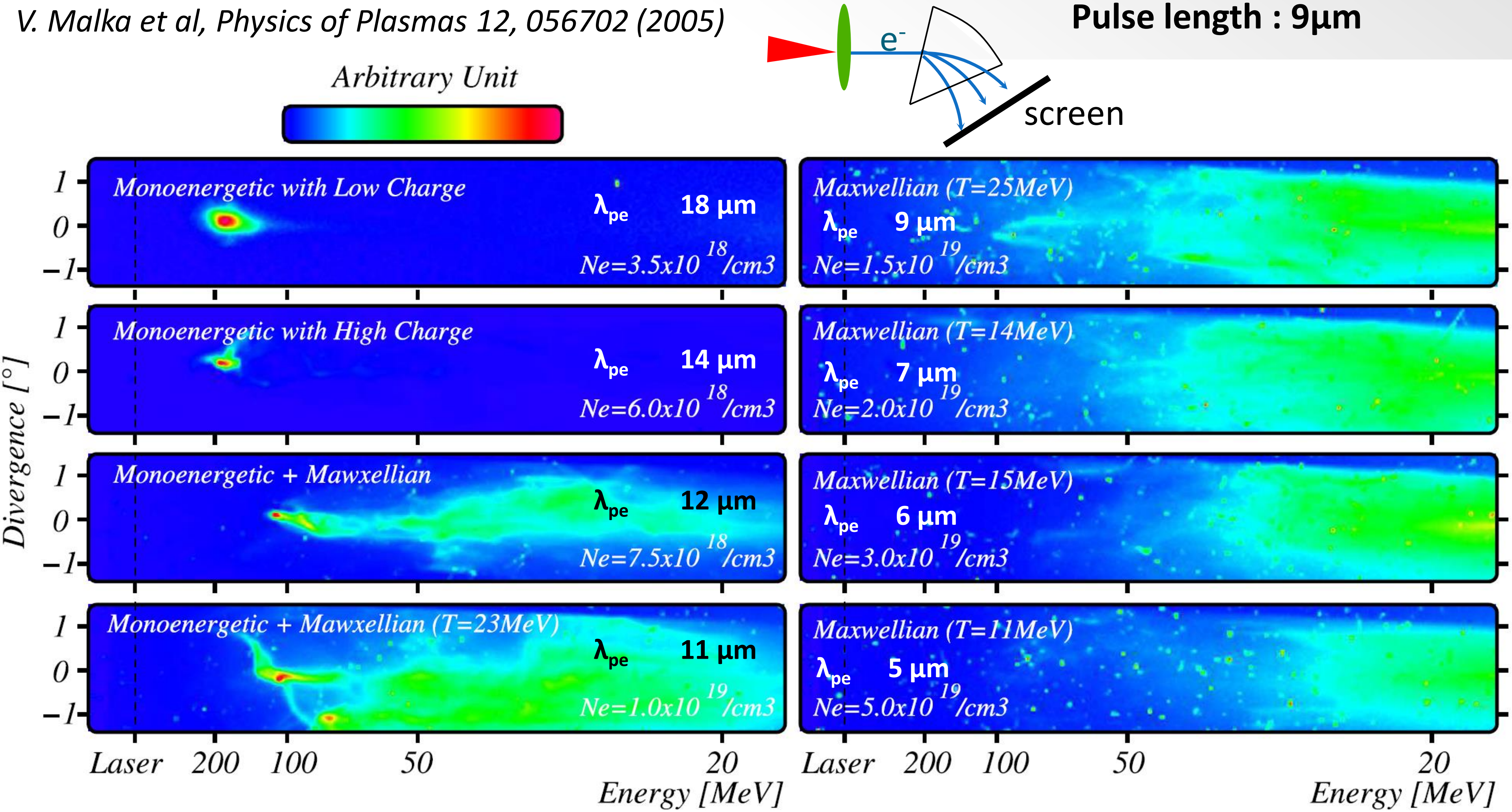
Electron source



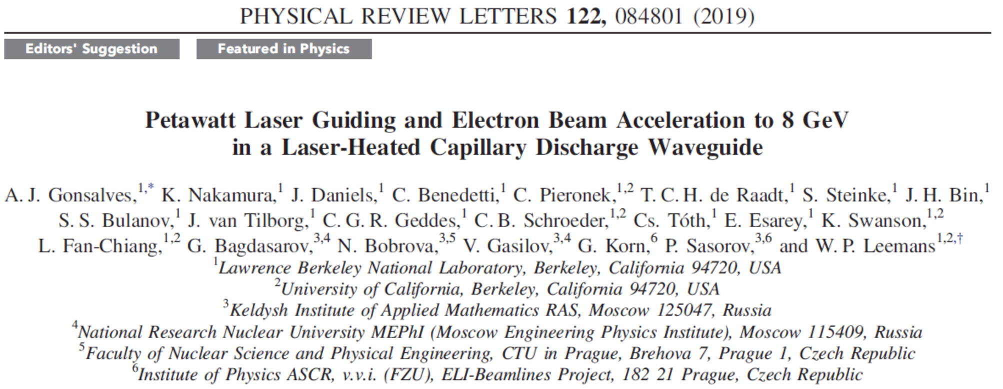
LOA « Salle Jaune » : Ti :Saphir λ_L = 820 nm, Δt=30 fs a_0 = 1.3

V. Malka et al, Physics of Plasmas 12, 056702 (2005)

Pulse length : 9µm



Electron source



PHYSICAL REVIEW LETTERS **122,** 084801 (2019)

Editors' Suggestion **Featured in Physics**

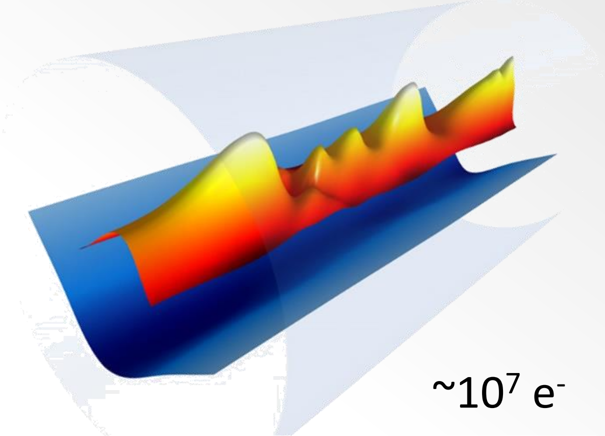
Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide

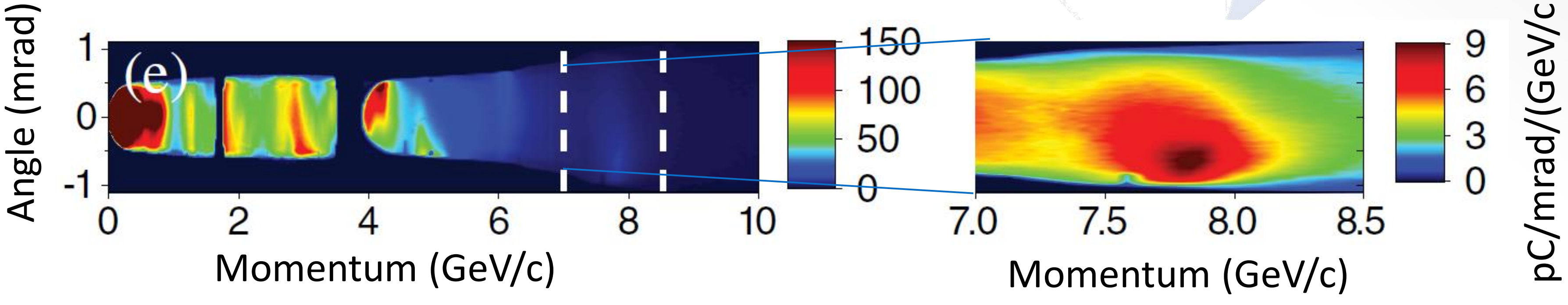
A. J. Gonsalves,[1,*] K. Nakamura,[1] J. Daniels,[1] C. Benedetti,[1] C. Pieronek,[1,2] T. C. H. de Raadt,[1] S. Steinke,[1] J. H. Bin,[1] S. S. Bulanov,[1] J. van Tilborg,[1] C. G. R. Geddes,[1] C. B. Schroeder,[1,2] Cs. Tóth,[1] E. Esarey,[1] K. Swanson,[1,2] L. Fan-Chiang,[1,2] G. Bagdasarov,[3,4] N. Bobrova,[3,5] V. Gasilov,[3,4] G. Korn,[6] P. Sasorov,[3,6] and W. P. Leemans[1,2,†]

[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*University of California, Berkeley, California 94720, USA*
[3]*Keldysh Institute of Applied Mathematics RAS, Moscow 125047, Russia*
[4]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow 115409, Russia*
[5]*Faculty of Nuclear Science and Physical Engineering, CTU in Prague, Brehova 7, Prague 1, Czech Republic*
[6]*Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project, 182 21 Prague, Czech Republic*

Bella PW laser : E_L = 31 J ; Δt = 35 fs

In 20 cm capillary n_e = 3 .10^{17} /cm^3



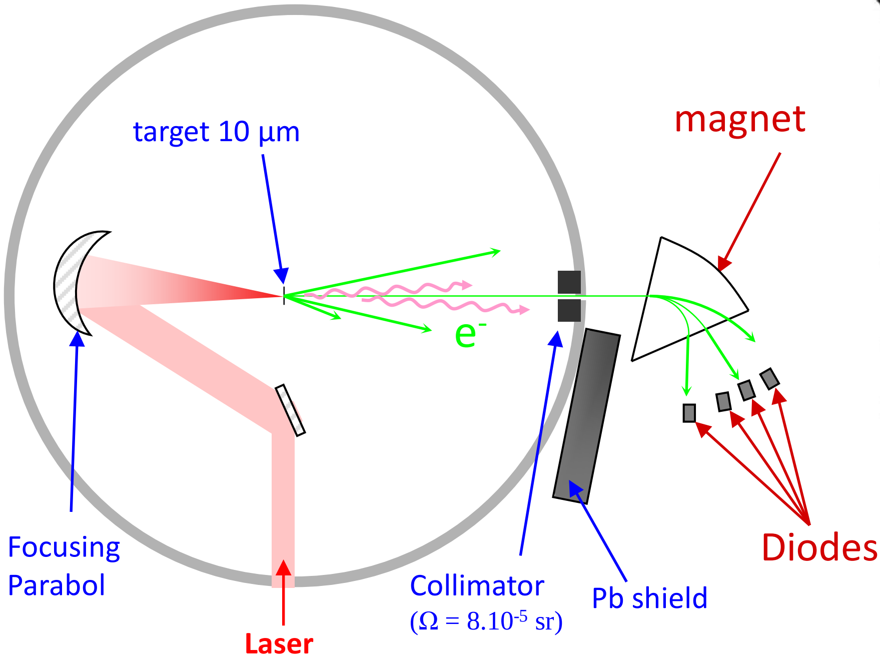


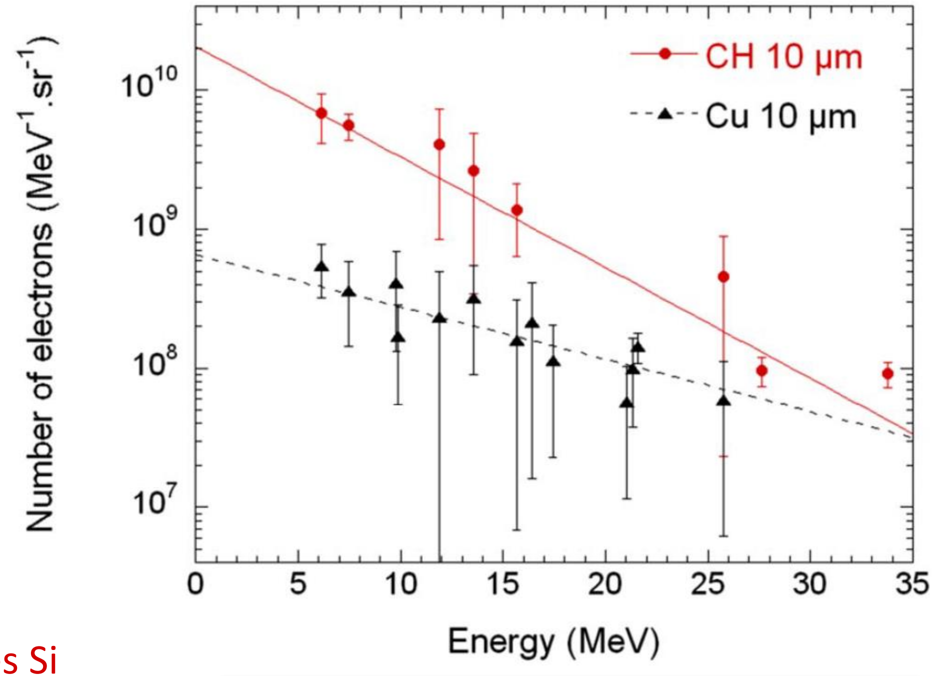
~10^7 e^-

For nuclear reactions, we need tens of MeV electrons in huge quantity for bremsstrahlung

Electron source from solid targets

Laser	Energy (Joules)	pulse duration (fs)	power (TW)	focal (µm)	rate (Hz)	Intensity (W/cm²)
LOA salle jaune	1	30	33	25	10	7,E+18





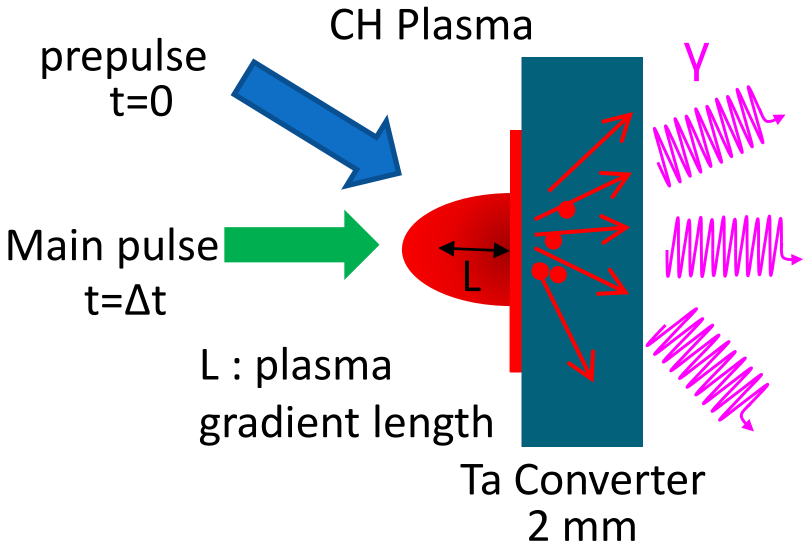
$\Omega = 8.10^{-5}$ sr

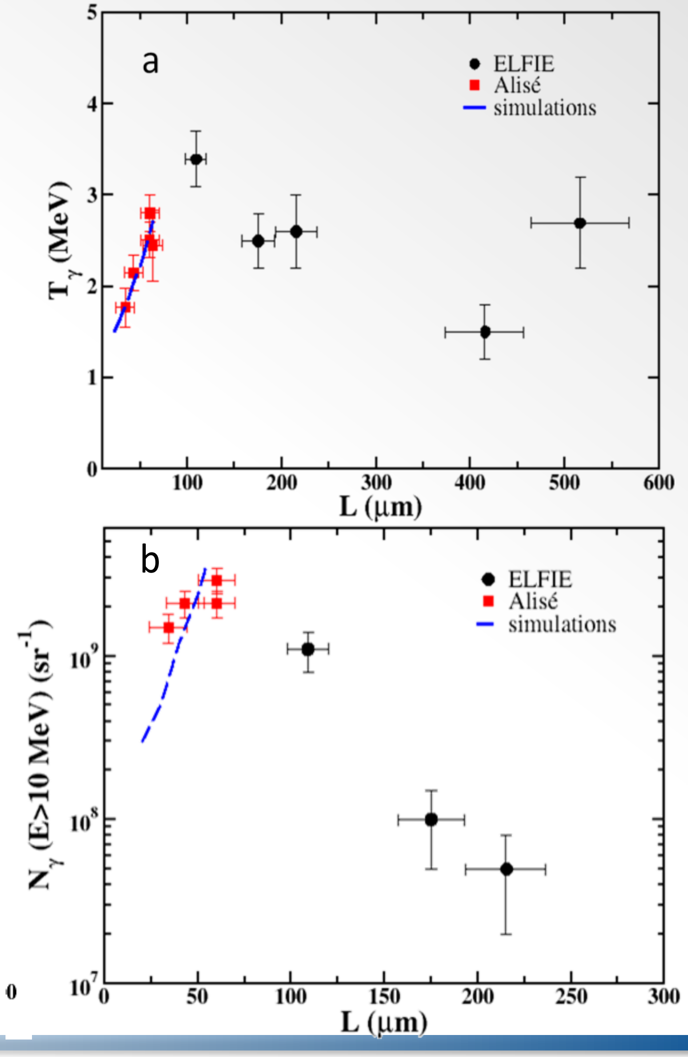
10 µm target	Temperature (MeV)
CH	5.9 ± 0.8
Cu	10 ± 2

M. Gerbaux et al,, Journal de Physique IV France,133,1139-1141 (2006)

Bremsstrahlung source

Laser	Energy (Joules)	Pulse duration(ps)	power (TW)	focal (µm)	rate (1/min)	Intensity (W/cm²)
Pre-pulse	40	600	0,07	160	1/20	3,3E+14
Main pulse	7	0,4	17,5	17	1/20	8.E+18

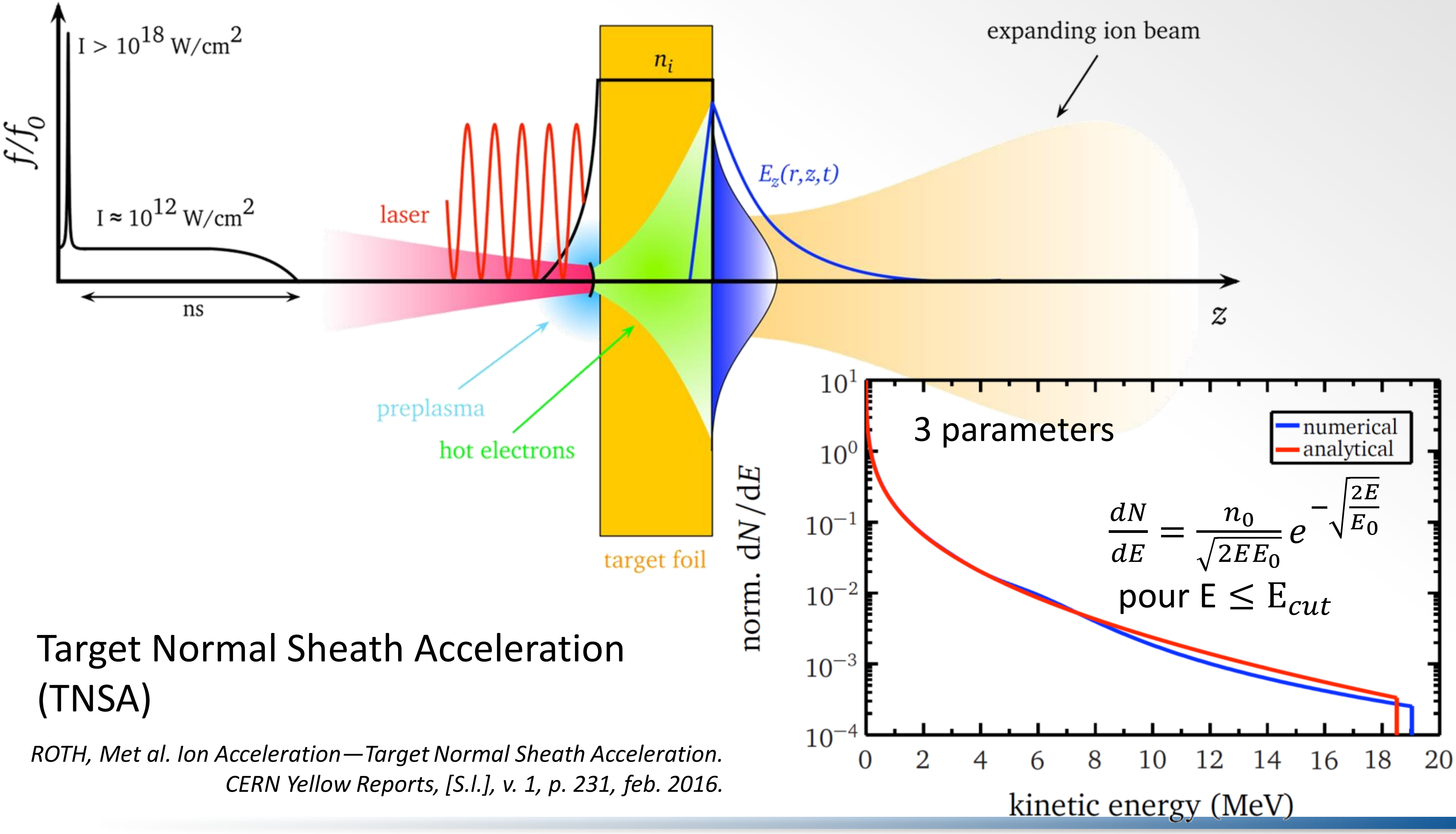




Photon source optimal (number and temperature)
L ≈ 100 µm

C.Courtois et al., Physics of Plasmas 16, 013105(2009)

Laser driven ion source with solid targets



3 parameters

$$\frac{dN}{dE} = \frac{n_0}{\sqrt{2EE_0}}\, e^{-\sqrt{\frac{2E}{E_0}}}$$

pour E $\leq E_{cut}$

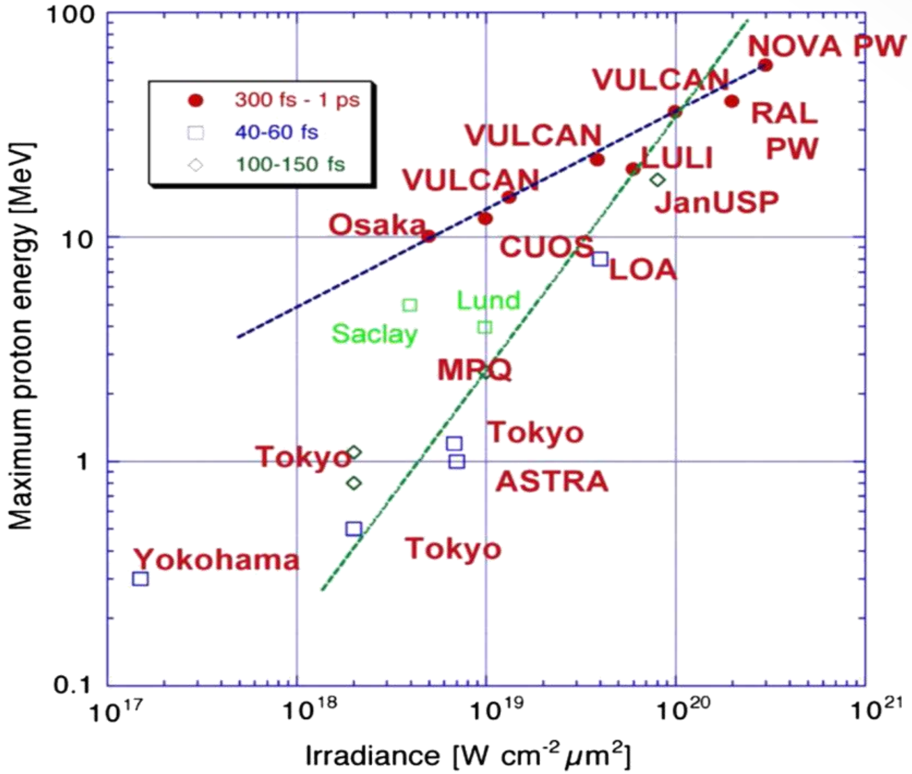
Target Normal Sheath Acceleration (TNSA)

ROTH, Met al. Ion Acceleration—Target Normal Sheath Acceleration. CERN Yellow Reports, [S.l.], v. 1, p. 231, feb. 2016.

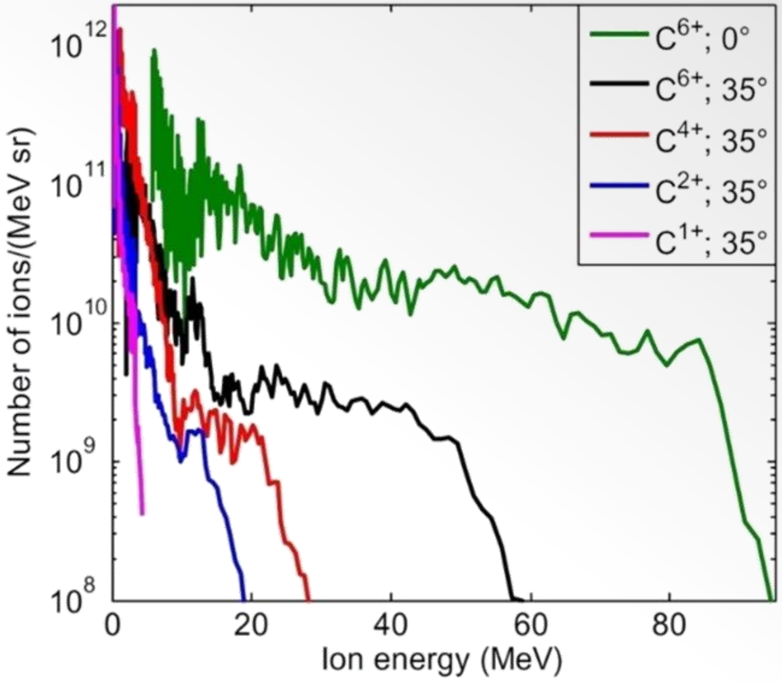
Laser driven ion source

with solid targets

Laser accelerated protons overview



Macchi et al. Rev. Mod. Phys, ***85****, 751 (2013)*



Carroll, D. C et al.,New Journal of Physics **12** (2010) 045020 (15pp)

Astra-Gemini Laser : 115 TW ; 6 J ; 50 fs

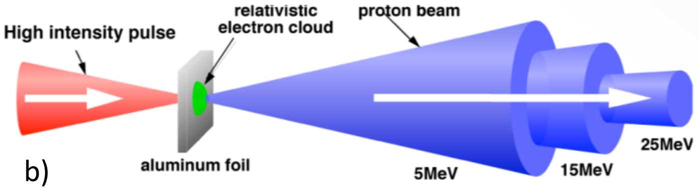
=>7×10^{20}Wcm^{-2}

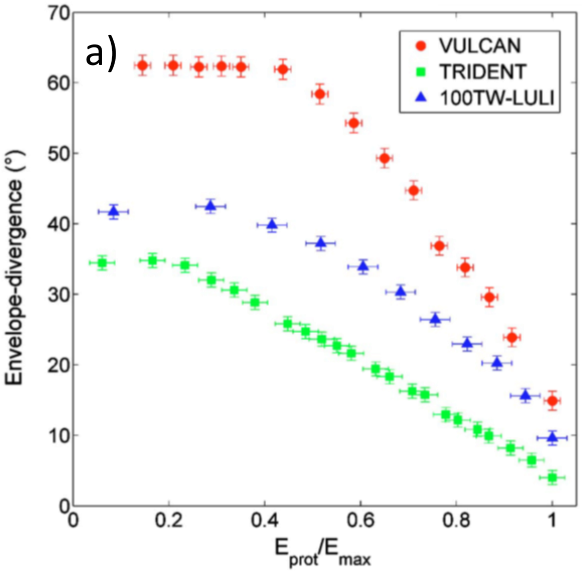
TNSA

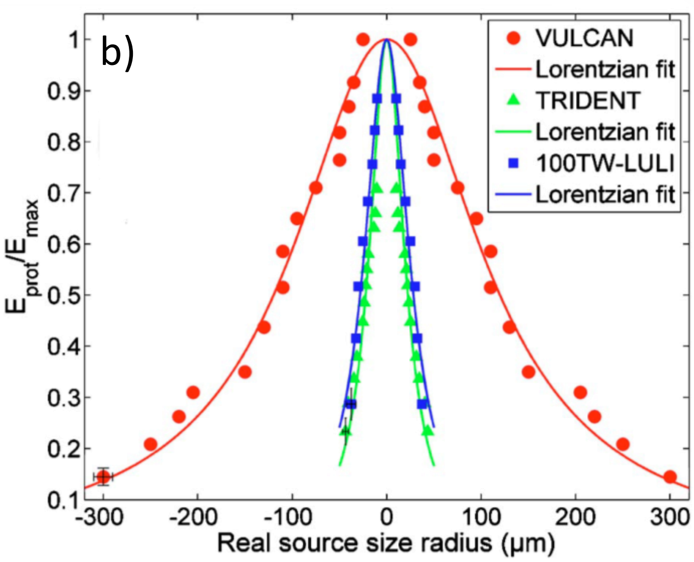
Laser driven ion source

with solid targets

Laser	Energy (J)	duration (fs)	Focal spot (µm)	Gold Target thickness (µm)	E_{max} (MeV) (cut-off)	ϕ (µm) source diameter @E_{max}
Vulcan	125	1000	5	25	17.4	80
Trident	19	600	14	10	13.5	20
100 TW-Luli	15	350	8	50	13.3	20







Good emittance for injectors in conventional accelerators

F. Nürnberg et al., Rev.Sci.Instrum, 80, 033301 (2009)

TNSA well known, reliable, suitable energies BUT not compatible with new generation of lasers

Laser driven ion source with gas jet targets

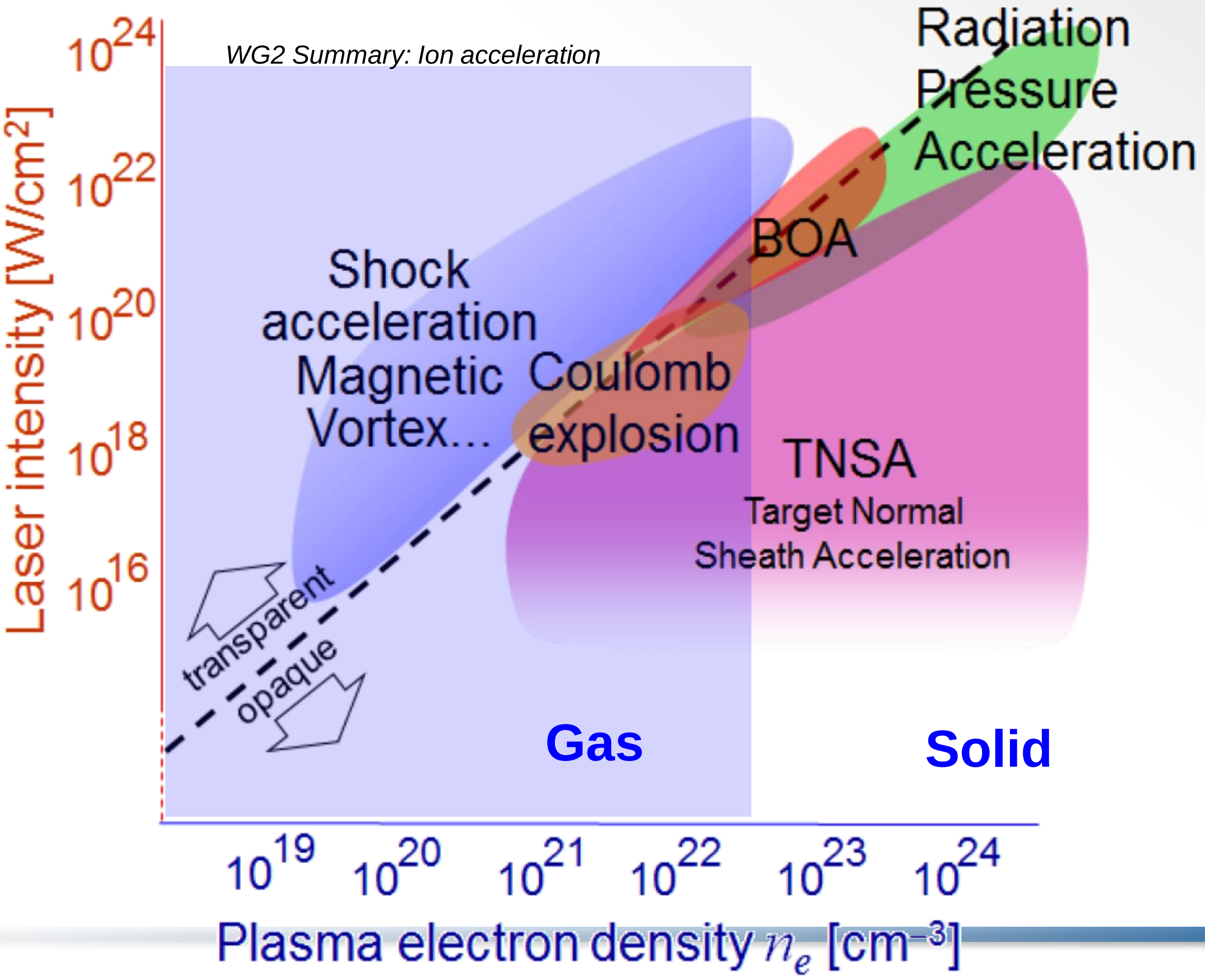
Because of high-repetition rate lasers (0,01-10 Hz)

Cilex Apollon	CLPU CENTRO DE LÁSERES PULSADOS	eli extreme light infrastructure
10 PW every minute	1 PW every second	1 PW every 0.1 second

- ✓ Target regeneration and alignment
- ✓ Less debris production (25 weeks of pico 2000 ≈ 2 min ELI-BL HAPLS@10Hz)
- ✓ Repeatability shot to shot
- ✓ Easy access to different ions
- ✓ Promote acceleration processes for high energies, high flux of ions and no maxwell distribution of energy

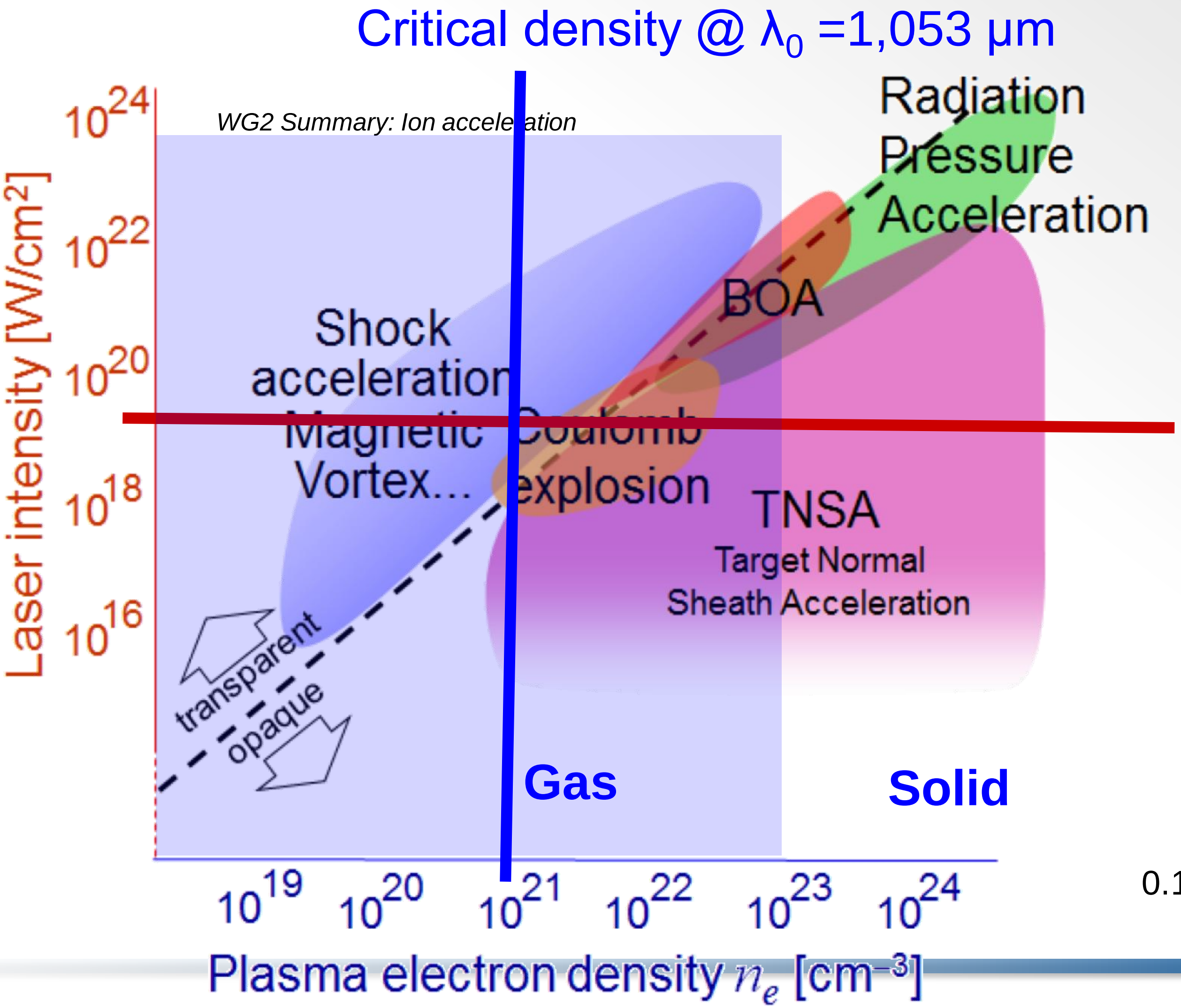
Laser driven ion source with gas jet targets

Ion acceleration processes



Laser driven ion source with gas jet targets

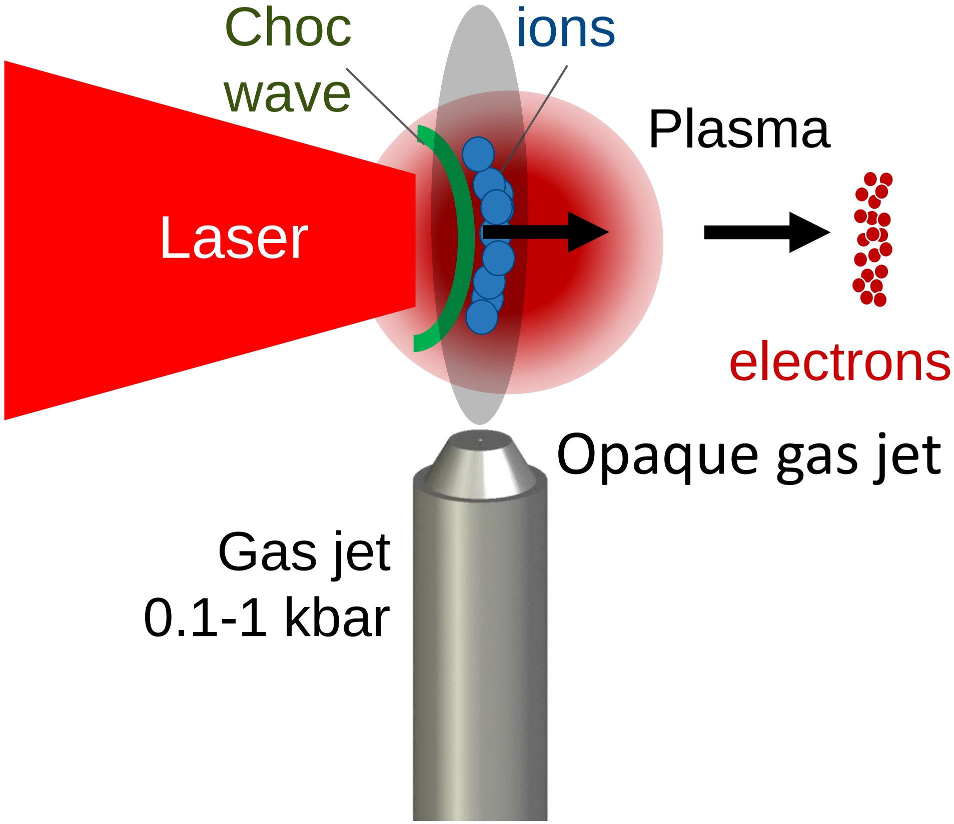
Laser PICO2000 :
50J ; 1ps ;
5.10^{19} W/cm²
λ_0 =1,053 µm



Gas jet
target
0.1-1 kbar

Laser driven ion source with gas jet targets

Collisionless Shock Acceleration (CSA)



Choc wave

ions

Plasma

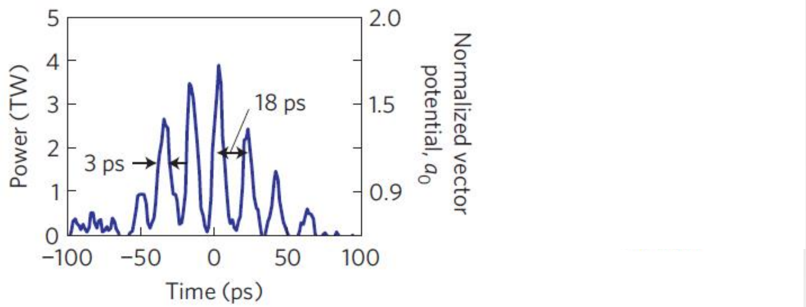
Laser

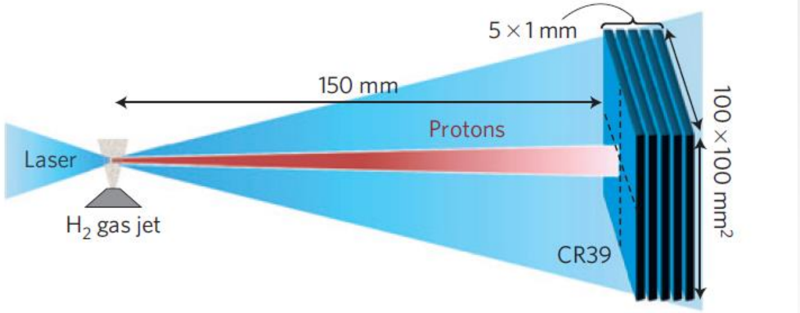
electrons

Opaque gas jet

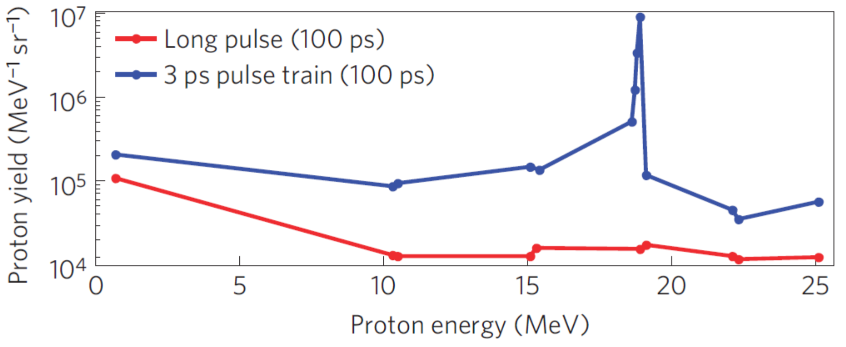
Gas jet
0.1-1 kbar

CC

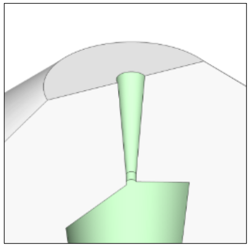


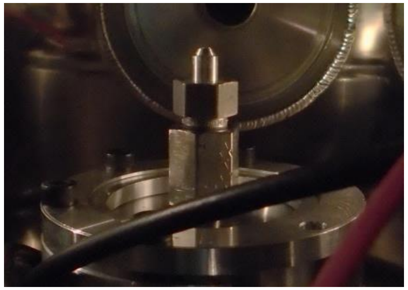


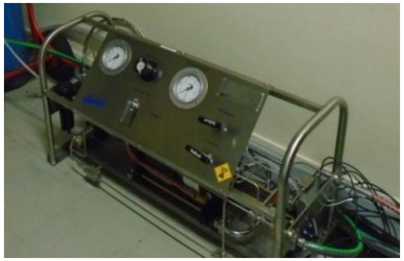
Dan Haberberger et al., Nature Physics, Vol8, 95-99 (2012)



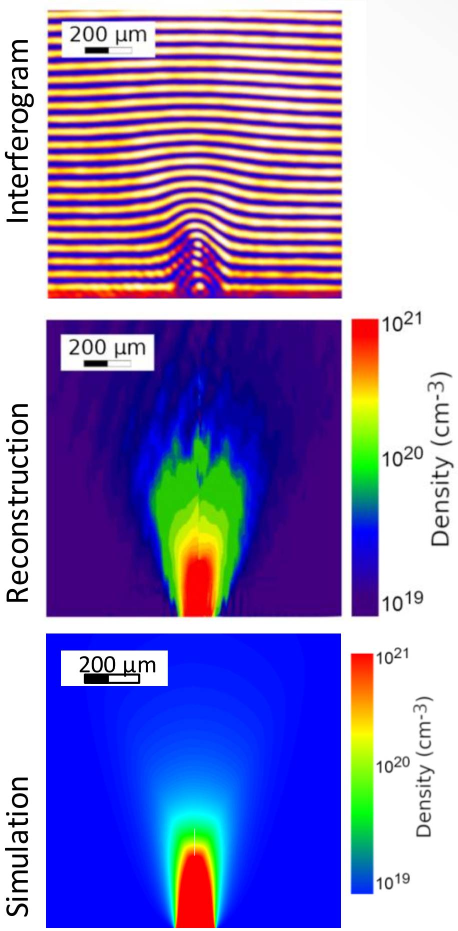
Laser driven ion source with gas jet targets

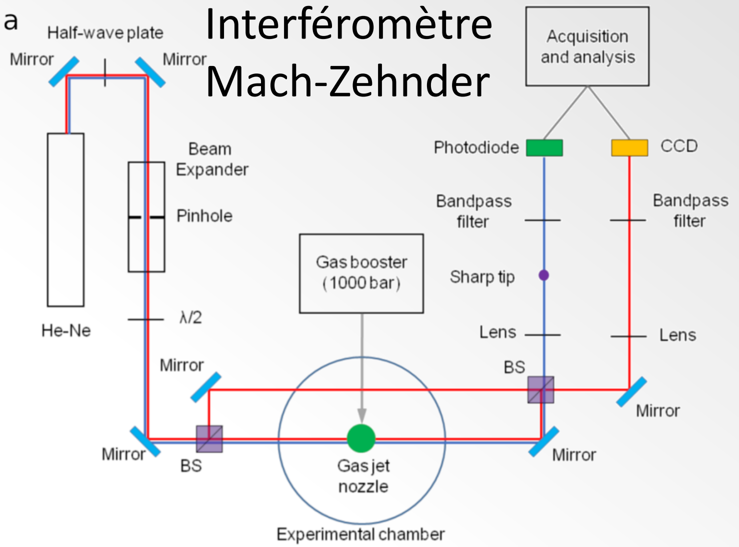




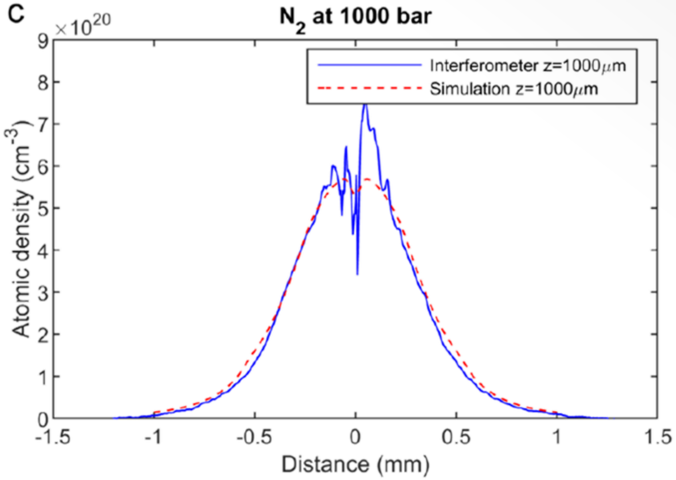


ANSYS FLUENT





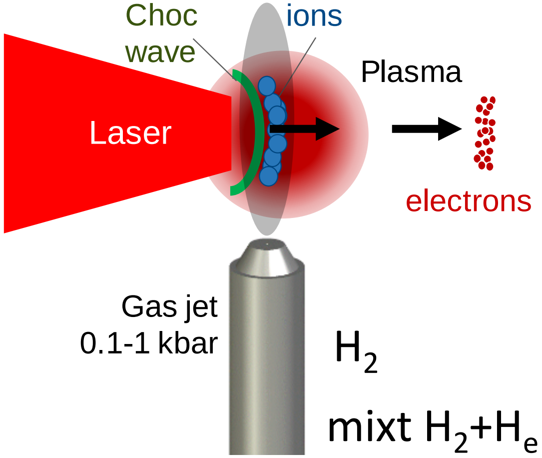
Interféromètre Mach-Zehnder



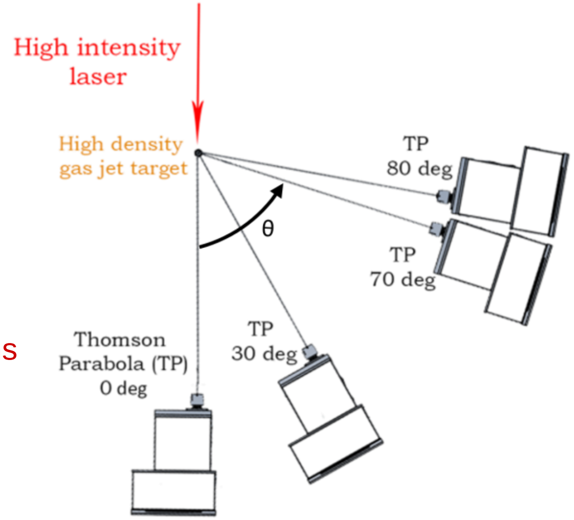
J.L. Henares, et al. Rev. Sci. Instrum. 90, 063302 (2019)
J L Henares, J. Phys. : Conf. Ser. 1079 012004 (2018)

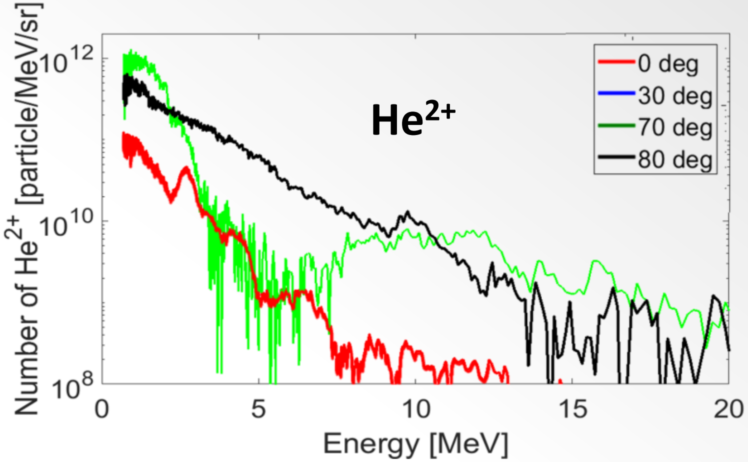
Laser driven ion source with gas jet targets

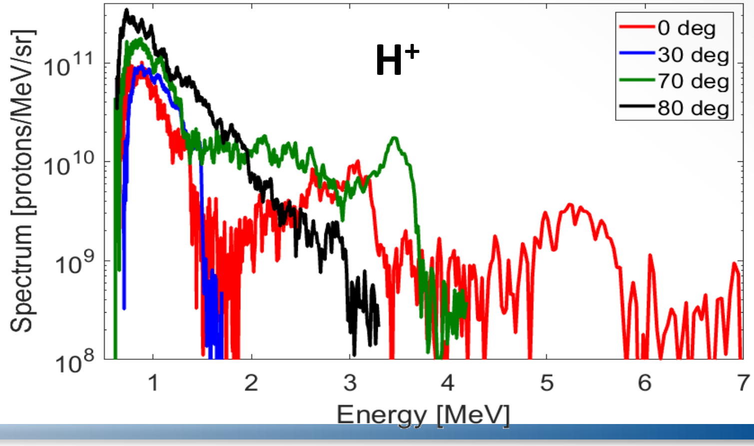
Laser	Energie (Joules)	Durée du pulse (ps)	Puissance (TW)	focal (µm)	Intensité (W/cm²)
PICO 2000	60	1	60	13	5E+19



CSA :
Collisionless Shock Acceleration



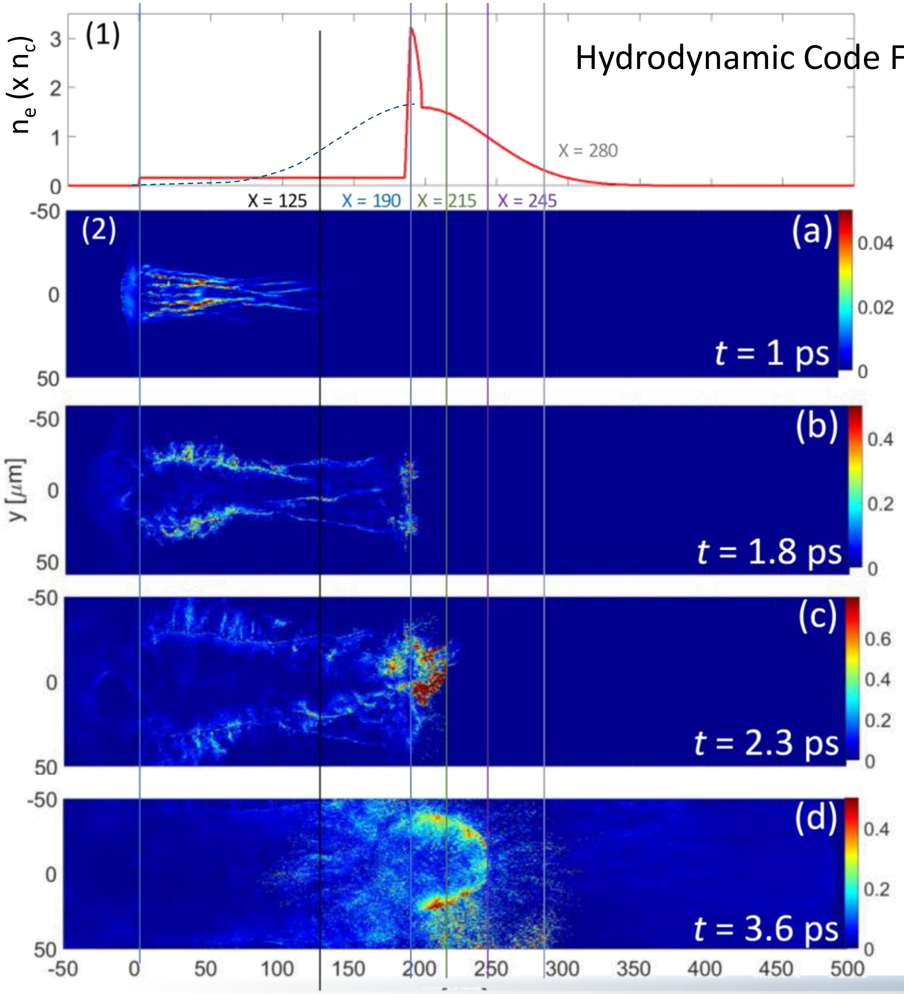




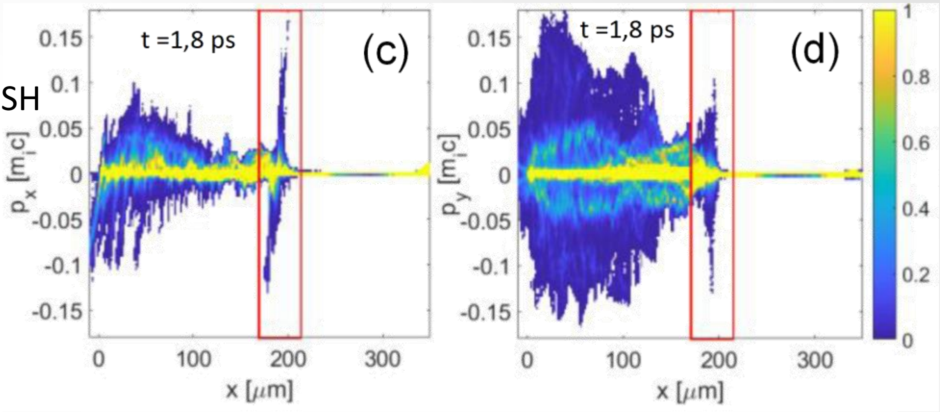
P. Puyuelo-Valdes, Proc. SPIE 11037, Laser Acceleration of Electrons, Protons, and Ions V, 110370B (2019)
P. Puyuelo-Valdes, soumis à Phys. Of Plasma (2019)

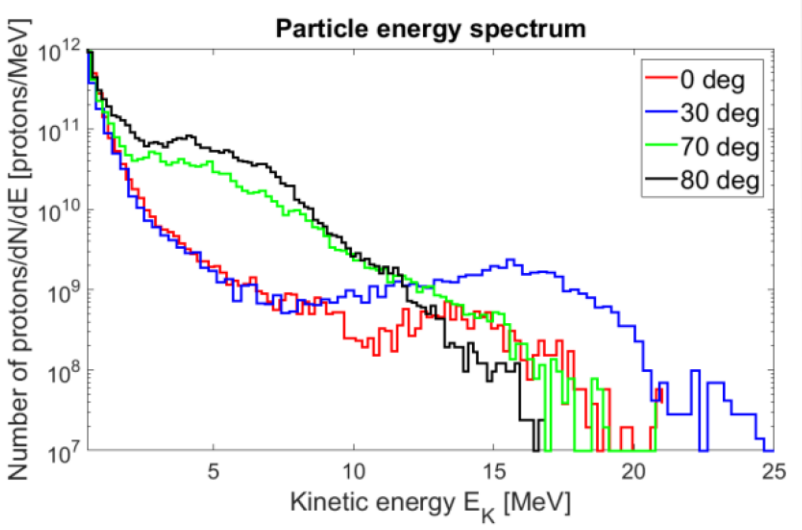
Laser driven ion source with gas jet targets

Code Particle In Cell : PICLS



Hydrodynamic Code FLASH

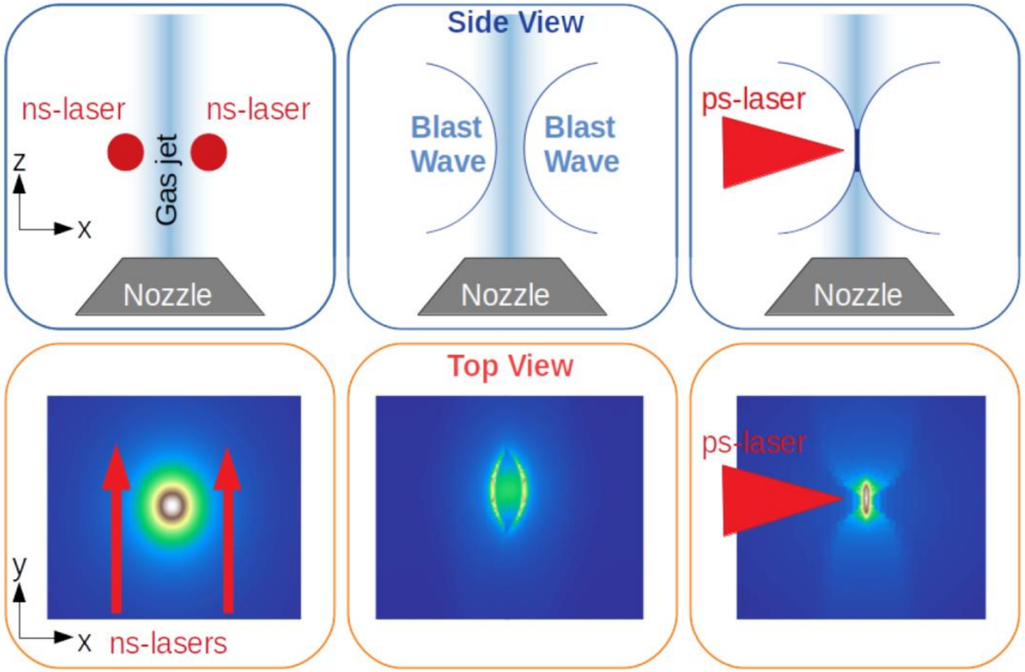




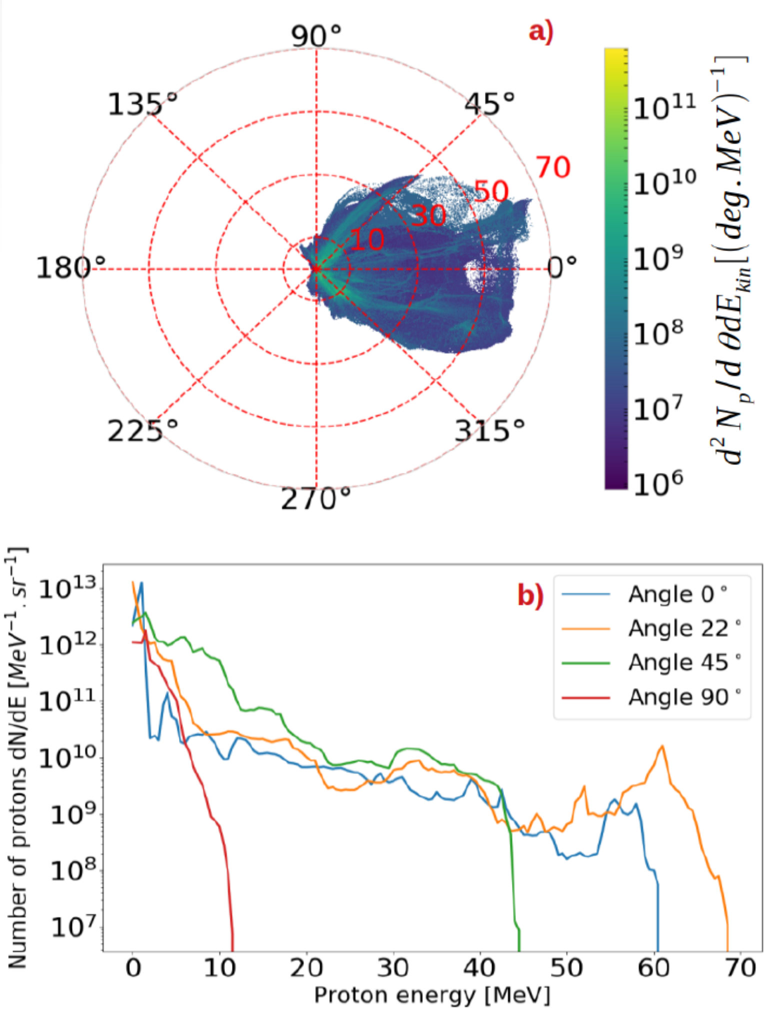
Hole Boring involved but no CSA

Laser driven ion source with gas jet targets

To promote the CSA process … the **Plasma Tailoring**



- Experiment at GSI in November 2020 : structuresof energy distribution confirmed, but energy around 1 – 2 MeV



J.-R. Marques, et al. , Phys Plasma, 28, issue 2, (février 2021)

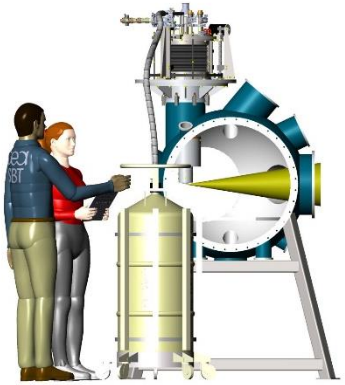
J.Bonalet et al., accepted to Phys Plasma (2021)

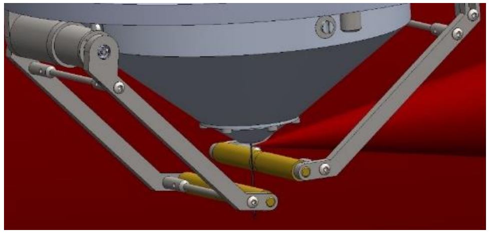
Laser driven ion source with other targets

- TNSA on cryogenic target

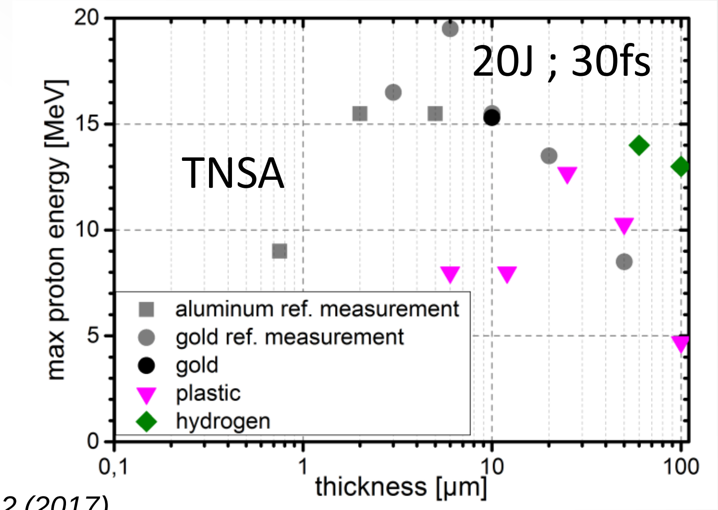
"First demonstration of multi-MeV proton acceleration from a cryogenic hydrogen ribbon target » Plasma Phys. Control. Fusion 60 (2018) 044010 (6pp)

Ribbon 1mm x 100µm



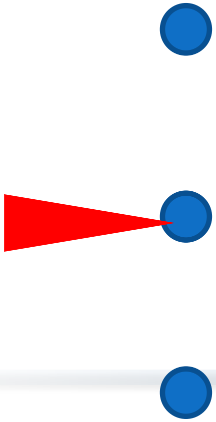


Courtesy F.Souris ; D-SBT - CEA/Université Grenoble Alpes



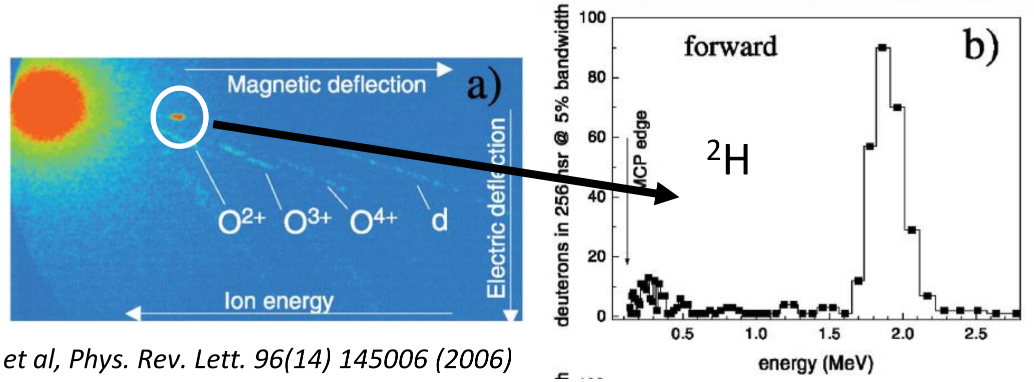
- Liquid targets *M. Gauthier, et al. Appl. Phys. Lett. 111, 114102 (2017)*

Liquid H2 jet



20 µm droplet of heavy water

750 mJ ; 40 ; 10^{19} W/cm² ; 10 Hz



S. Ter-Avetisyan et al, Phys. Rev. Lett. 96(14) 145006 (2006)

Indirect Laser driven neutron source

Secondary source, the same as conventional accelerators

- **Laser accelerated Ions (protons, deutons) impinging a converter (Li; ^{2}H; ^{3}H …)**
- Bramsstrahlung radiation impinging a converter
- 2 GeV impinging a spallation target (not yet relevant)

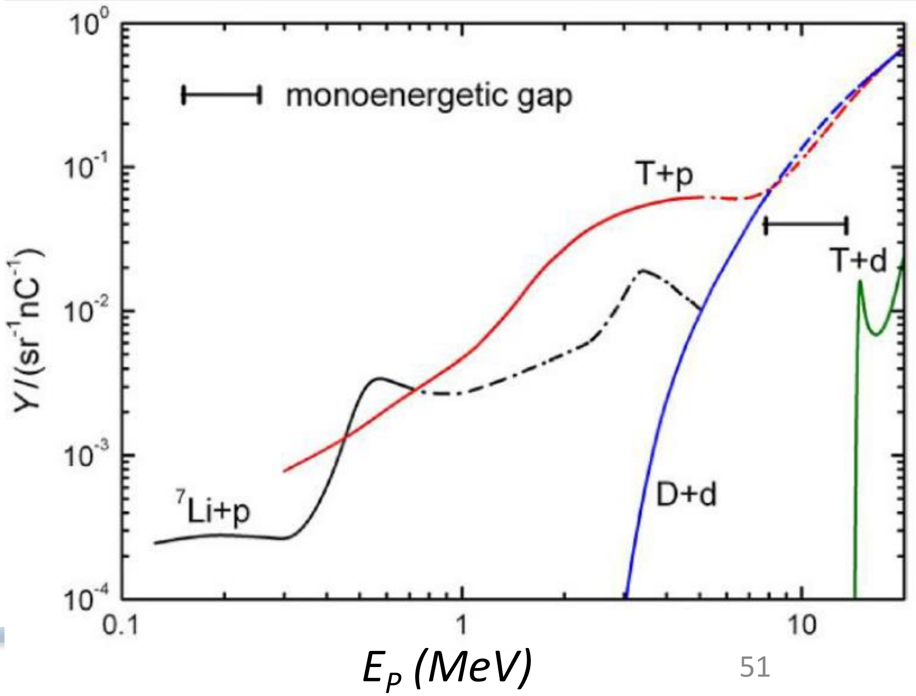
A.R. Junghans, EJC "Neutrons and Nuclei », https://ejc2014.sciencesconf.org (2014)

Reaction	Neutron Energy (MeV)
$p+^7Li \rightarrow n+^7Be$	[0.121 - 0.649]
$p+T \rightarrow n+^3He$	[0.6 - 2.6]
$d+D \rightarrow n+^3He$	$2.45 + f(E_{projectile})$
$d+T \rightarrow n+^4He$	$\sim 14.1 + g(E_{projectile})$

Neutron energy depends on the emission angle

Require :

- a well define projectile beam axis
- A mono energetic projectile



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- Bramsstrahlung radiation impinging a converter
- 2 GeV impinging a spallation target (not yet relevant)

	Laser	Acceleration process	Neutron production reaction	Number of neutrons/ shot	Neutron energies
A	Vulcan : 200J, 3×10^{20} W/cm²	TNSA : CD 10 µm	CD 2 mm : D(p,n+p)^{1}H ; D(d,n)^{3}He	10^{9} /sr	[0-25] MeV
B	Trident : 60 J, 600 fs ; 10^{21} W/cm²	BOA : CD 400 nm	Be ~ mm : Deuteron break-up, ^{9}Be(p,n)^{9}B, ^{9}Be(d,n)^{10}B	1.2×10^{10} /sr	[10-150] MeV
C	Elfie : 10 J, 350 fs ; 1.1×10^{19} W/cm²	TNSA : CH 50 µm on 14 nm Al	LiF 2mm : ^{7}Li(p,n)^{7}Be ; ^{6}Li(p,n)^{6}Be ; ^{19}F(p,n)^{19}Ne ;	~1×10^{4} /sr	[0.1-4] MeV

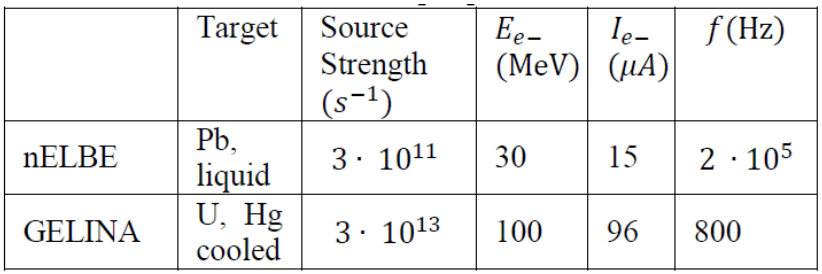
A) *S. Kar et al, New J. Phys. 18 053002, (2016)*
B) *M. Roth et al, Journal of Physics: Conference Series 688, 012094, (2016)*
C) *D.P. Higginson et al, PRL 115(5), [054802], (2015)*

Indirect Laser driven neutron source

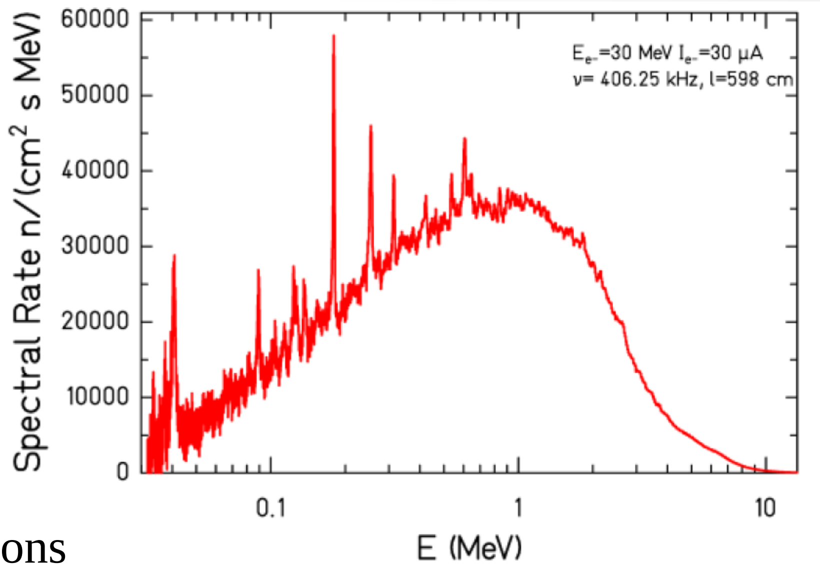
Secondary source, the same as conventional accelerators

- Laser accelerated Ions (protons, deutons) impinging a converter (Li; ^{2}H; ^{3}H …)
- **Bramsstrahlung radiation impinging a converter**
- 2 GeV impinging a spallation target (not yet relevant)

2 Facilities in Europe : ELBE at Dresden, Gemany and GELINA at Geel, Belgium.



	Target	Source Strength (s^{-1})	E_{e-} (MeV)	I_{e-} (μA)	f (Hz)
nELBE	Pb, liquid	$3 \cdot 10^{11}$	30	15	$2 \cdot 10^5$
GELINA	U, Hg cooled	$3 \cdot 10^{13}$	100	96	800



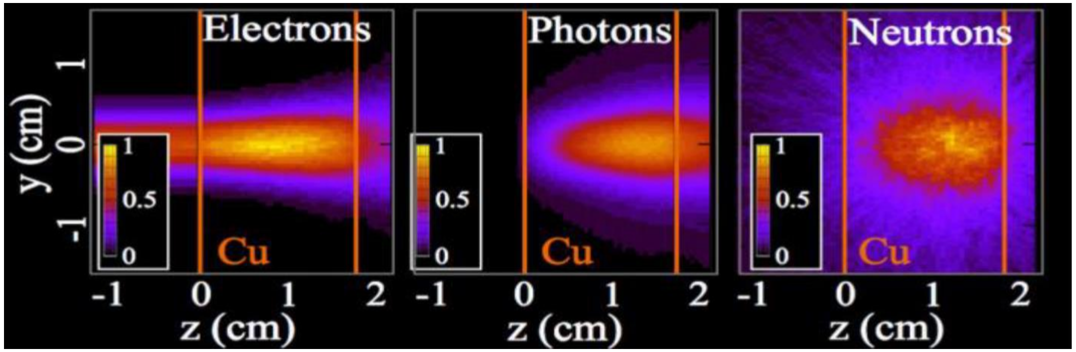
n-ELBE : 10^6 neutrons in 4π from 5×10^8 electrons

Indirect Laser driven neutron source

Secondary source, the same as conventional accelerators

- Laser accelerated Ions (protons, deutons) impinging a converter (Li; ^{2}H; ^{3}H …)
- **Bramsstrahlung radiation impinging a converter**
- 2 GeV impinging a spallation target (not yet relevant)

Laser 90J, 150fs



I. Pomerantz et al, PRL 113, 184801 (2014)

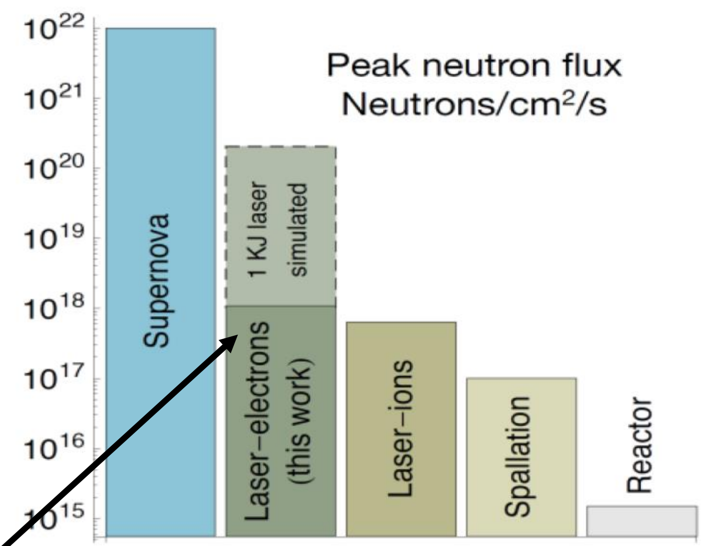
neutrons pulse duration : 50 ps

5×10^{8} n/shot

~4×10^{7} n/sr / shot

⬄ ~10^{8} n/cm² / shot @ 50 cm from source

⬄ A peak of ~10^{18} n/cm² / s



But not a continuous source but @10Hz :

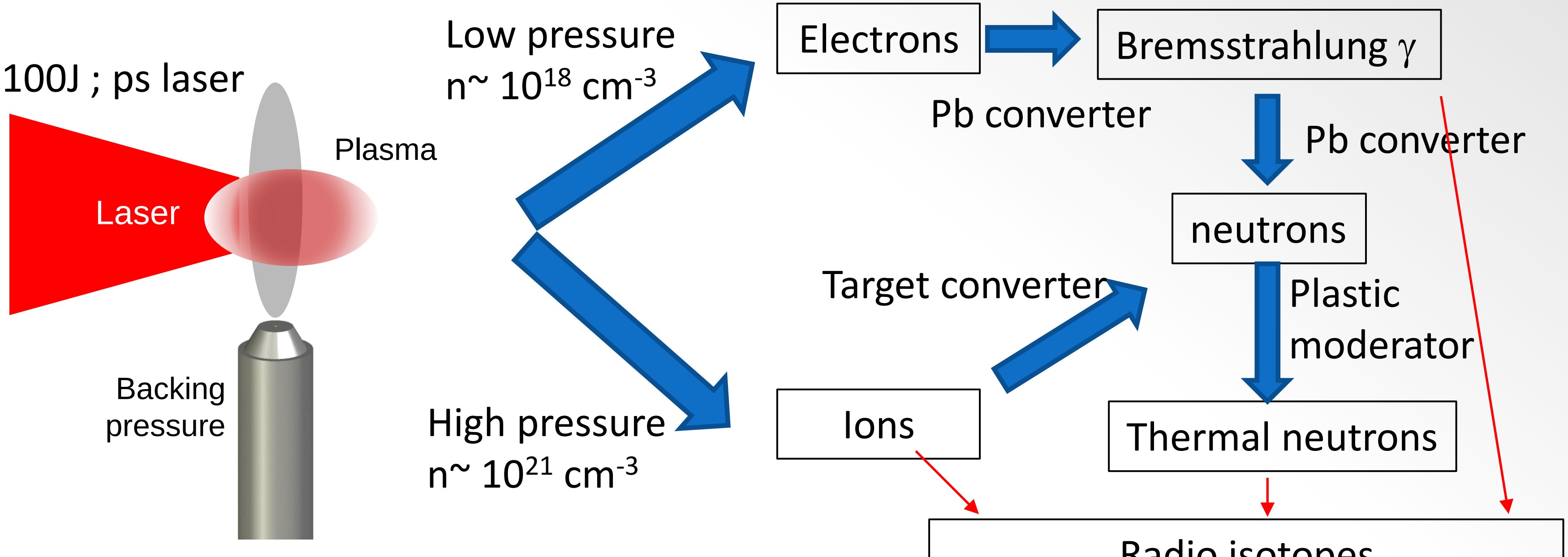
~10^{9} n/cm² /s @ 50 cm

~10^{13} n/cm² /s @ 5 mm

The dreaming part…

Open your mind,…..
breathe, …
take time to dream…

A versatile source



100J ; ps laser

Low pressure
n~ 10^{18} cm^{-3}

High pressure
n~ 10^{21} cm^{-3}

Electrons

Bremsstrahlung γ

Pb converter

Pb converter

neutrons

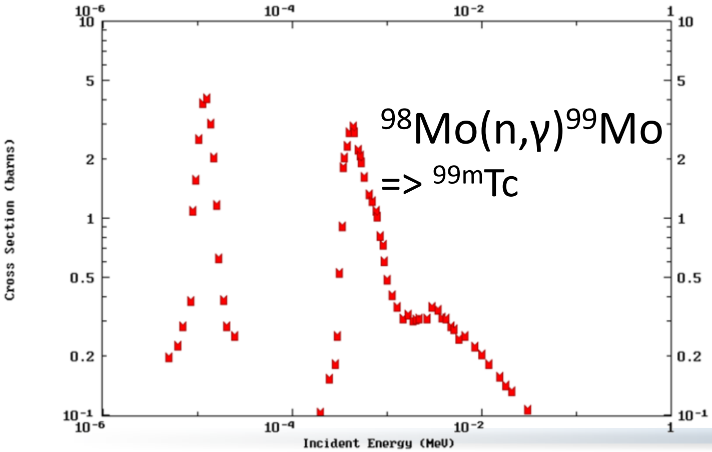
Plastic moderator

Thermal neutrons

Target converter

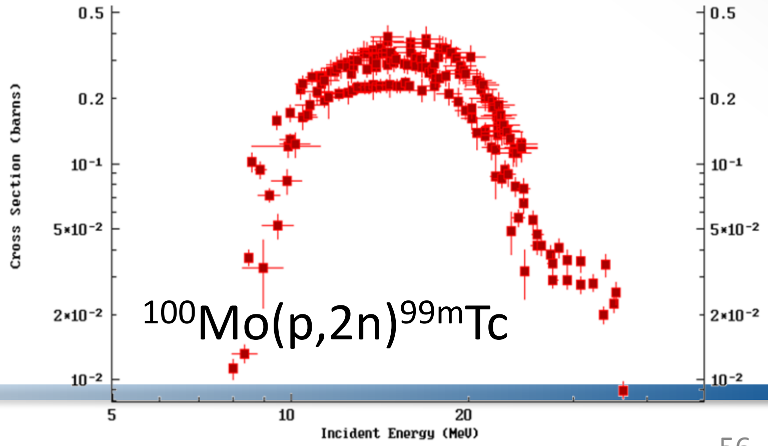
Ions

Radio isotopes



^{98}Mo(n,γ)^{99}Mo
=> ^{99m}Tc

Medical
radioisotopes

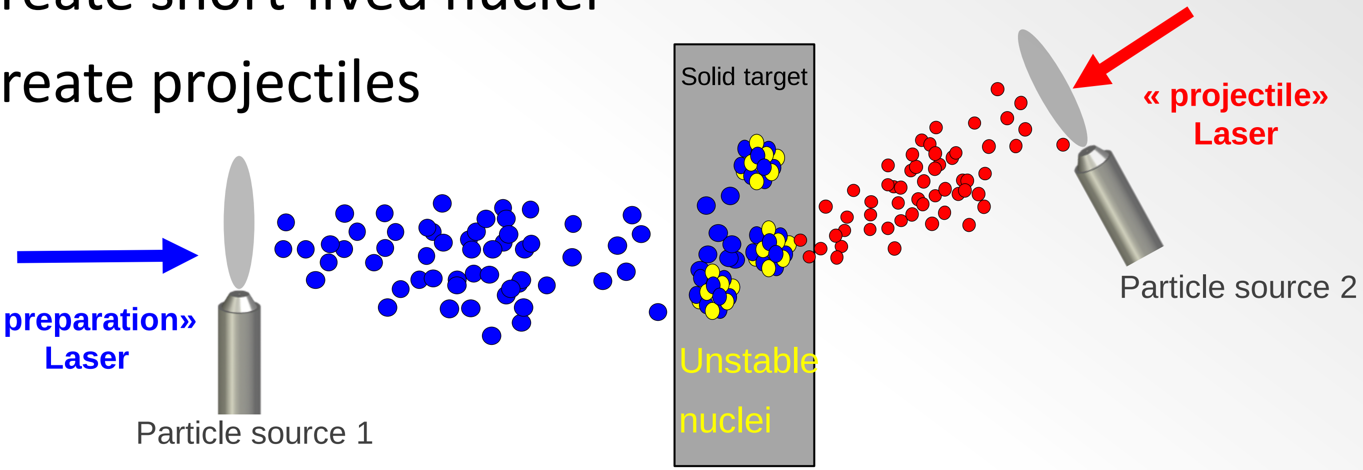


^{100}Mo(p,2n)^{99m}Tc

New type of nuclear physics experiments

- ✓ A beam to create short-lived nuclei
- ✓ A beam to create projectiles

Split the same laser



Particle from source 1

Projectiles : **10^{13}** particles on **Ø 100µm** spot ; cross section: **0,1 barn**,
Primary target: 10^{21} nuclei/cm² (ex : 100µm thick carbon)
→ 10^{9} unstable nuclei on Ø 100µm ↔ 10^{13} nuclei / cm²

Wait Δt then

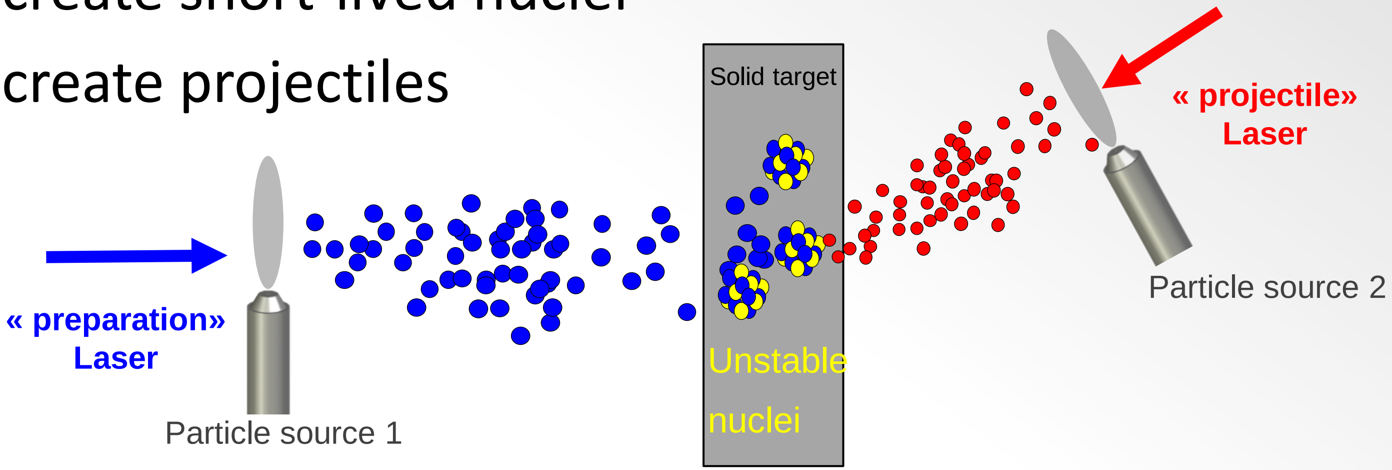
Particle from source 2

Projectiles : **10^{13}** particles on **Ø 100µm** spot ; cross section: **0,1 barn**,
secondary target: 10^{13} nuclei / cm²
→ 10 reactions/shot ; 1 shot / min → ~14 400 reactions/day

M.Tarisien, et al., IEEE Transactions on Nuclear Science, Vol 65, issue 8, p.2216-2219 (2018)

New type of nuclear physics experiments

- ✓ A beam to create short-lived nuclei
- ✓ A beam to create projectiles

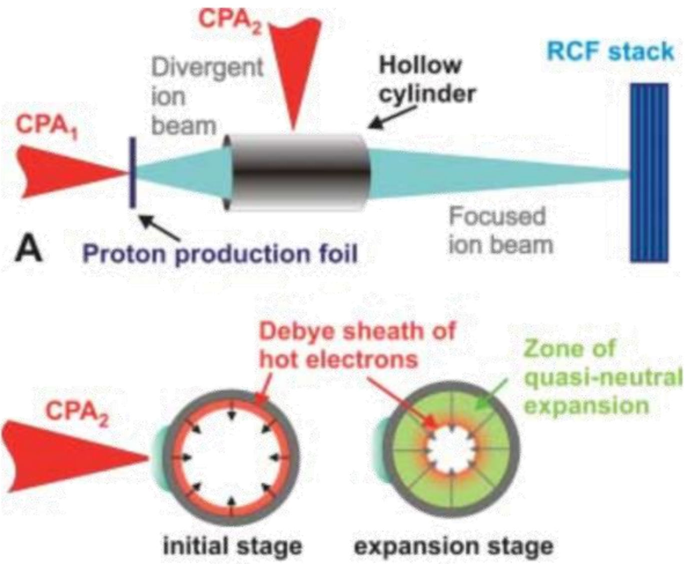


~10 000 reactions/day (0.1 barn)

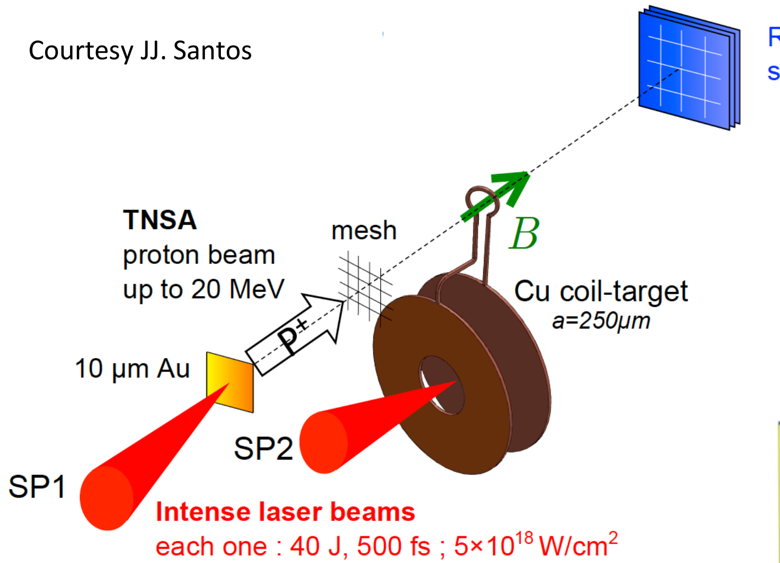
- ✓ Nuclear reactions on very short-lived radioactive nuclei (down to few ns)
- ✓ Nuclear reactions on excited nuclei
- ✓ BUT need to detect nuclear signal ☹

New type of nuclear physics experiments

- ✓ Beam transport difficult because charge space :
  - ✓ 10^{13} protons @10 MeV in 1 mm diameter cylinder, flying in 100 ps bunch duration ↔ 1,6 kA in cylinder ; 5 .10^{-4} C/cm^3

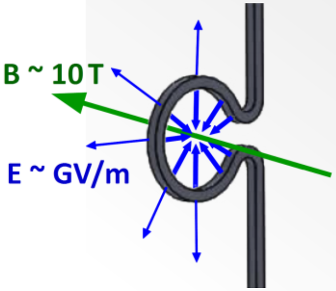


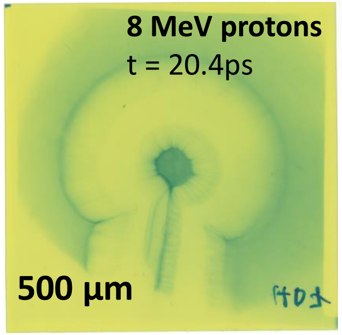
T. Toncian, et al. Science 312, 410-413 (2006)



Courtesy JJ. Santos

Intense laser beams
each one : 40 J, 500 fs ; 5×10^{18} W/cm^2





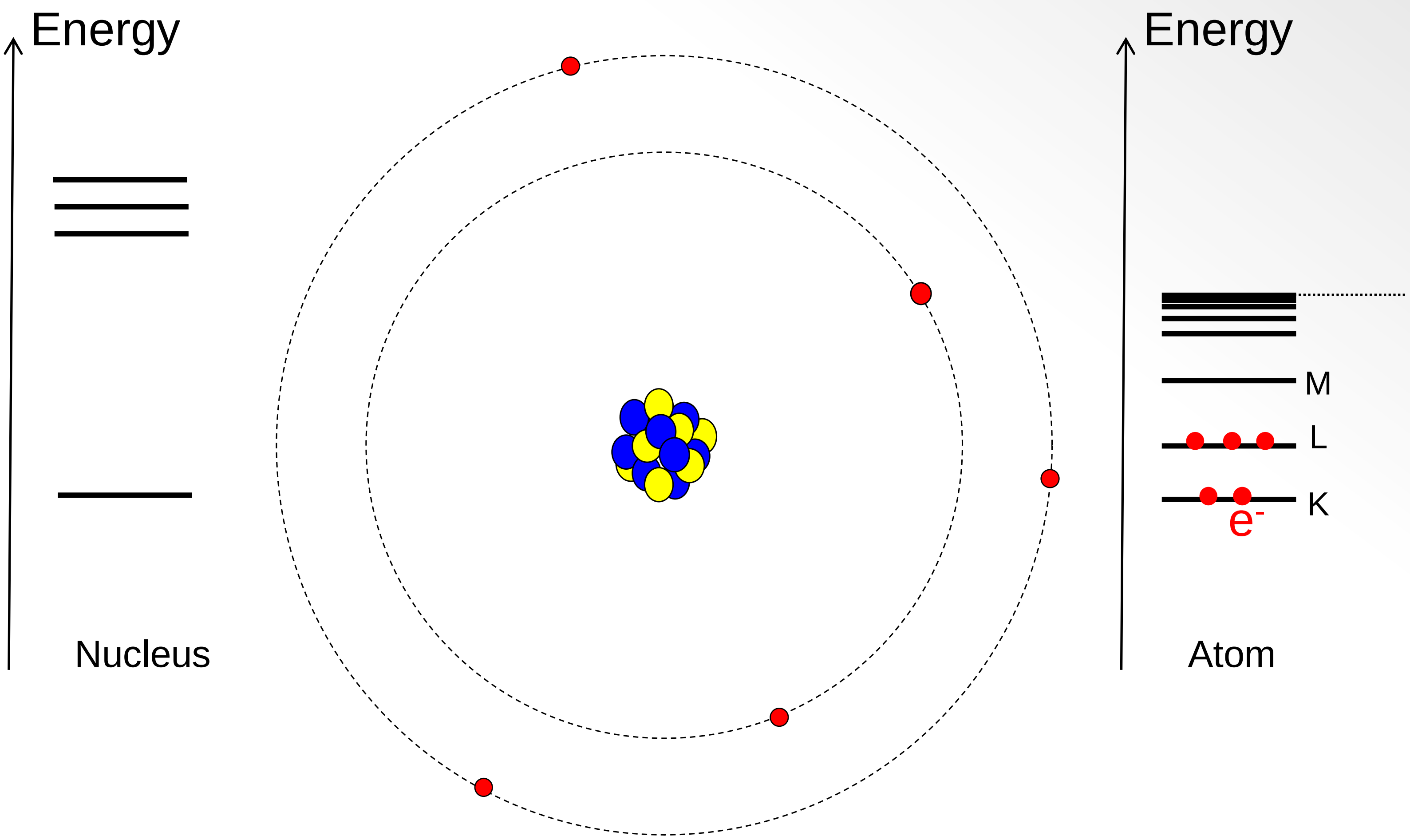
P Bradford et al 2021 Plasma Phys. Control. Fusion ***63*** *084008*

Part 3

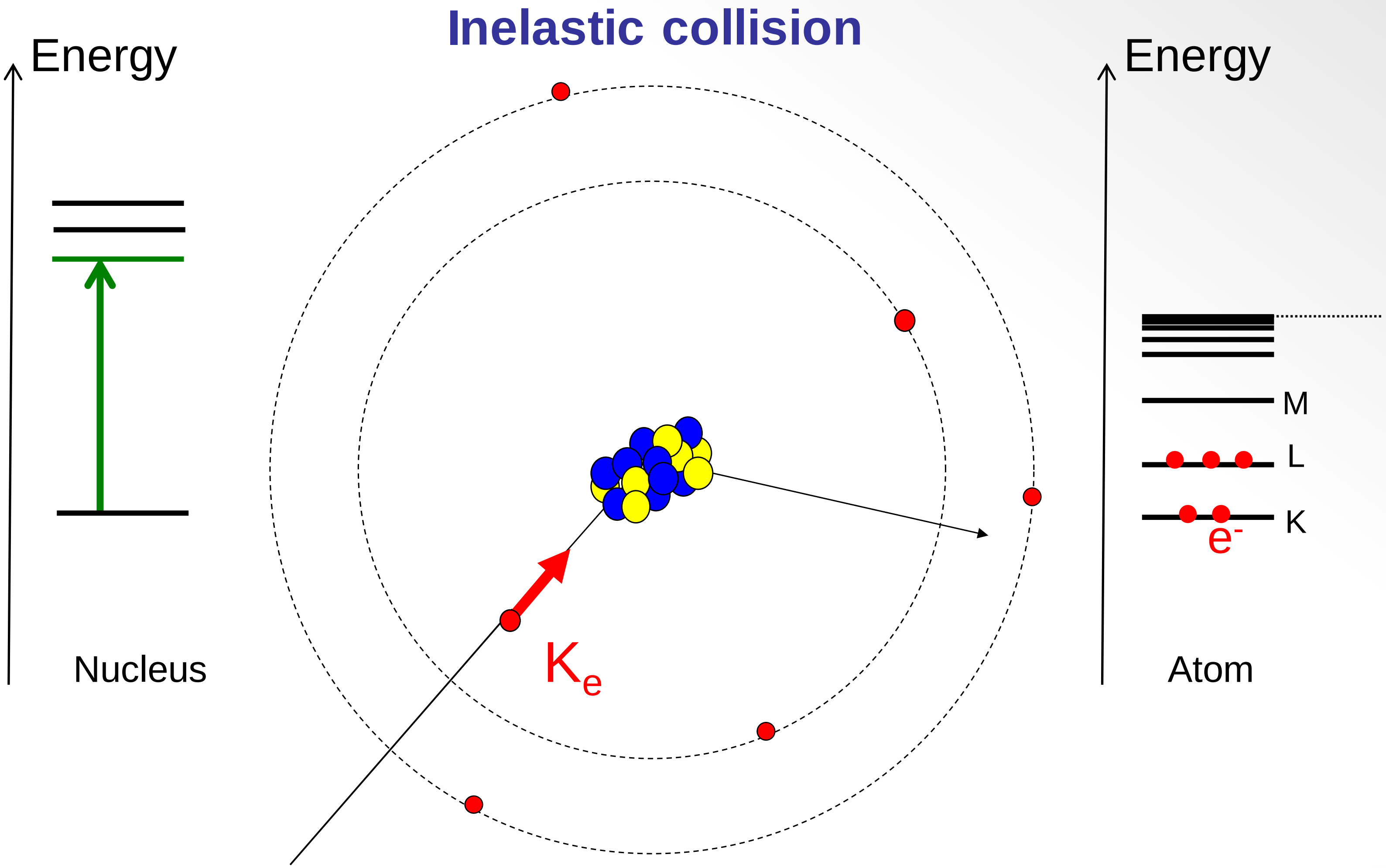
NUCLEAR PHYSICS IN PLASMAS

- The interplay between atomic electrons and nucleus
- Cross section modifications
- Half life modification : case of ^{84}Rb

Nuclear excitation / de-excitation

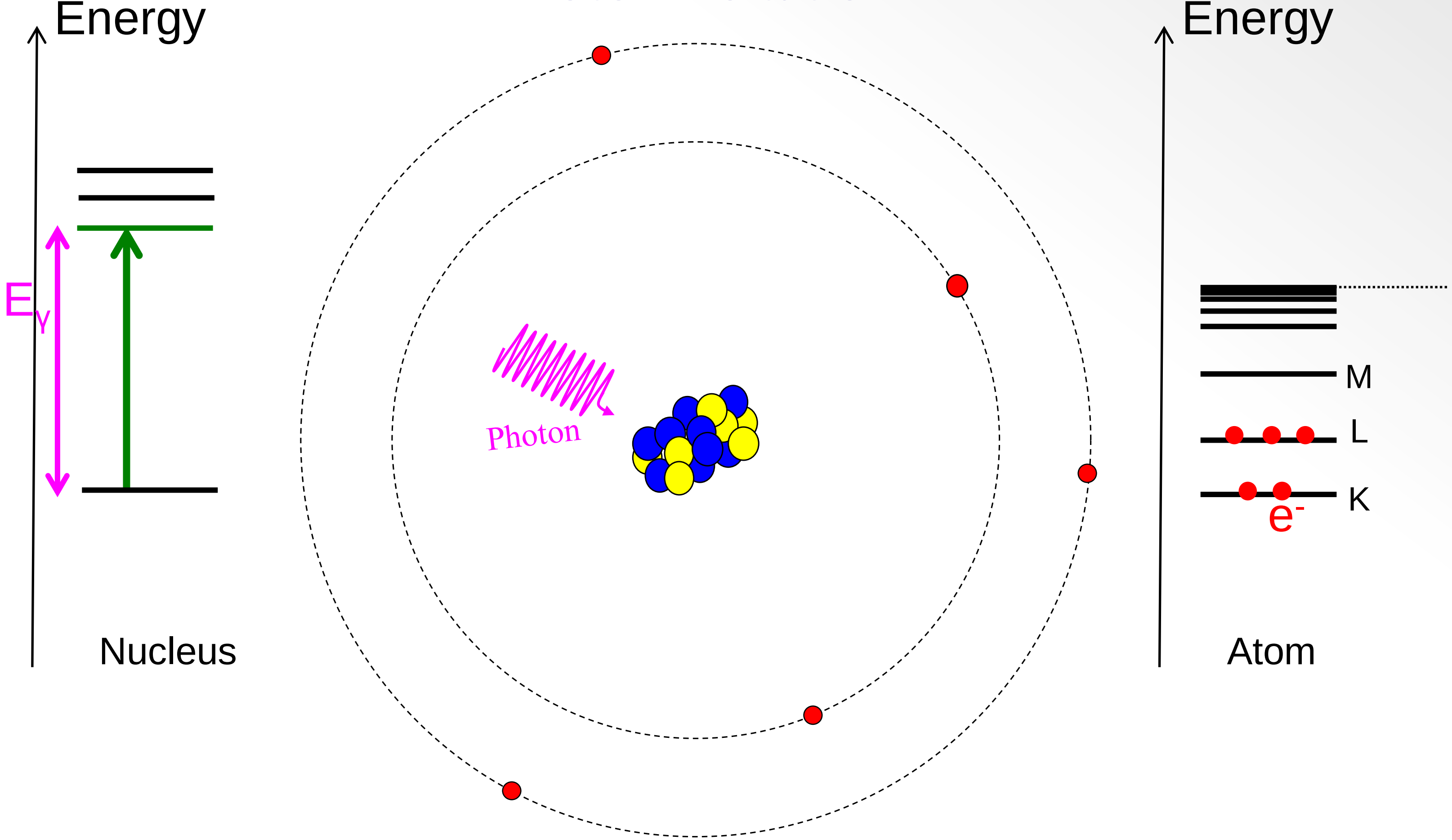


Nuclear **excitation** / de-excitation



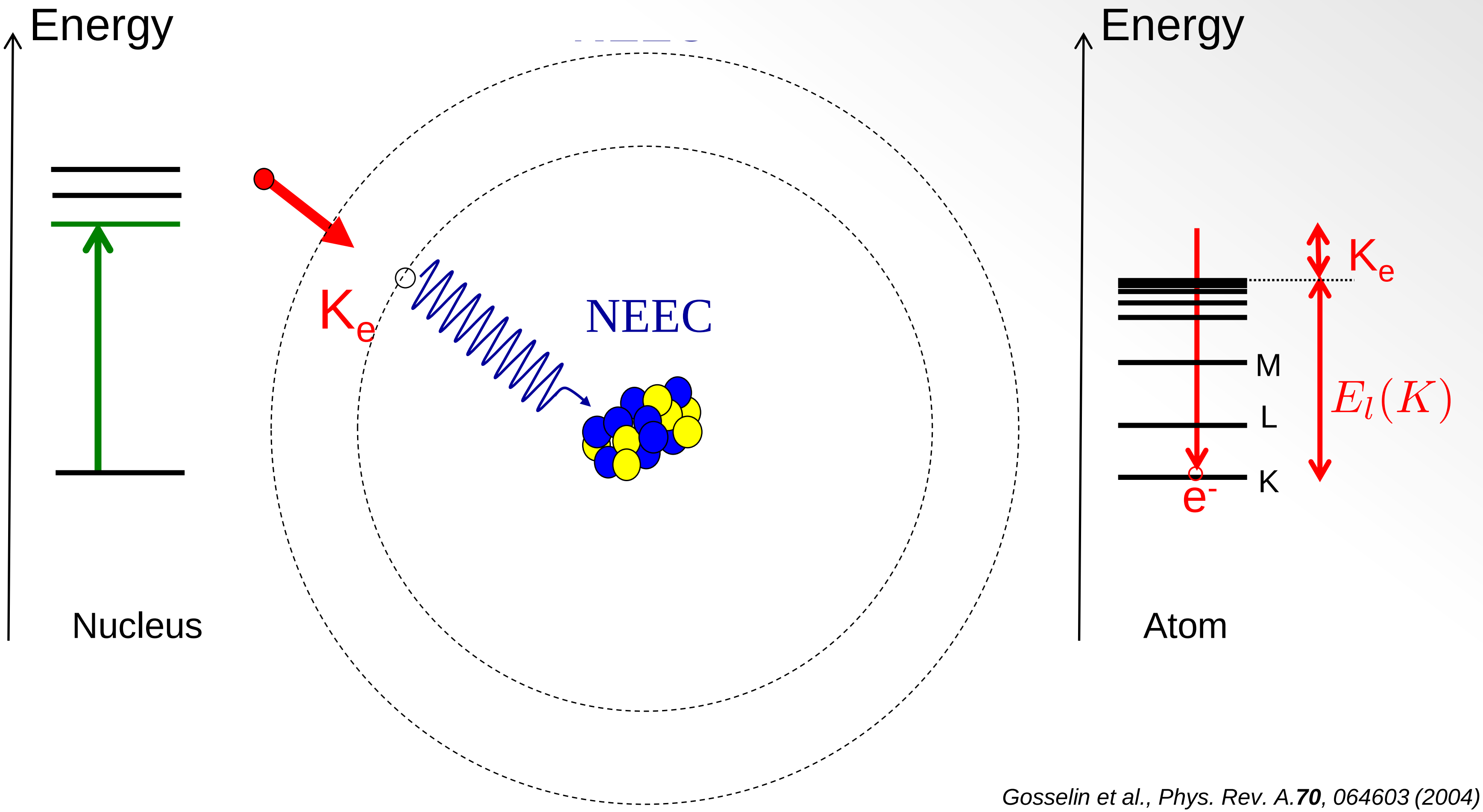
Nuclear **excitation** / de-excitation

Photo-Excitation



Nuclear **excitation** / de-excitation

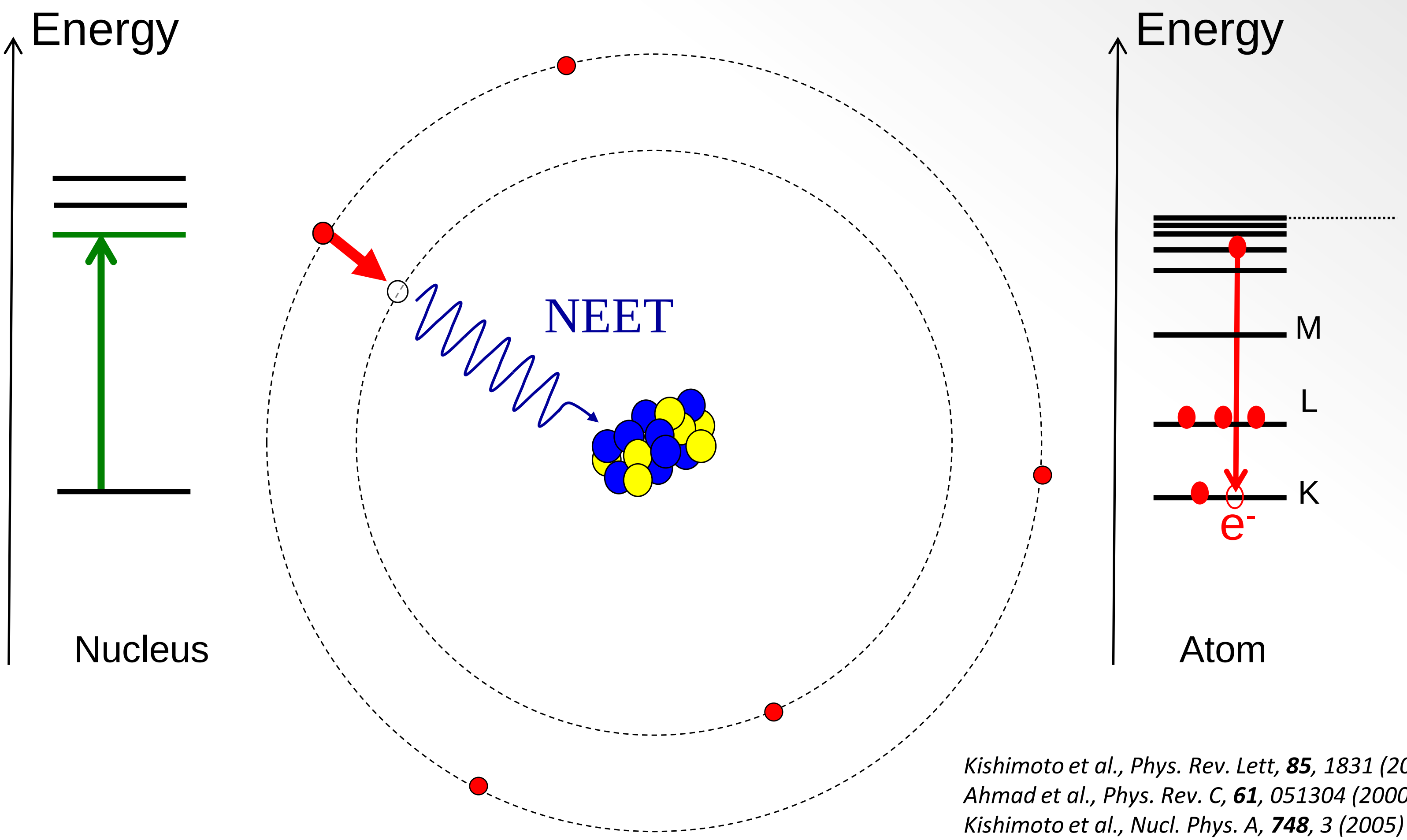
Nuclear Excitation by Electron Capture



*Gosselin et al., Phys. Rev. A.**70**, 064603 (2004)*

Nuclear **excitation** / de-excitation

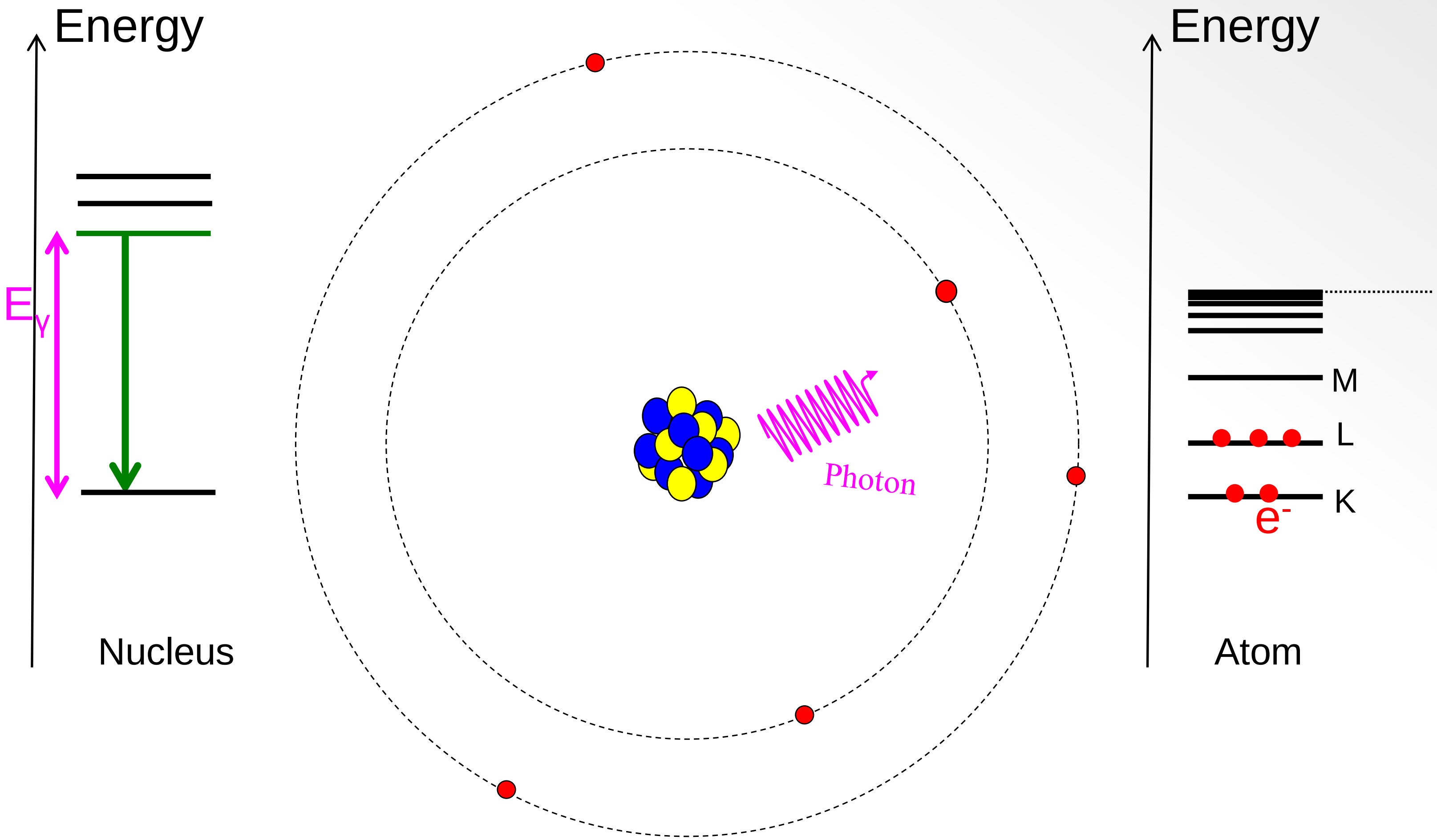
Nuclear Excitation by Electronic Transition



*Kishimoto et al., Phys. Rev. Lett, **85**, 1831 (2000)*
*Ahmad et al., Phys. Rev. C, **61**, 051304 (2000)*
*Kishimoto et al., Nucl. Phys. A, **748**, 3 (2005)*

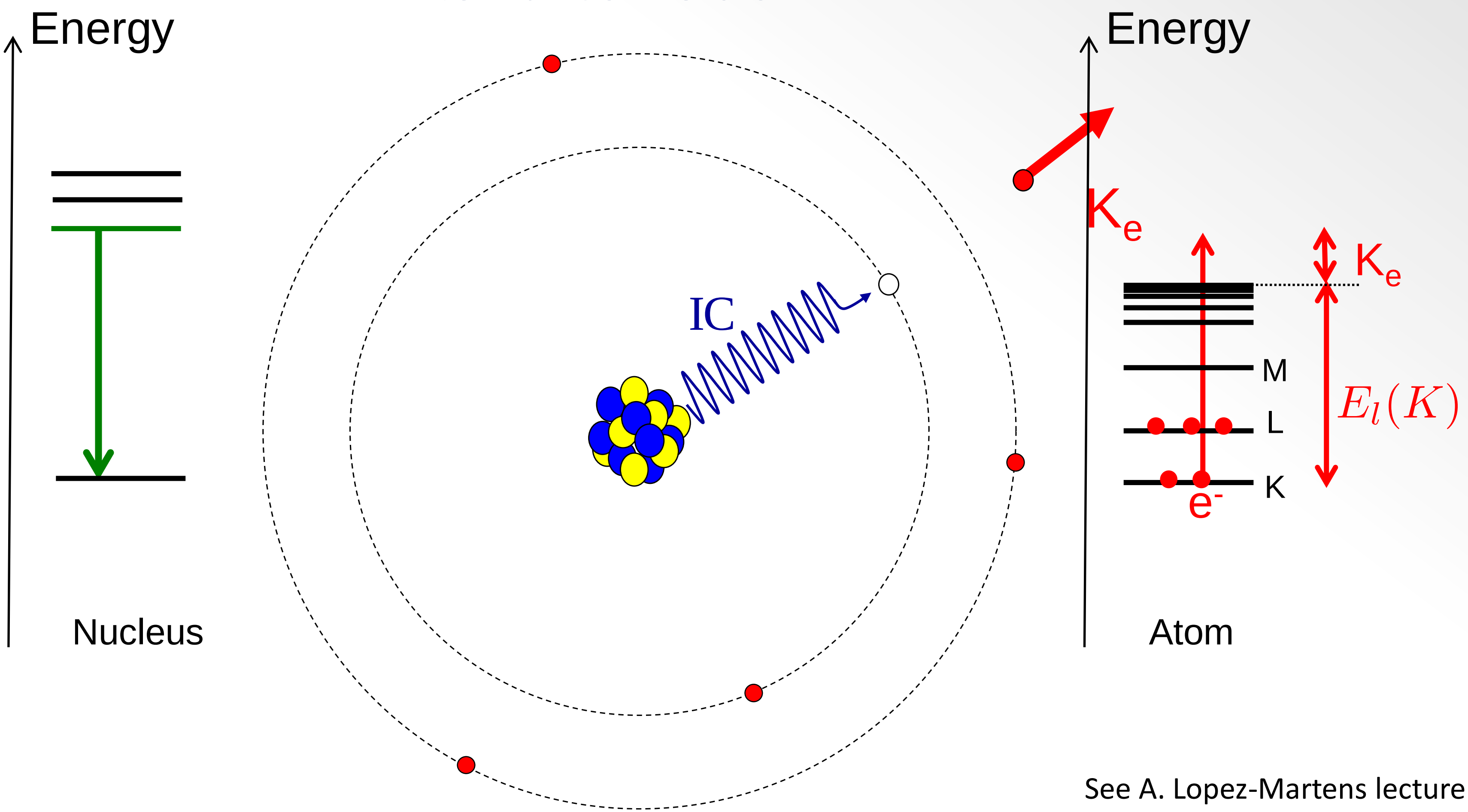
Nuclear excitation / **de-excitation**

Gamma emission



Nuclear excitation / **de-excitation**

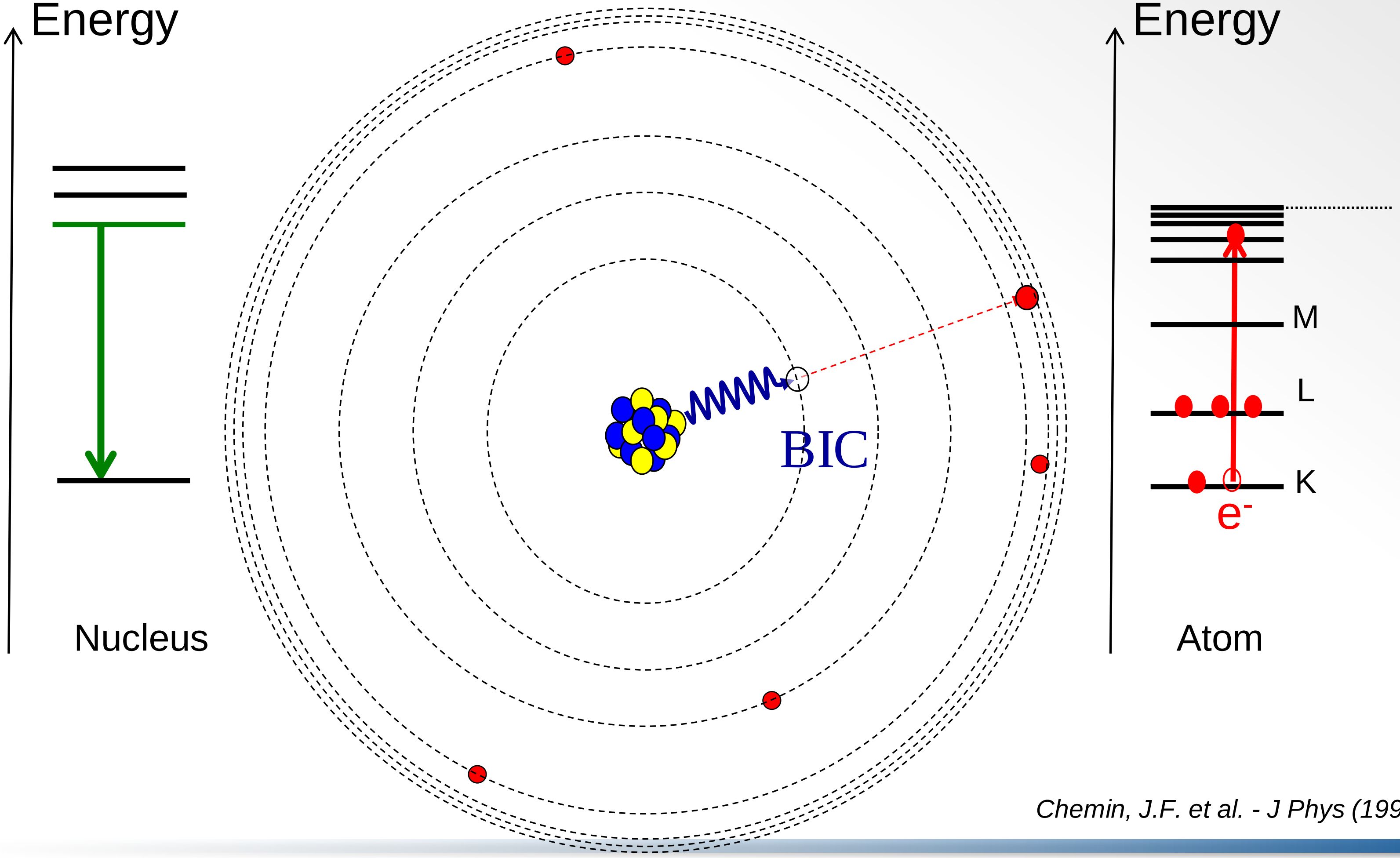
Internal Conversion



See A. Lopez-Martens lecture

Nuclear excitation / **de-excitation**

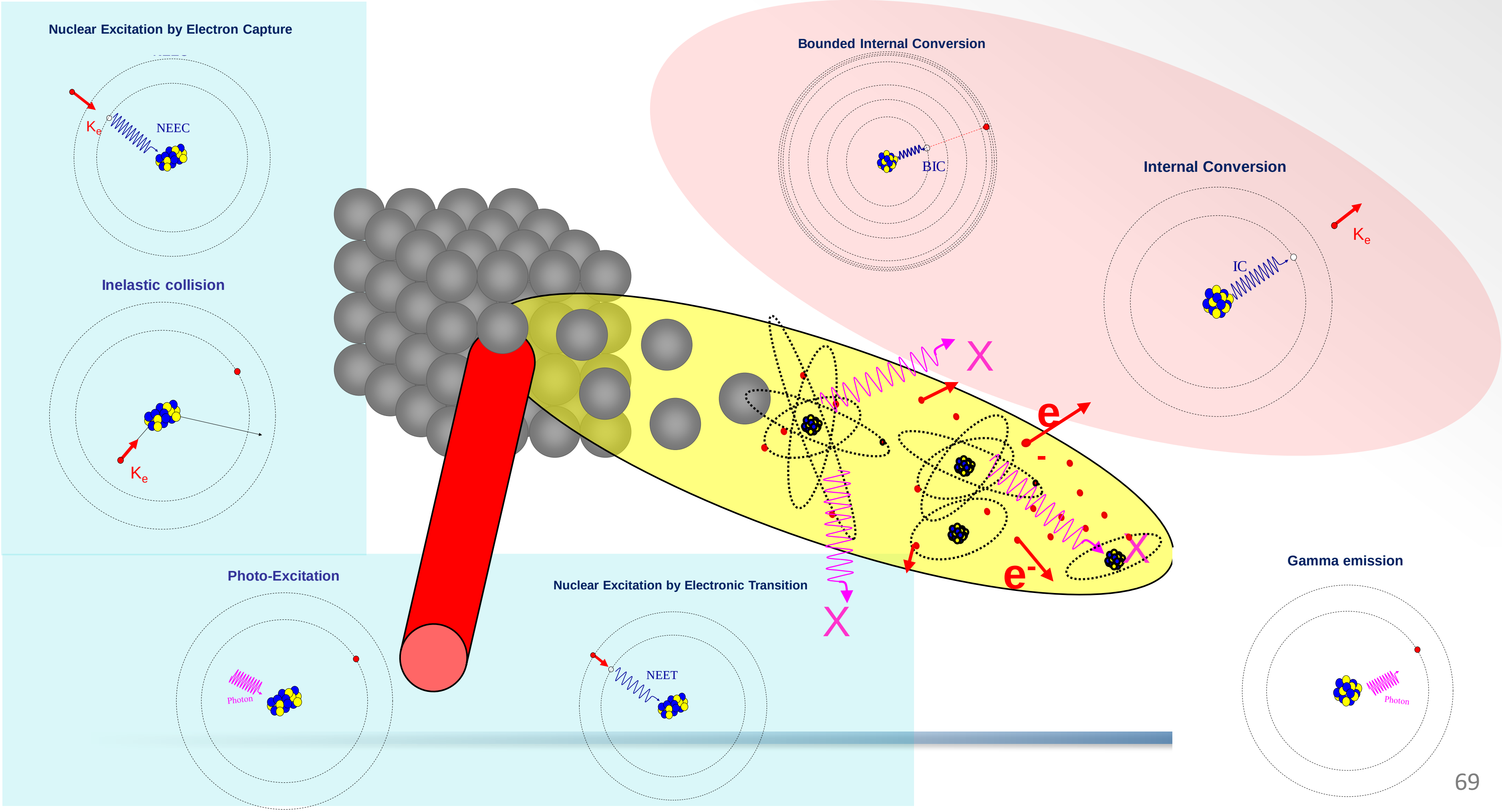
Bounded Internal Conversion



Chemin, J.F. et al. - J Phys (1999) 53: 633.

Nuclear excitation / de-excitation

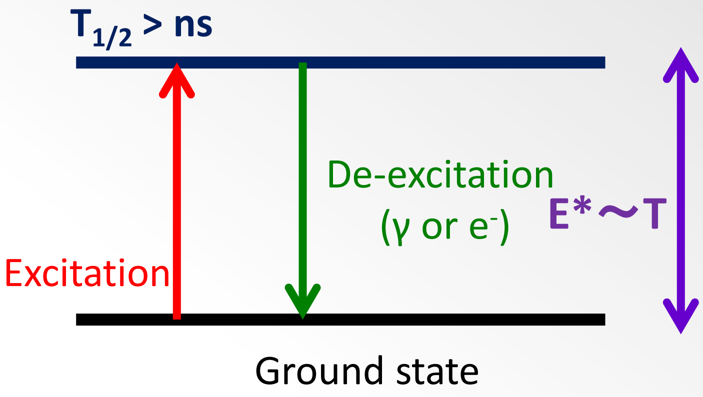
- Half-life modified because of de-excitation processes
- But also because of excitation processes



Nuclear excitation / de-excitation

Evidence of nuclear excitation in plasmas

- Laser created plasmas:
  - Temperature (LTE) range of 10 eV- few keV
- Nuclear excitations in plasmas can only studied in specific nuclei:
  - Low energy excited state: excitation energy E*～T
  - Isomeric state: lifetime longer than the plasma emission duration



➢Very few candidates (～ 10 stable nuclei with E*<15 keV)

	^{45}Sc	^{169}Tm	^{181}Ta	^{201}Hg	^{83}Kr	^{73}Ge	^{57}Fe	^{187}Os	^{235}U	^{205}Pb
E* (keV)	14.2	8.4	6.2	1.55	9.4	13.3	14.4	9.7	0.077	2.3
$T_{1/2}$	318 ms	4.1 ns	6.1 µs	81 ns	154ns	2.9 µs	98 ns	2.4 ns	27 m	24 µs

*C.Granja et al. Nucl. Phys. A **784,**1 (2007)*

Nuclear excitation / de-excitation

Evidence of nuclear excitation in plasmas

- Experiments are challenging:

Experiments on stable nuclei

  - Nuclear excitation cross sections are orders of magnitude smaller than atomic ones
  - Low signal and high background !
  - Isomeric state: weakly coupled state → excitation more difficult for this state

Nucleus	**^{181}Ta**	**^{235}U**	**^{57}Fe**
E* (keV)	6.2	0.077	14.4
$T_{1/2}$	6.1 µs	27 m	98 ns
Process	Direct excitation	NEET	Direct excitation

Gobet et al., J.Phys. B **41**, 145701 (2008)
Spohr et al., Mod Opt **53** 2633 (2006)
Andreev et al., JETP **91**, 1063 (2000)

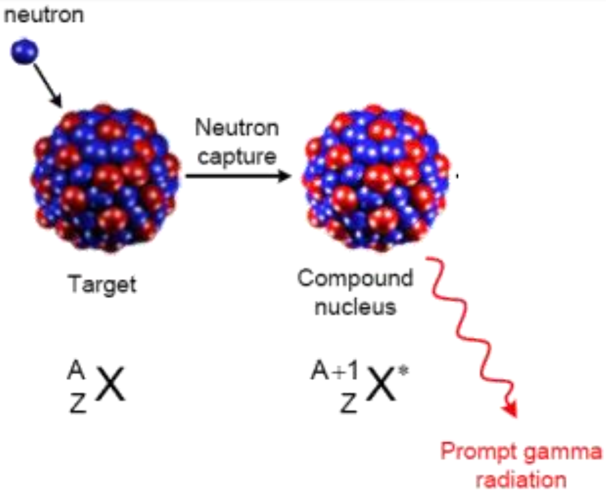
Claverie et al, Phys. Rev. C **70**,044303 (2004)
Bouns et al. Phys. Rev. C, **46**,852 (1992)
Arutyunyan et al., Sov.J.NP **53**, 23 (1991)
Izawa et al, Phys. Lett. **88B**,59 (1979)

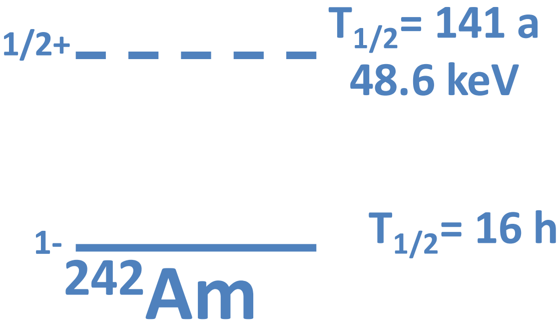
Chefonov et al. Laser Phys. **24,** 116002 (2014)
Golovin et al. Quant. Electro. **41,** 222 (2011)

➤**Up to now: no clear evidence of nuclear excitation in plasmas**

Cross section modifications on excited nucleus

What would be changed in a plasma?

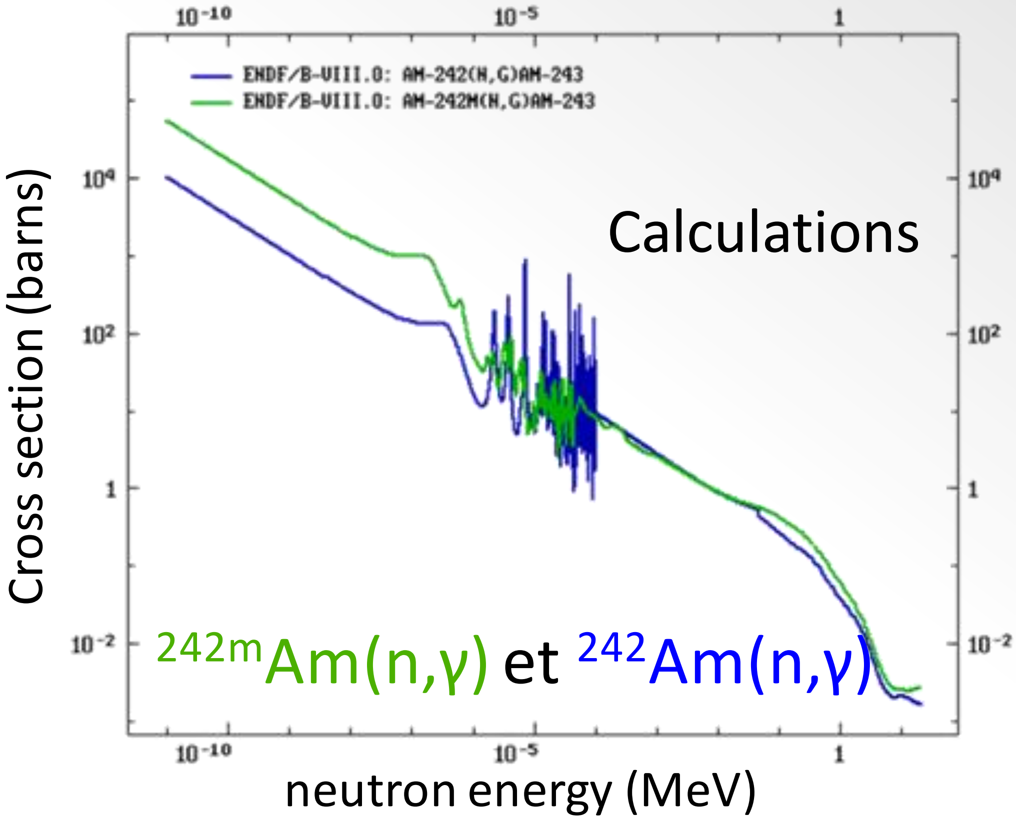




1/2+ **$T_{1/2}$= 141 a**
48.6 keV

1- **$T_{1/2}$= 16 h**

^{242}Am



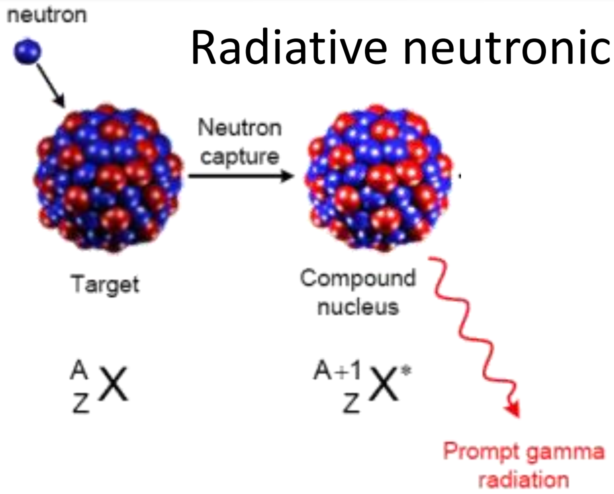
Calculations

^{242m}Am(n,γ) et ^{242}Am(n,γ)

M.Q. Buckner et al, Phys. Rev. C, 95, 061602(R) (2017)

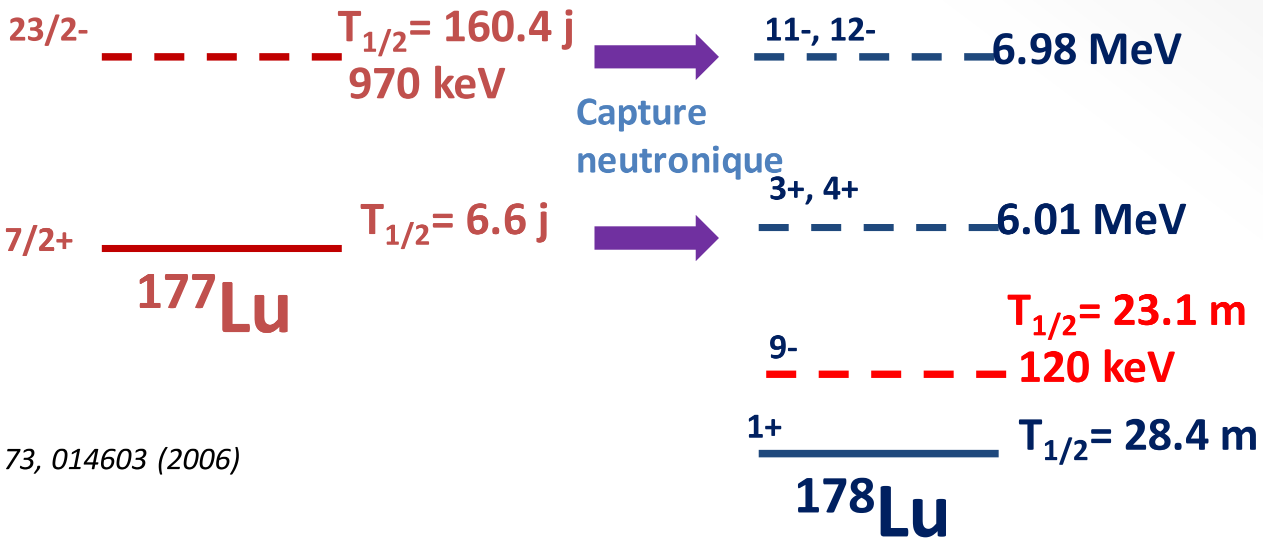
Cross section modifications on excited nucleus

What would be changed in a plasma?



Radiative neutronic capture

Neutron energy	$^{177m}Lu(n,\gamma)^{178m}Lu$ / $^{177}Lu(n,\gamma)^{178m}Lu$
< 25 meV	0,47 +/- 0,07

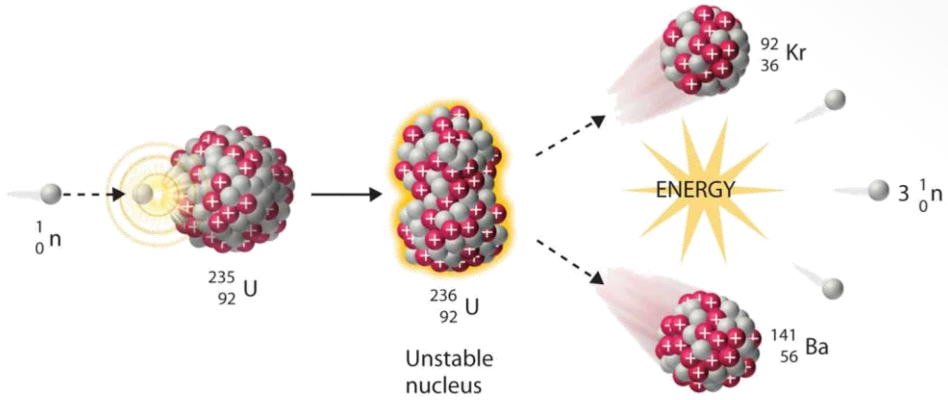


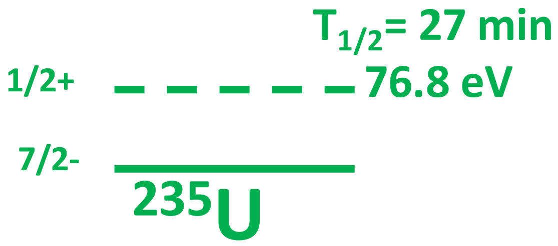
G. Bélier et al., Phys. Rev. C 73, 014603 (2006)

Cross section modifications on excited nucleus

What would be changed in a plasma?

Neutron-capture-induced Fission





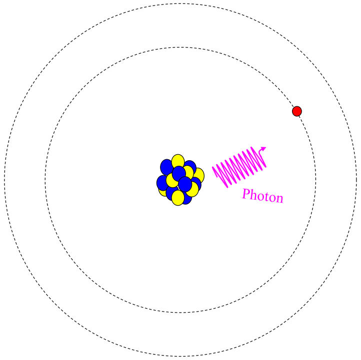
Neutron energy	$^{235m}U(n,f)$ / $^{235}U(n,f)$
< 25 meV	1,61 +/- 0,44
50 meV	2,47 +/- 0,45

A. D'Eer et al, Phys. Rev. C 38, 1270 (1988)

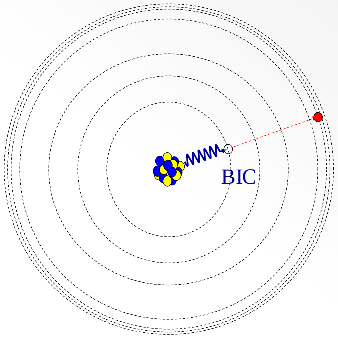
Half-life of an excited state

What would be changed in a plasma?

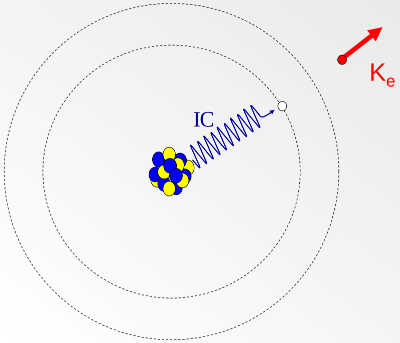
Gamma emission



Bounded Internal Conversion

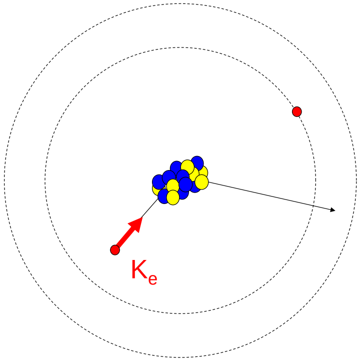


Internal Conversion



$$T_{1/2} = \frac{\ln(2)}{\lambda_\gamma + \sum_i \lambda_i}$$

Inelastic collision



Nuclear Excitation by Electron Capture

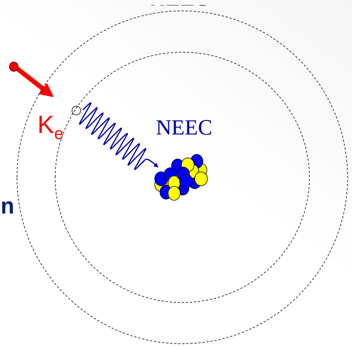
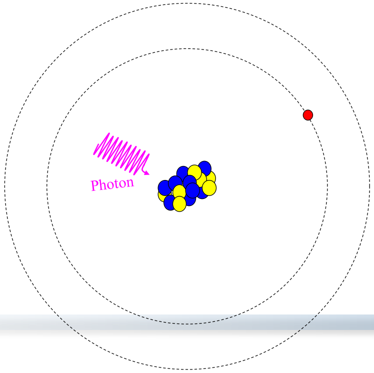
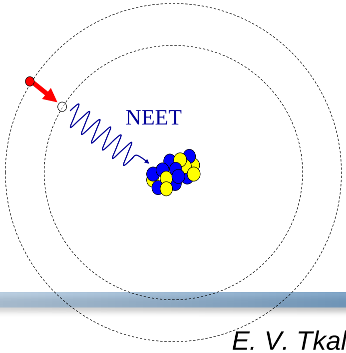


Photo-Excitation



Nuclear Excitation by Electronic Transition



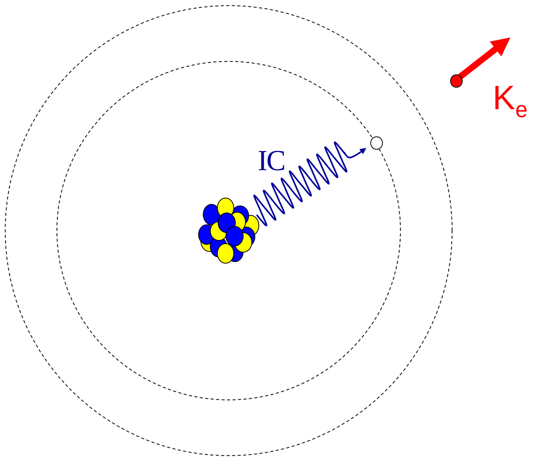
E. V. Tkalya et al. Phys. Rev. C 86, 014608 (2012)
Srinivas K. Phys. Rev. A 85, 012710 (2012)

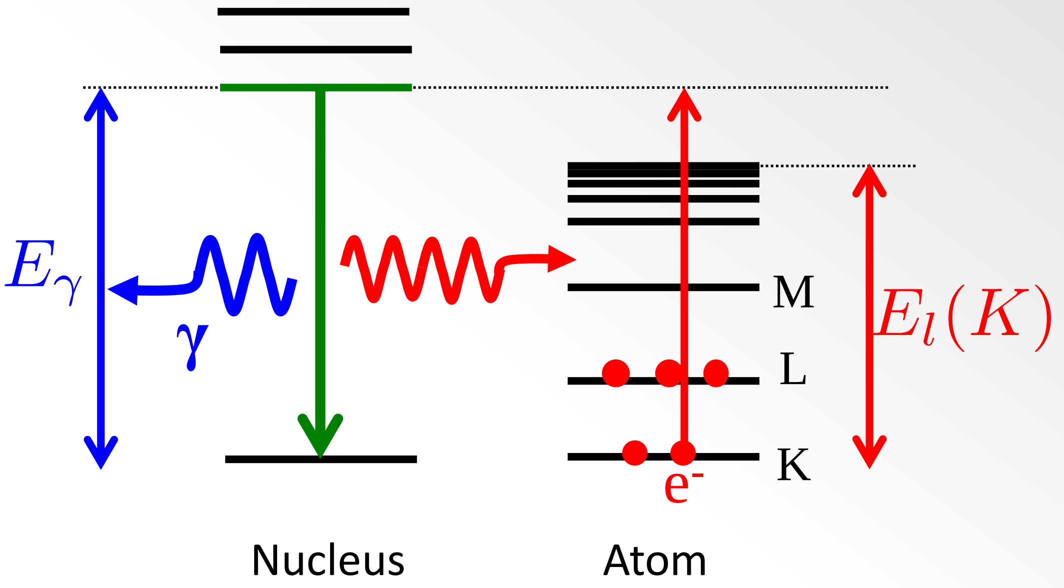
Half-life of an excited state

$$T_{1/2} = \frac{\ln(2)}{\lambda_\gamma + \lambda_e}$$

Ion charge effect

Internal Conversion





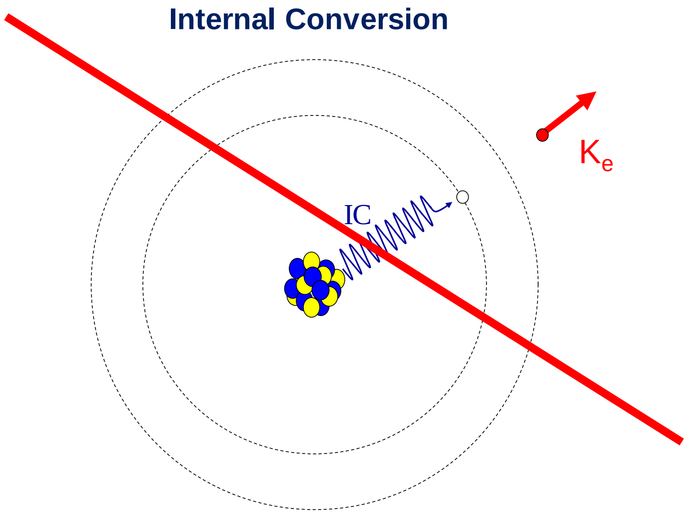
$^{125}_{52}\mathrm{Te}$ 1er état excité à 35,5 keV

Q	$T_{1/2}$ (ns)	E_l(K) (keV)
0 (neutral)	1,49	31,8
48^+	11 ± 2	36,6

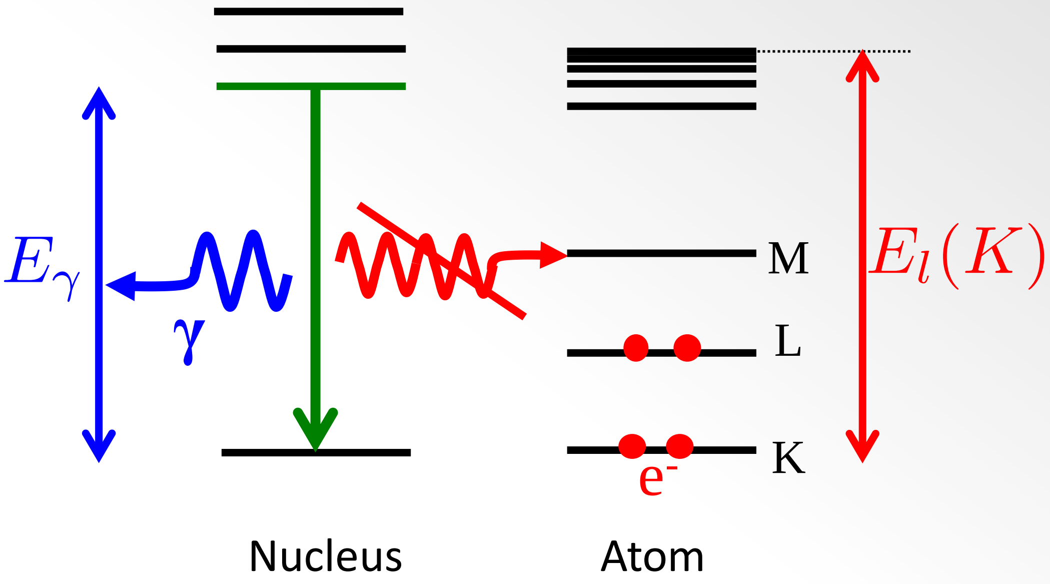
F. Attallah et al. Phys. Rev. Lett. ***75****,1715*

Half-life of an excited state

$$T_{1/2} = \frac{\ln(2)}{\lambda_\gamma + \cancel{\lambda_e}}$$



Ion charge effect



$^{125}_{52}\mathrm{Te}$ 1er état excité à 35,5 keV

Q	$T_{1/2}$ (ns)	$E_l(K)$ (keV)
0 (neutral)	1,49	31,8
48^+	11 ± 2	36,6

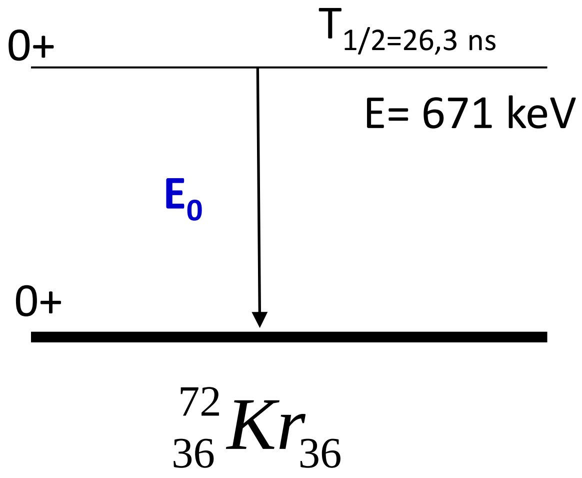
Charge state can modify apparent nuclear properties

F. Attallah et al. Phys. Rev. Lett. ***75****,1715*

Half-life of an excited state

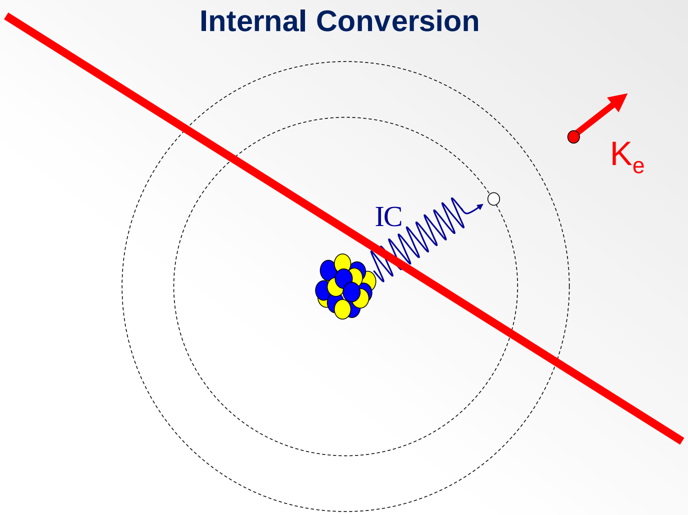
fully stripped ion

E. Bouchez et al, Phys. Rev. Lett. 90, 082502 (2003)



0^+-0^+ transition :
No γ allowed

$$T_{1/2} = \frac{\ln(2)}{\lambda_{IC}}$$

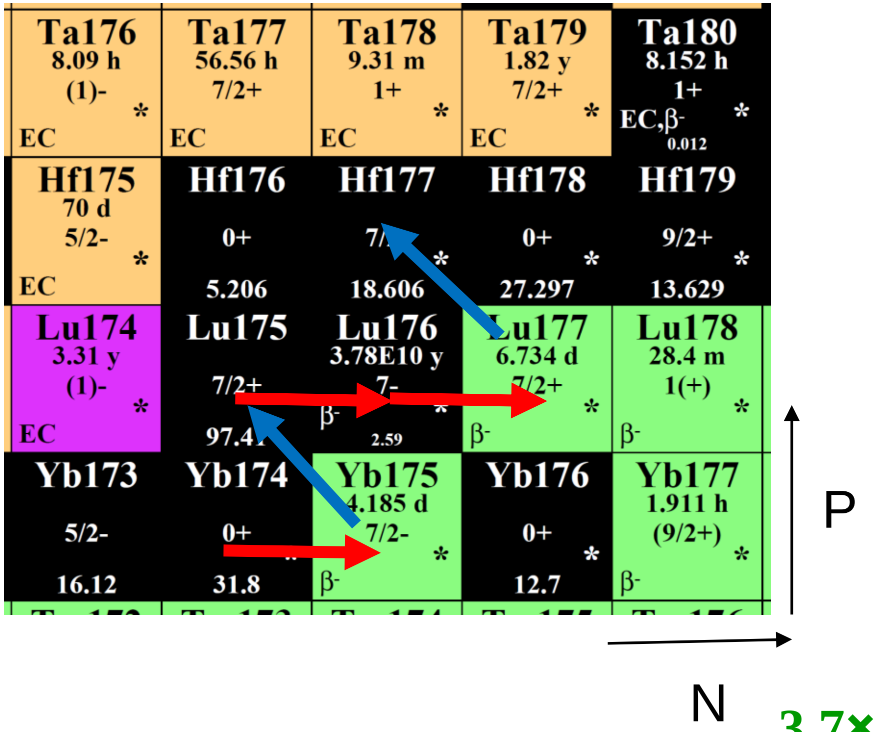


Isomer state E= 671 keV

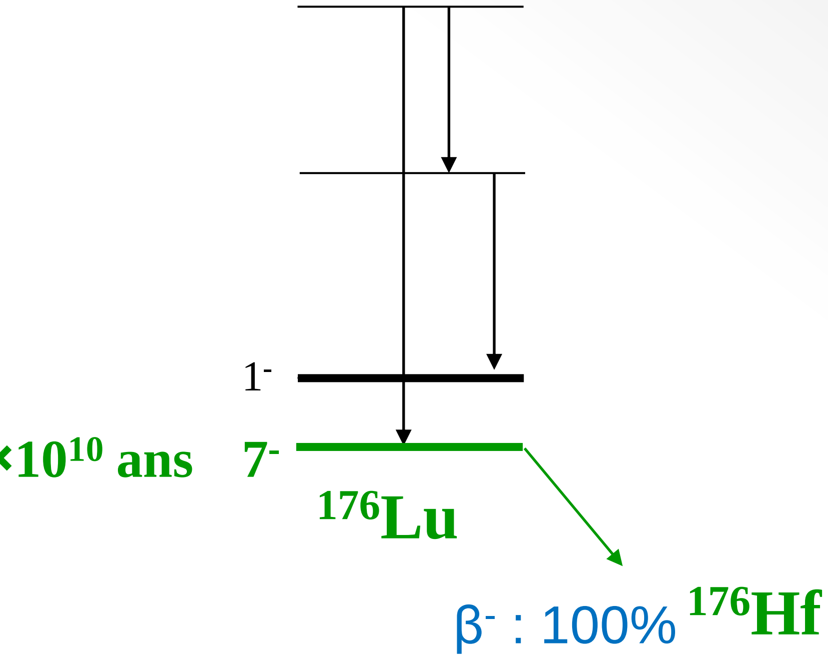
- $T_{1/2}$= 26.3 ns in neutral atom
- « Stable » in fully stripped ion : Kr^{36+}

Half-life of an excited state

Astrophysical consequences : S process and abundances

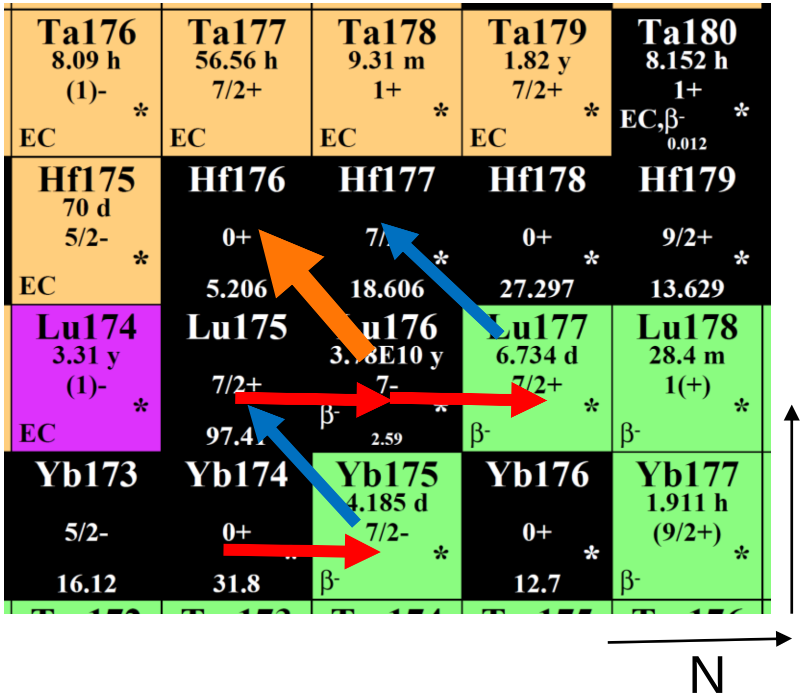


Ta176 8.09 h (1)- * EC	**Ta177** 56.56 h 7/2+ EC	**Ta178** 9.31 m 1+ * EC	**Ta179** 1.82 y 7/2+ * EC	**Ta180** 8.152 h 1+ EC,β- * 0.012
Hf175 70 d 5/2- * EC	**Hf176** 0+ 5.206	**Hf177** 7/ * 18.606	**Hf178** 0+ * 27.297	**Hf179** 9/2+ * 13.629
Lu174 3.31 y (1)- * EC	**Lu175** 7/2+ 97.41	**Lu176** 3.78E10 y 7- β- * 2.59	**Lu177** 6.734 d 7/2+ * β-	**Lu178** 28.4 m 1(+) * β-
Yb173 5/2- 16.12	**Yb174** 0+ 31.8	**Yb175** 4.185 d 7/2- * β-	**Yb176** 0+ * 12.7	**Yb177** 1.911 h (9/2+) * β-

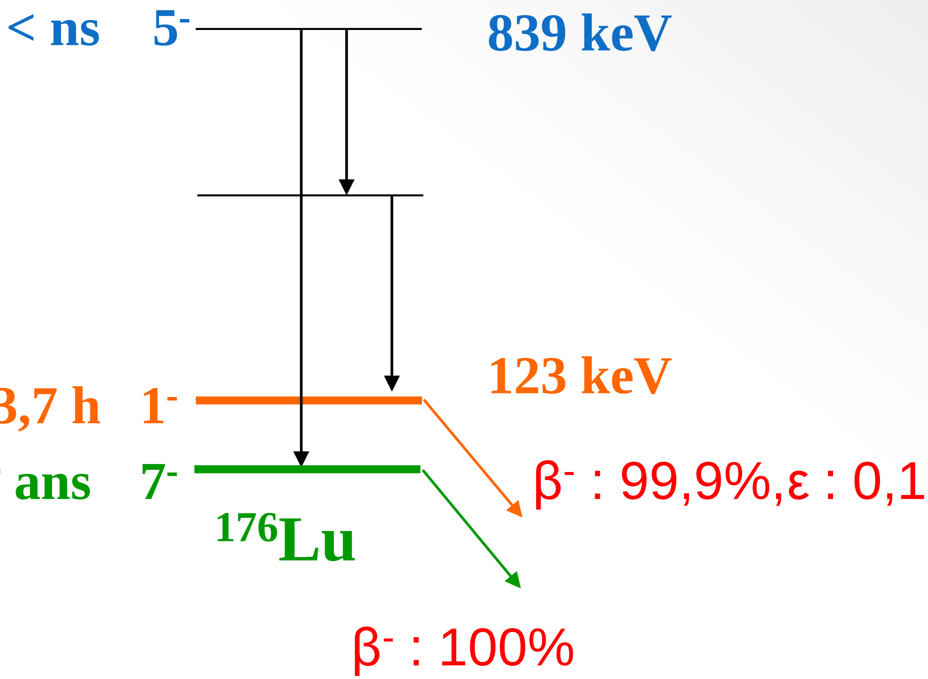


Half-life of an excited state

Astrophysical consequences : S process and abundances



Ta176 8.09 h (1)- * EC	**Ta177** 56.56 h 7/2+ EC	**Ta178** 9.31 m 1+ * EC	**Ta179** 1.82 y 7/2+ * EC	**Ta180** 8.152 h 1+ EC,β- * 0.012
Hf175 70 d 5/2- * EC	**Hf176** 0+ 5.206	**Hf177** 7/ * 18.606	**Hf178** 0+ * 27.297	**Hf179** 9/2+ * 13.629
Lu174 3.31 y (1)- * EC	**Lu175** 7/2+ 97.41	**Lu176** 3.78E10 y 7- β- * 2.59	**Lu177** 6.734 d 7/2+ * β-	**Lu178** 28.4 m 1(+) * β-
Yb173 5/2- 16.12	**Yb174** 0+ 31.8	**Yb175** 4.185 d 7/2- * β-	**Yb176** 0+ * 12.7	**Yb177** 1.911 h (9/2+) * β-



< ns 5^- 839 keV

3,7 h 1^- 123 keV

$3{,}7\times10^{10}$ ans 7^-

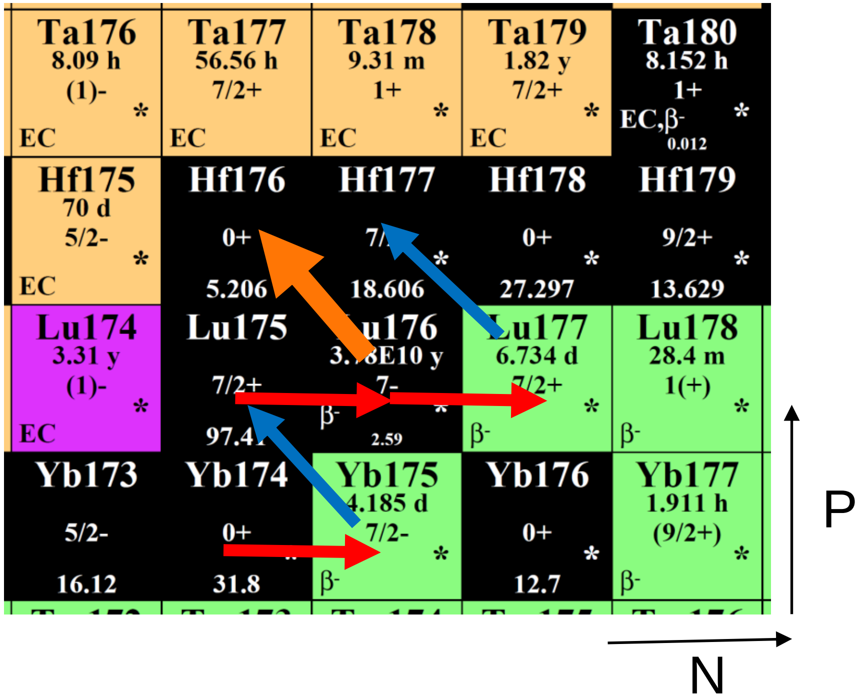
^{176}Lu

β^- : 99,9%,ε : 0,1

β^- : 100%

Half-life of an excited state

Astrophysical consequences : S process and abundances



Ta176 8.09 h (1)- * EC	**Ta177** 56.56 h 7/2+ EC	**Ta178** 9.31 m 1+ * EC	**Ta179** 1.82 y 7/2+ * EC	**Ta180** 8.152 h 1+ EC,β- * 0.012
Hf175 70 d 5/2- * EC	**Hf176** 0+ 5.206	**Hf177** 7/ * 18.606	**Hf178** 0+ * 27.297	**Hf179** 9/2+ * 13.629
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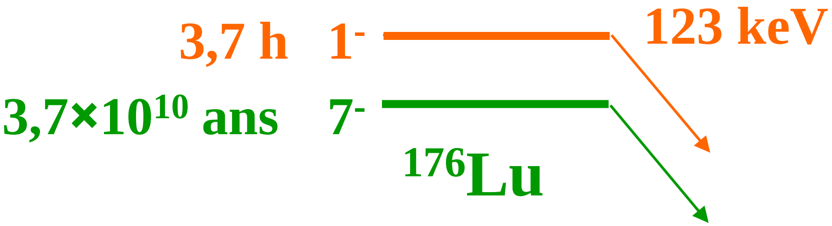
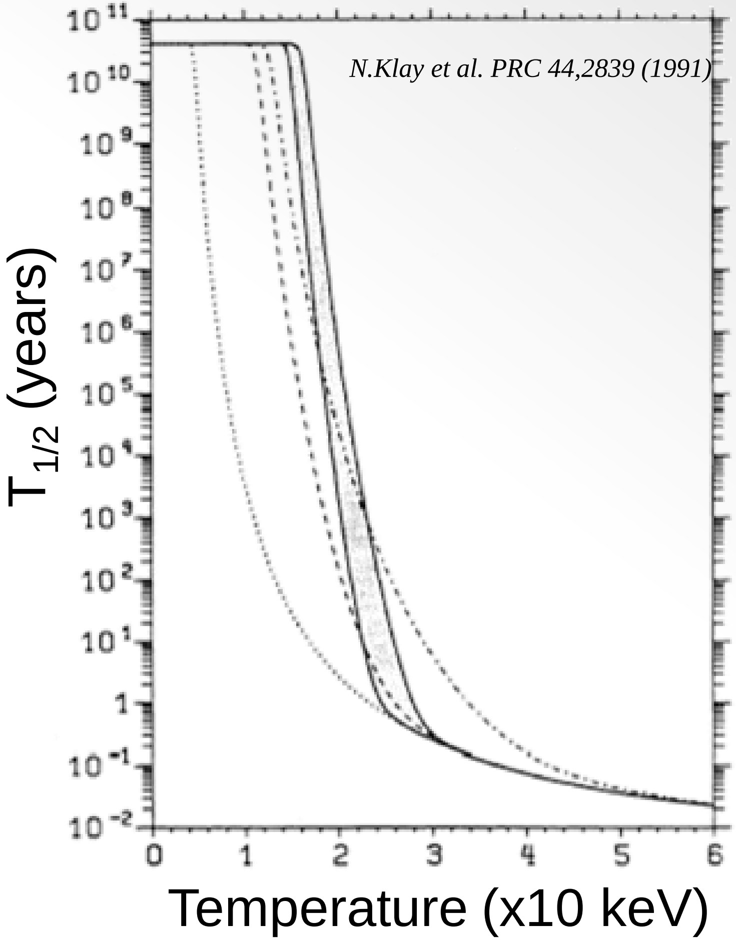


3,7 h 1- 123 keV

$3,7\times10^{10}$ ans 7-

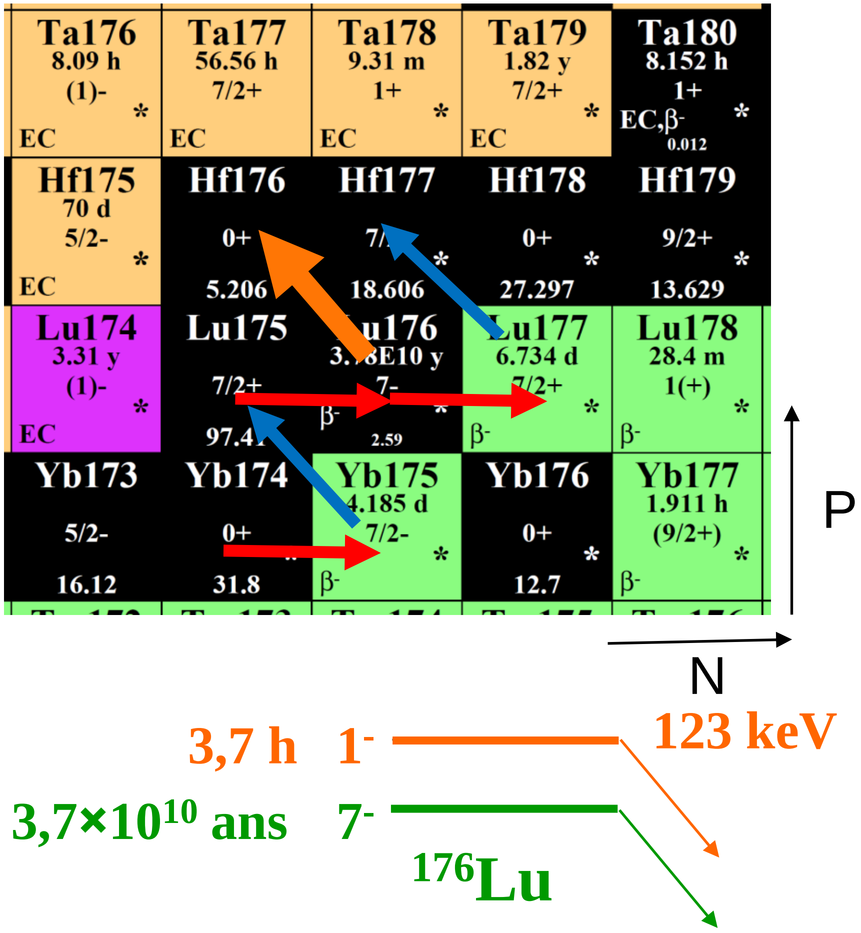
^{176}Lu



N.Klay et al. PRC 44,2839 (1991)

Half-life of an excited state

Astrophysical consequences : S process and abundances



Ta176 8.09 h (1)- * EC	**Ta177** 56.56 h 7/2+ EC	**Ta178** 9.31 m 1+ * EC	**Ta179** 1.82 y 7/2+ * EC	**Ta180** 8.152 h 1+ EC,β- * 0.012
Hf175 70 d 5/2- * EC	**Hf176** 0+ 5.206	**Hf177** 7/ * 18.606	**Hf178** 0+ * 27.297	**Hf179** 9/2+ * 13.629
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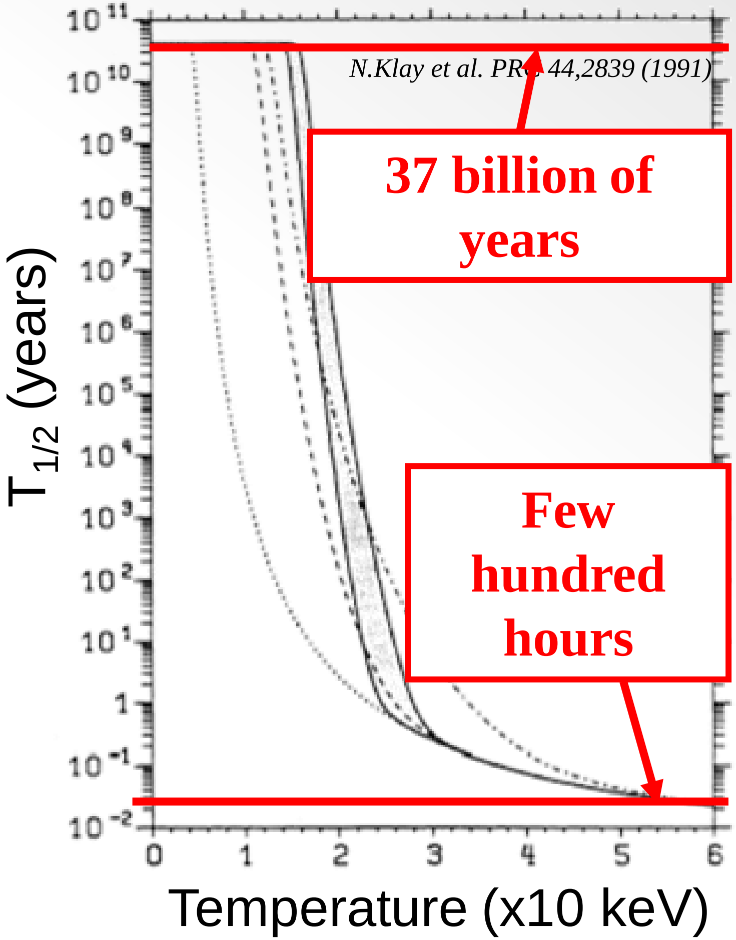


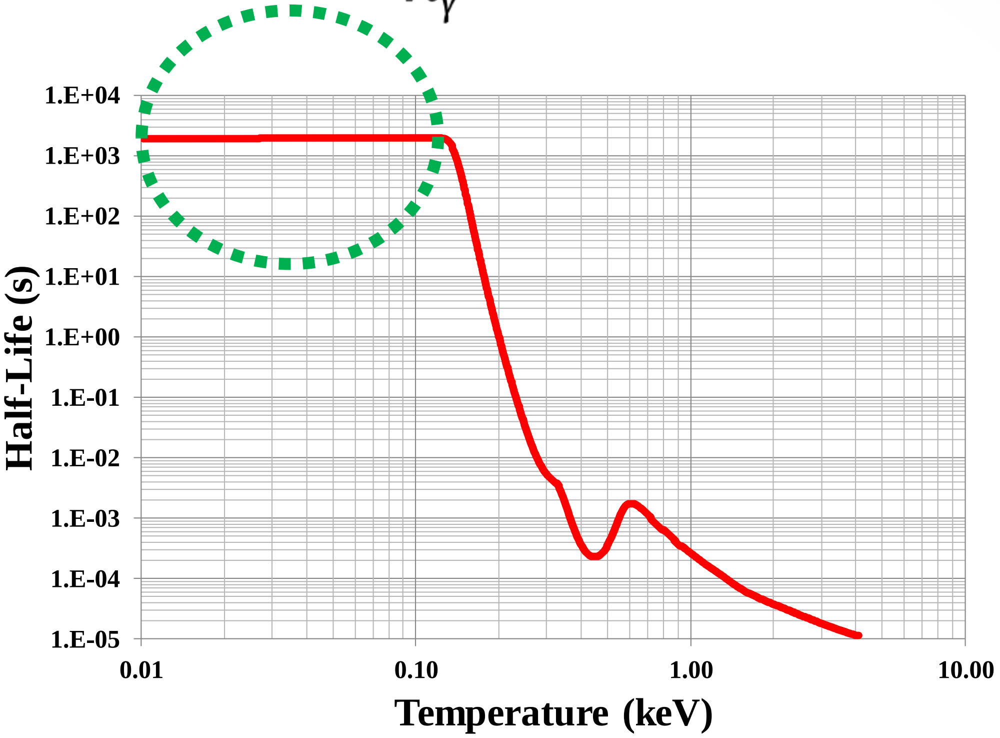
N.Klay et al. PRC 44,2839 (1991)

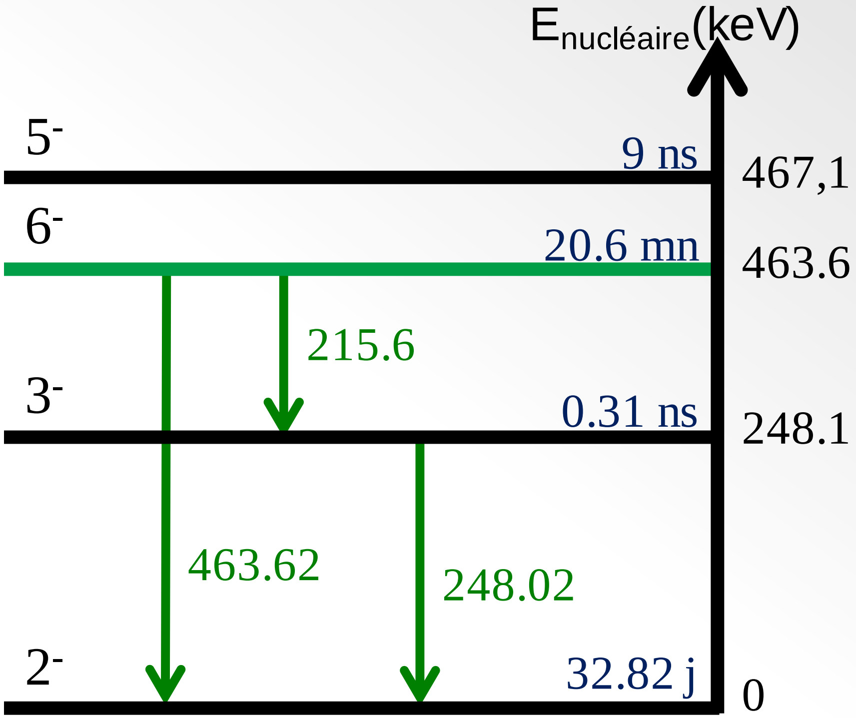
The abundance ratio between ^{176}Hf / ^{177}Hf is modified in a hot plasma

Half-life of an excited state

Demonstration of $T_{1/2}$ modification in a plasma : ^{84}Rb case

$$T_{1/2} = \frac{\ln(2)}{\lambda_\gamma}$$





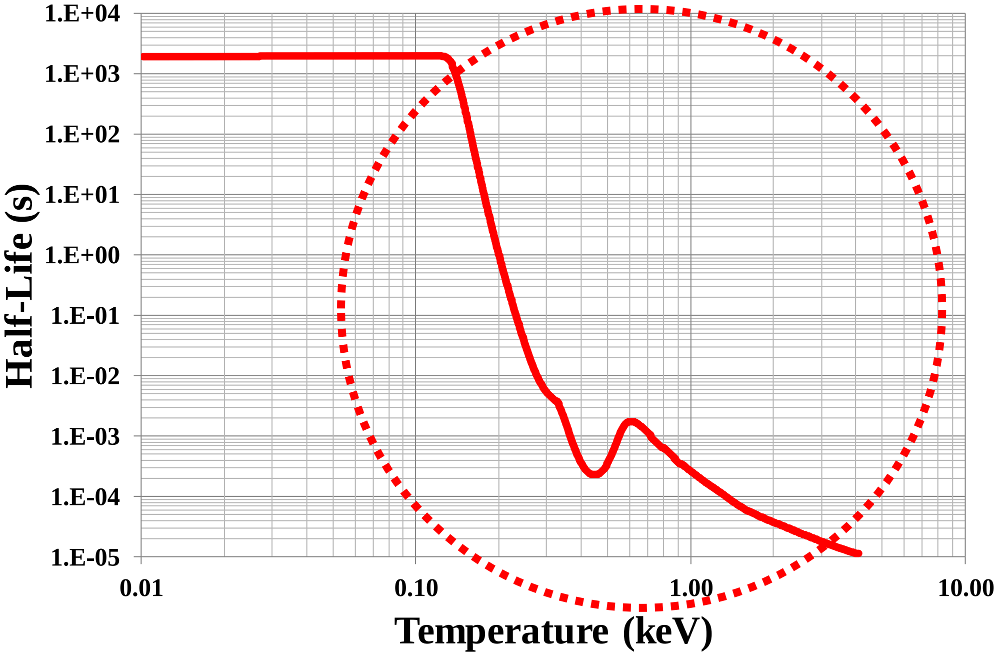
Partial level scheme of ^{84}Rb nucleus

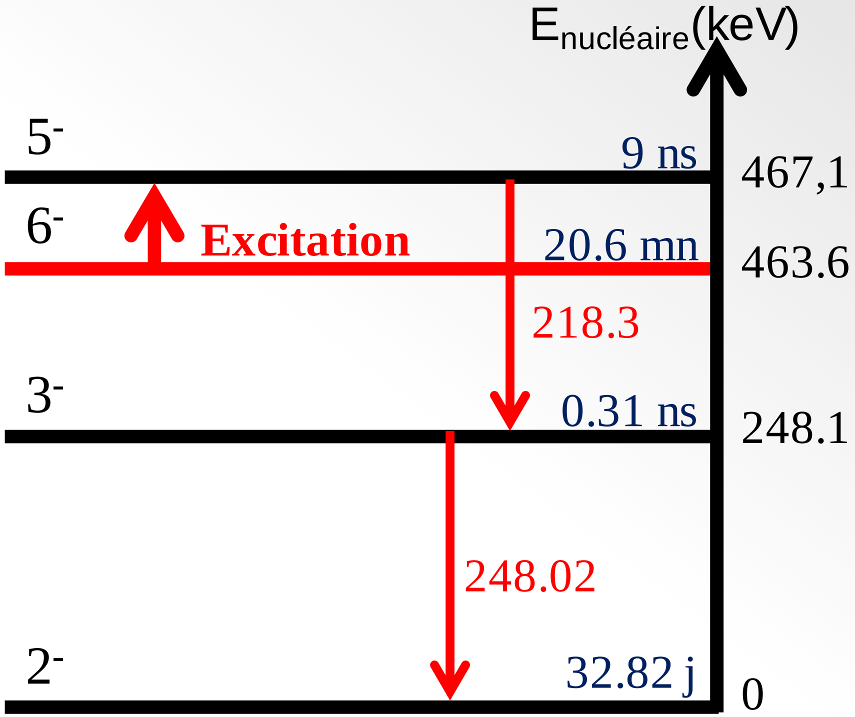
D.Denis-Petit et al. Ch.21, Applications of Laser-Driven Particle Acceleration, Eds. Parodi, Bolton, Schreiber, CRC press, ISBN 9781498766418 (2018)

Half-life of an excited state

Demonstration of $T_{1/2}$ modification in a plasma : ^{84}Rb case

$$T_{1/2} = \frac{\ln(2)}{\lambda_\gamma + \lambda_{excit}}$$





Partial level scheme of ^{84}Rb nucleus

D.Denis-Petit et al. Ch.21, *Applications of Laser-Driven Particle Acceleration*, Eds. Parodi, Bolton, Schreiber, CRC press, ISBN 9781498766418 (2018)

Half-life of an excited state

Demonstration of $T_{1/2}$ modification in a plasma : ^{84}Rb case

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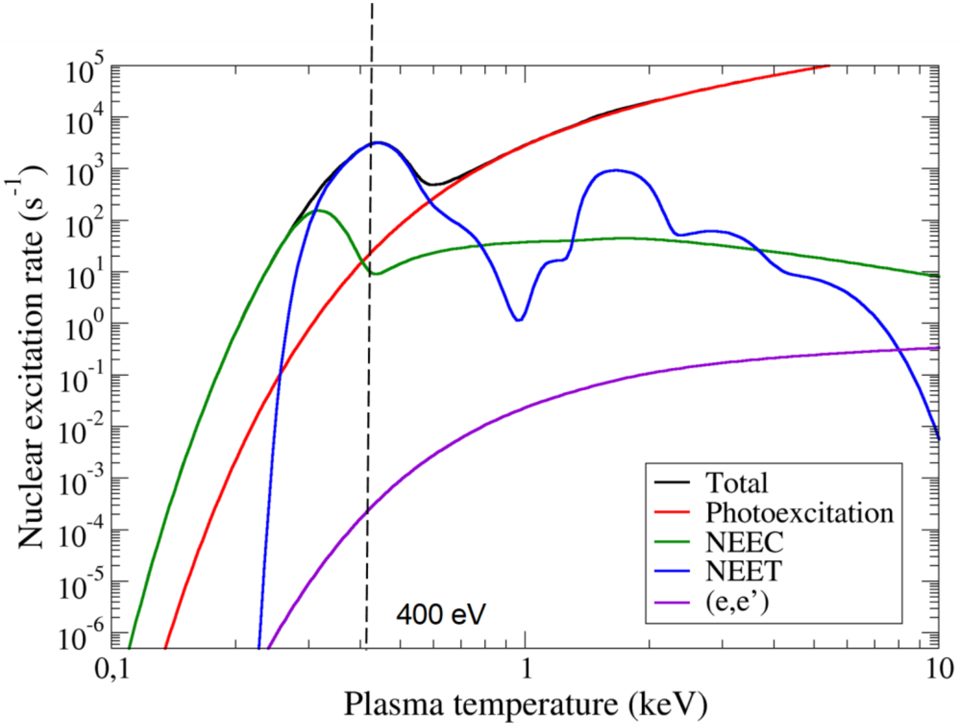
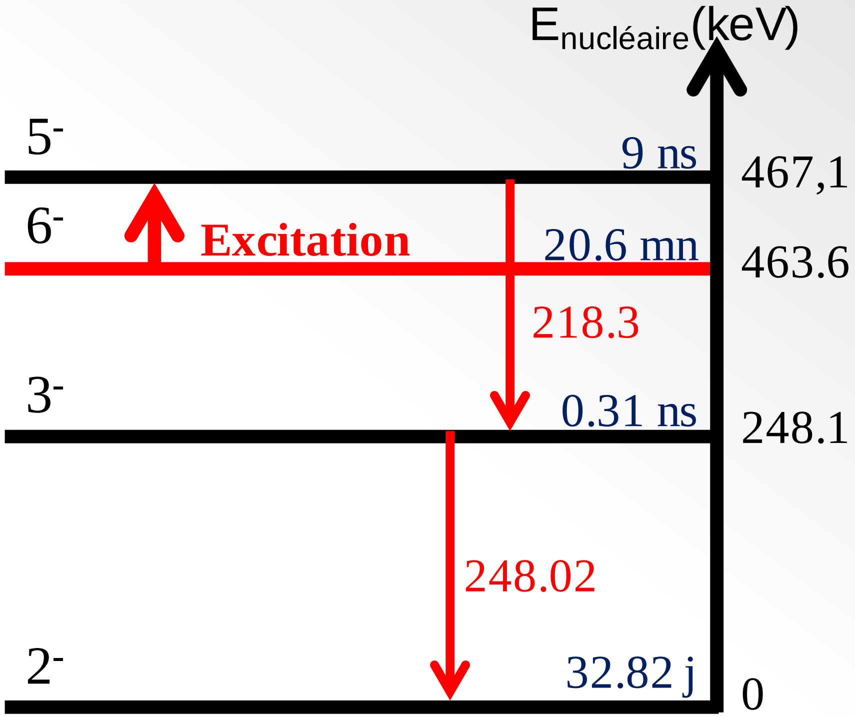




Partial level scheme of ^{84}Rb nucleus

ISOMEX code based on a Relativistic Average Atom Model under LTE hypothesis.

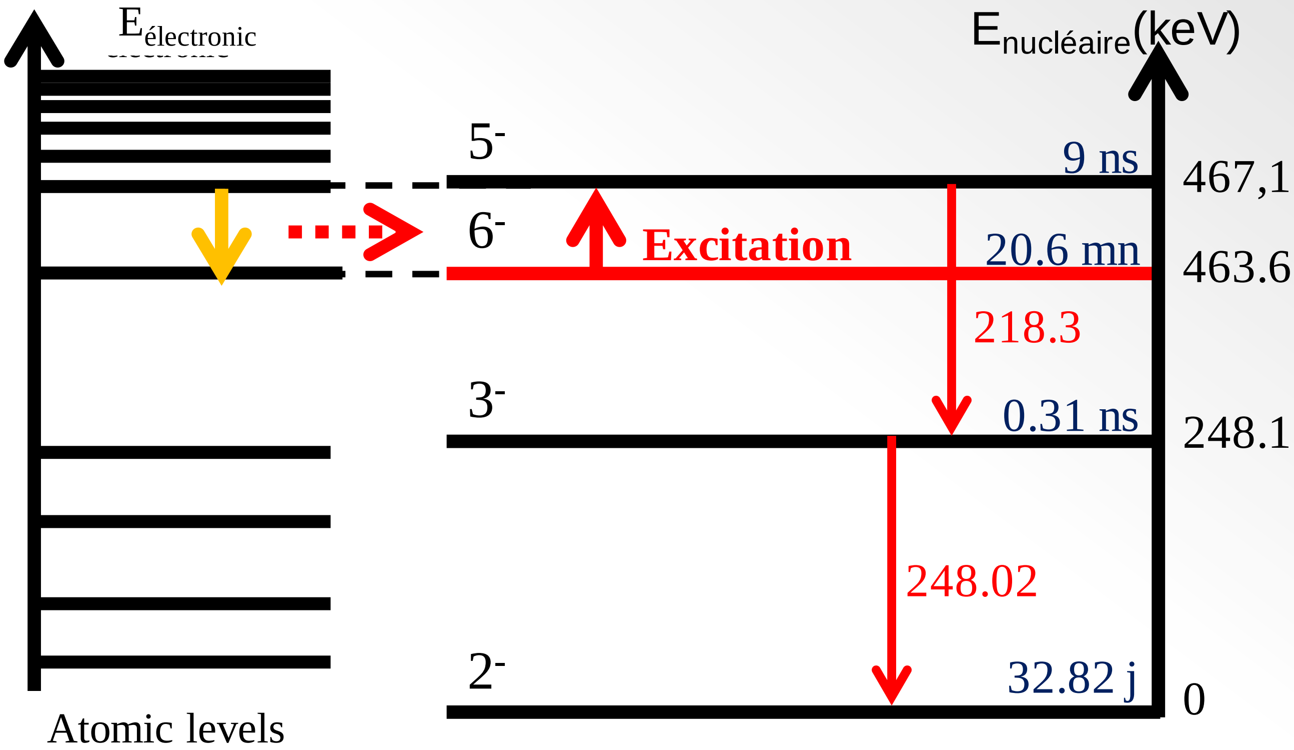
All the ions in plasmas are described by one average ion : still valid for resonant processes in light nucleus?

D. Denis-Petit, PhD thesis, University of Bordeaux , 2014

*B. Rozsnyai, Phys. Rev. A., **5**, 1137 (1972)*

Half-life of an excited state

NEET : Nuclear Excitation by Electronic Transition



Partial level scheme of ^{84}Rb nucleus

- Difference with photoexcitation: takes place in a single ion
- Nuclear and atomic transitions must be resonant
- Transitions with same multipolarities
- Observed in neutral target: ^{197}Au, ^{189}Os and ^{193}Ir

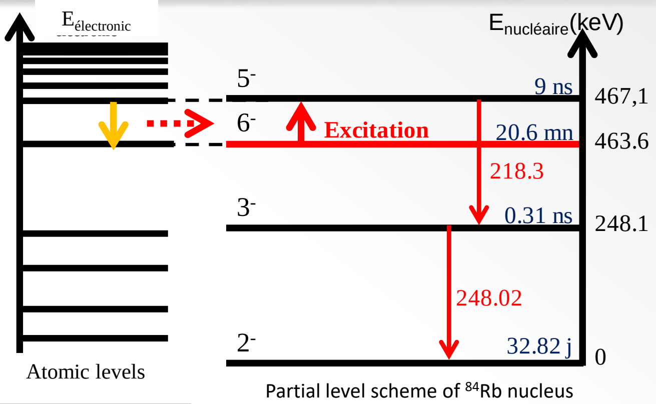
Kishimoto et al., Phys. Rev. Lett, ***85****, 1831 (2000)*
Ahmad et al., Phys. Rev. C, ***61****, 051304 (2000)*
Kishimoto et al., Nucl. Phys. A, ***748****, 3 (2005)*

- Not observed in plasmas: predictions

*Morel et al., Phys. Rev. A.****69****, 063414 (2004)*
Harston et al., Phys. Rev. C, ***59****, 2462 (1999)*

Half-life of an excited state

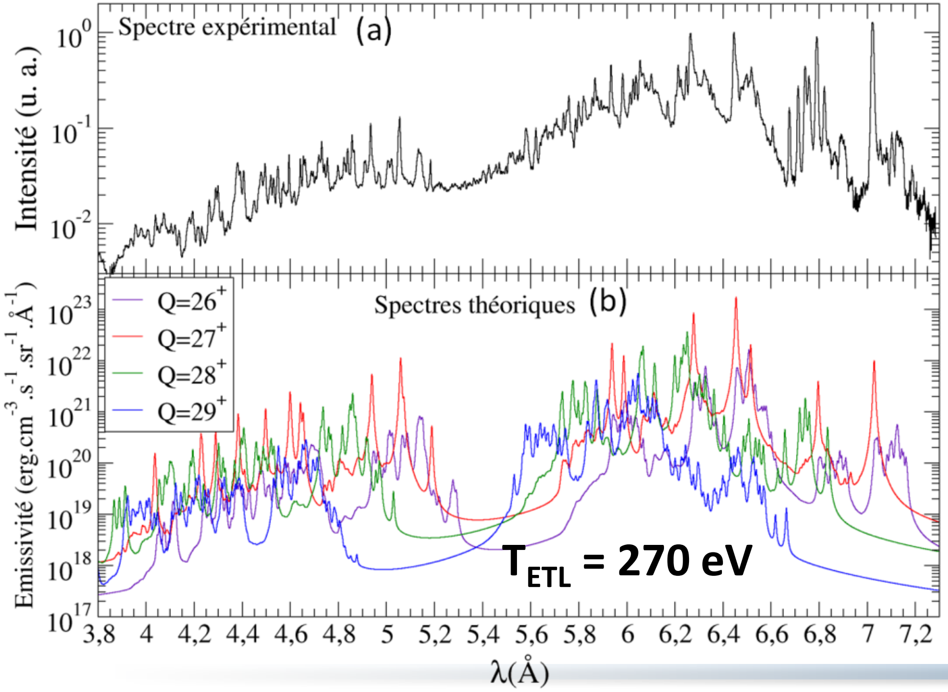
NEET rate estimation

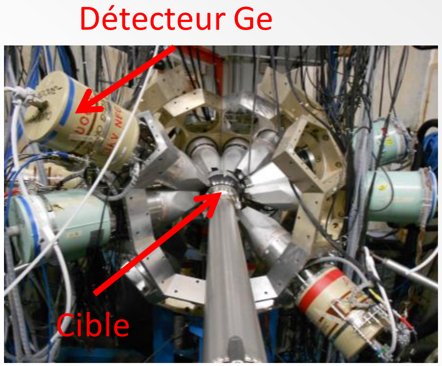


Partial level scheme of ^{84}Rb nucleus

Measurement of X Spectrum from a Rb plasma on PHELIX

Measurement of γ transition on ALTO / ORSAY





Transition	Nudat (keV)	Our results (keV)
$5^- \to 6^-$	2,69 ± 0,23 (γ) 3,05 ± 0,18 (levels) 3,4 (suggested)	3,498 ± 0,006

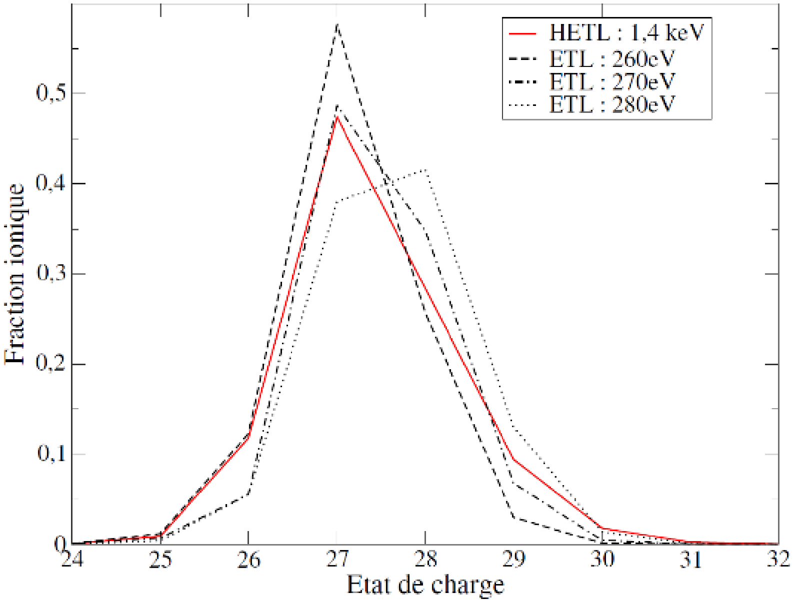
D. Denis-Petit et al.,Phys. Rev. C 96, 024604 (2017)

D. Denis-Petit et al., Journal of Quantitative Spectroscopy and Radiative Transfer 148 70-89 (2014)

Half-life of an excited state

NEET rate estimation

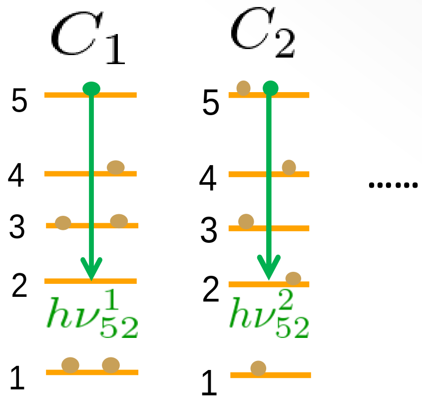
λ_{NEET} = **Plasma** + **Atom /ion** + **Nucleus**



Ionization Temperature (T_Z) model

$$\overline{Q_{ETL}}(\rho, T_Z) = \overline{Q_{NETL}}(\rho, T_e)$$

→Saha-Boltzmann distribution for electronic population



Multi-Configuration Dirac-Fock (MCDF) calculations of electronic configurations :
-atomic levels
-atomic transitions

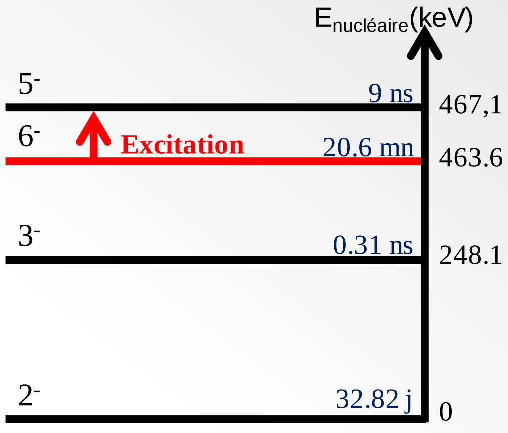


Schéma de niveaux partiel du ^{84}Rb

Shell model calculations of transition probability $B_{5^- \to 6^-}$ (M1)

But uncertainties exist on atomic calculations and nuclear transitions measurements

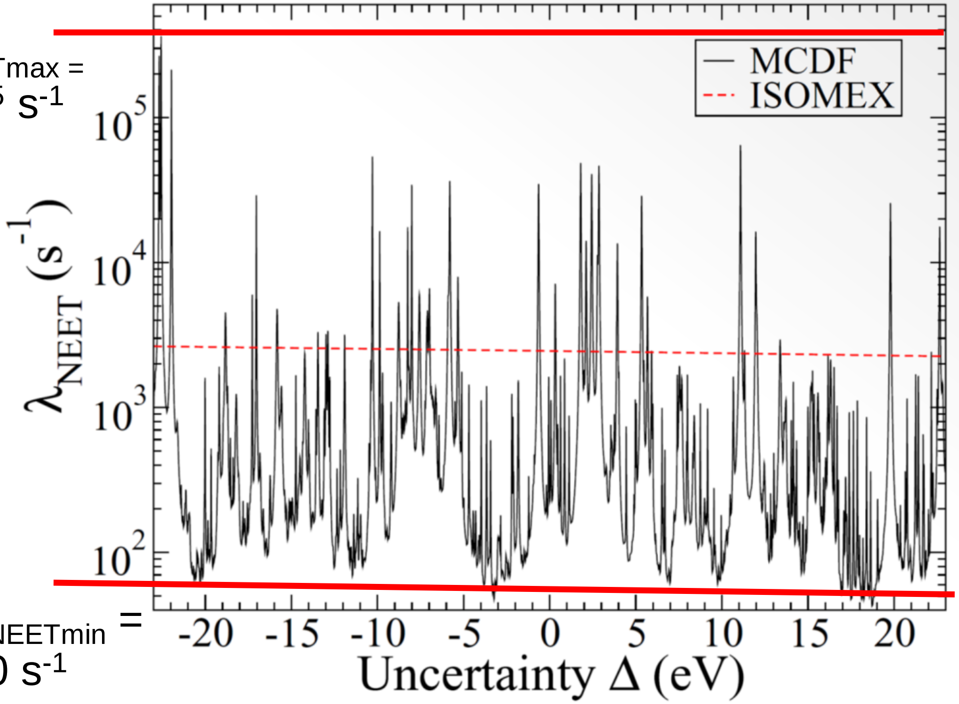
Half-life of an excited state

NEET rate estimation

- NEET rate evolution depending of uncertainty parameter Δ:

$$\left.\begin{array}{l} E_{nuclear} \pm \Delta E_{nuclear} \\ E_{electronic} \pm \Delta E_{electronic} \end{array}\right\} \quad \Delta^2 = \Delta E_{nuclear}^2 + \Delta E_{electronic}^2$$

Plasma :
$Q=29^+$ to 34^+
$T_Z = 400$ eV (LTE)
$T_e > 2$ keV (NLTE)
$\rho=10^{-2}$ g/cm^3



$\lambda_{NEETmax} = 4.10^5$ s^{-1}

$\lambda_{NEETmin} = 50$ s^{-1}

D. Denis-Petit et al. Phys. Rev. C 96, 024604 (2017)

Quantity	Value	Uncertainty
Atomic line energy	MCDF	5 eV at 1σ
Nuclear line energy	3,498 keV	6 eV at 1σ
Atomic line width	Baranger	Factor 10
Reduced transition probability	0.08 W.u.	Factor 2

M. Baranger, Phys. Rev. 112, 855 (1958)

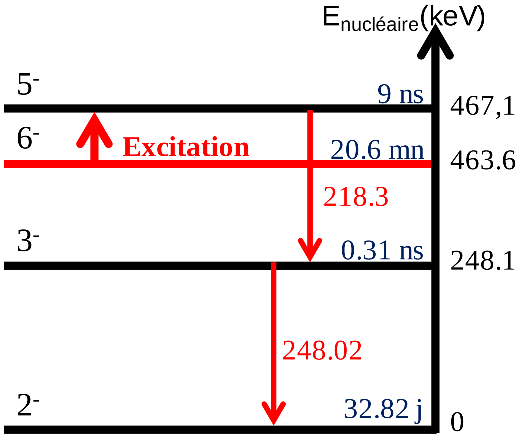
Half-life of an excited state

NEET rate estimation

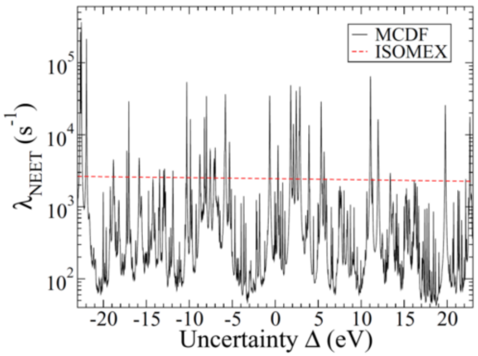
- NEET rate evolution depending of uncertainty parameter Δ:

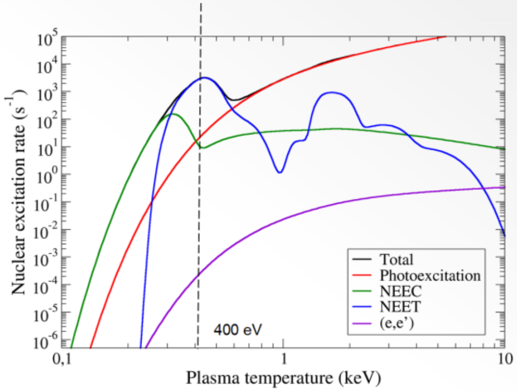
$$\left.\begin{array}{l} E_{nuclear} \pm \Delta E_{nuclear} \\ E_{electronic} \pm \Delta E_{electronic} \end{array}\right\}$$

$$\Delta^2 = \Delta E_{nuclear}{}^2 + \Delta E_{electronic}{}^2$$



Partial level scheme of ^{84}Rb nucleus





Plasma Temprature	$\lambda_{6^- \to 5^-}$ min	$\lambda_{6^- \to 5^-}$ max
270 eV LTE	~60 s^{-1}	~500 s^{-1}
400 eV LTE	~30 s^{-1}	~10^6 s^{-1}

Calculations not precise enough and can not deny the excitation → experiment needed

D. Denis-Petit et al. Phys. Rev. C 96, 024604 (2017)

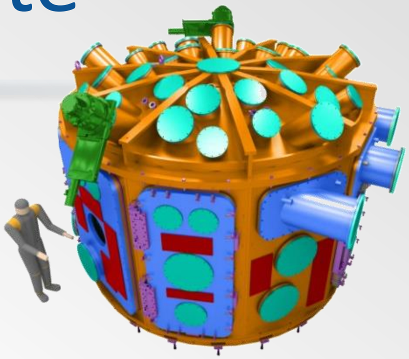
Half-life of an excited state

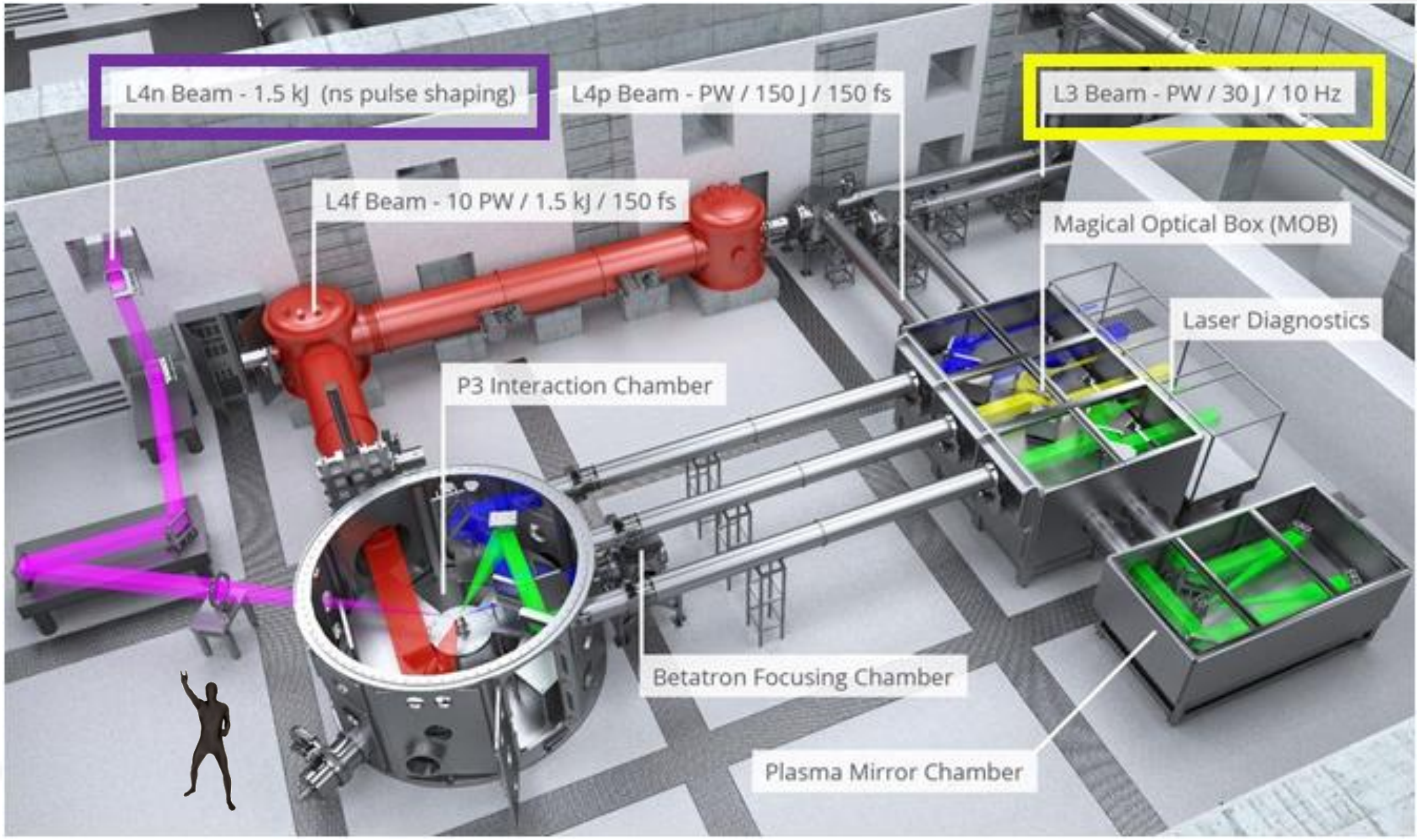
^{84}Rb experiment

ELI-Beamlines, Prague

30J ; 30 fs @10Hz

1.5 kJ ; 1 ns @ 1 tir/min

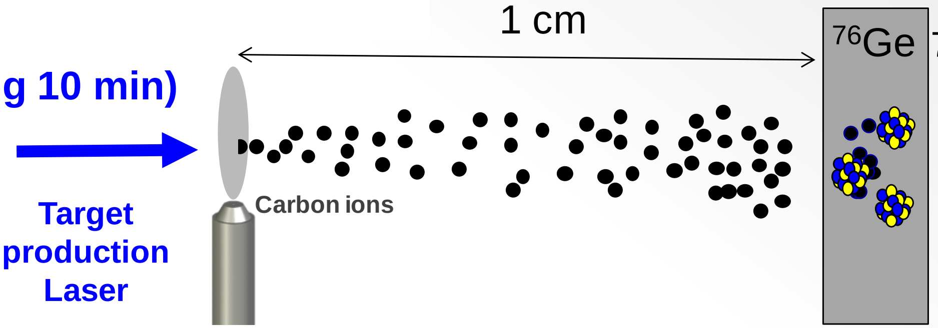




Half-life of an excited state

^{84}Rb experiment

1 PW @10Hz (during 10 min)
30J – 30 fs



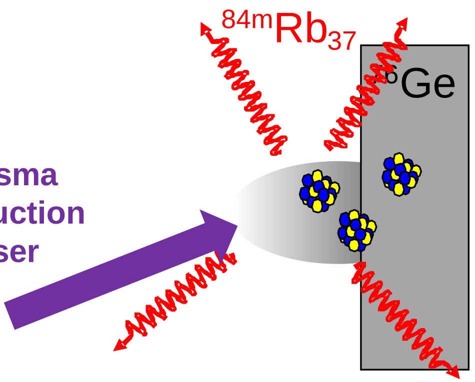
^{76}Ge(^{12}C,p+3n)^{84m}Rb

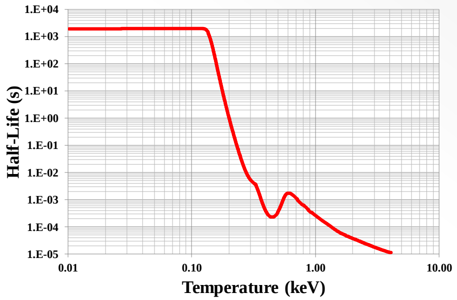
~10^8 nuclei of ^{84m}Rb produced in a ~5 mm diameter and 3 µm thick layer

γ 218 keV
γ 248 keV

1.5 TW / 10min

1.5 kJ – 1ns





Hypothesis on plasma characteristics:

30 µm thickness
250 µm diameter
Q=29+ to 34+
ρ =10^{-2} g/cm^3
} during 30 ps

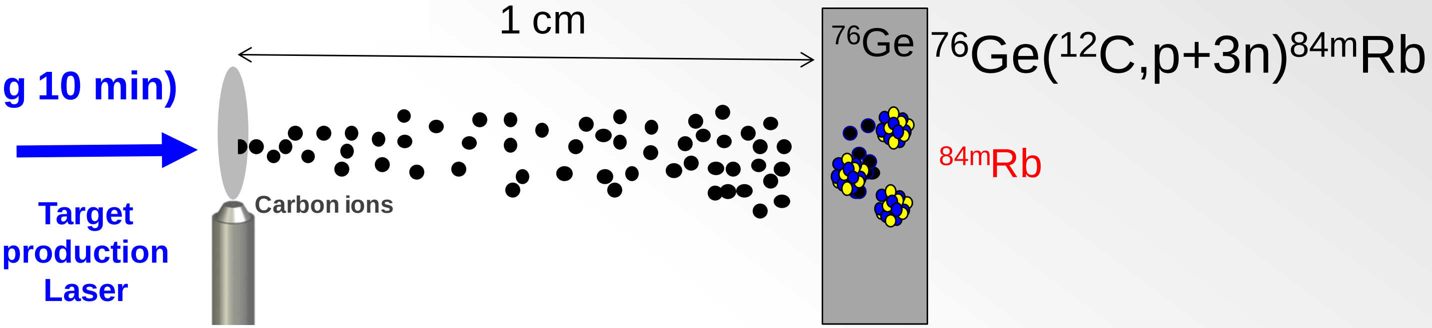
Per shot : $\sim 3 < N_{de\text{-}ex} < \sim 3000$
Per day: $\sim 100 < N_{de\text{-}ex} < \sim 400\,000$
with144 cycles /day

D.Denis-Petit et al. Ch.21, Applications of Laser-Driven Particle Acceleration, Eds. Parodi, Bolton, Schreiber, CRC press, ISBN 9781498766418 (2018)
F. Negoita et al. , Romanian Reports in Physics, Vol. 68, Supplement, P. S37–S144, 2016

Half-life of an excited state

^{84}Rb experiment

1 PW @10Hz (during 10 min)
30J – 30 fs



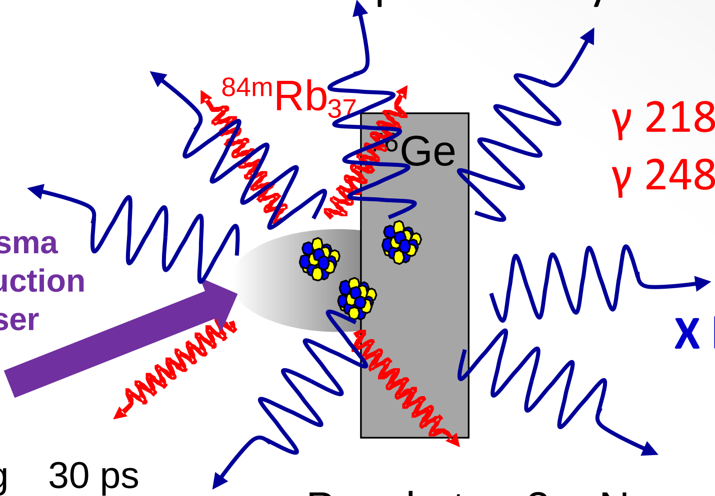
Target production Laser

^{76}Ge(^{12}C,p+3n)^{84m}Rb

~10^8 nuclei of ^{84m}Rb produced in a ~5 mm diameter and 3 µm thick layer

1.5 TW / 10min

1.5 kJ – 1ns



Plasma production laser

γ 218 keV
γ 248 keV

X background

Hypothesis on plasma characteristics:

30 µm thickness
250 µm diameter
Q=29+ to 34+ } during 30 ps
ρ =10^{-2} g/cm^3

Per shot : ~3 <N_{de-ex} < ~3000
Per day: ~100 <N_{de-ex} < ~400 000
with144 cycles /day

D.Denis-Petit et al. Ch.21, Applications of Laser-Driven Particle Acceleration, Eds. Parodi, Bolton, Schreiber, CRC press, ISBN 9781498766418 (2018)
F. Negoita et al. , Romanian Reports in Physics, Vol. 68, Supplement, P. S37–S144, 2016

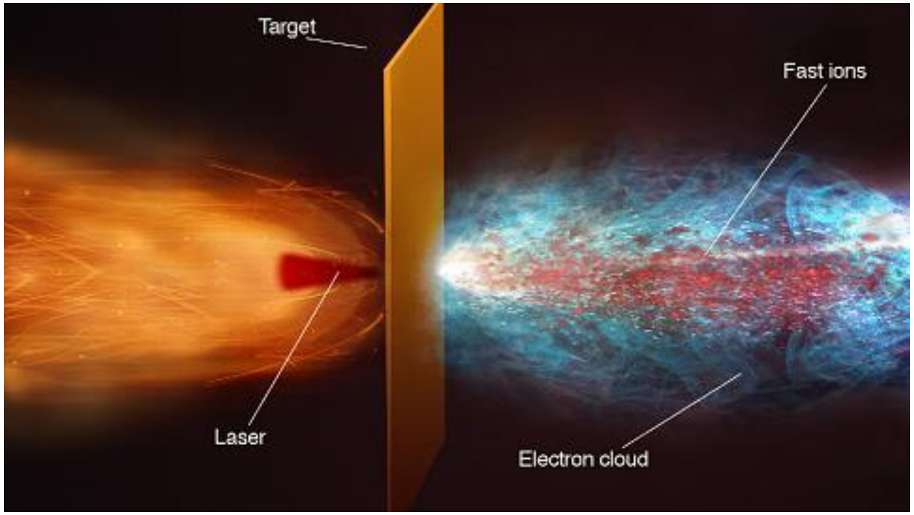
Part 4

CHALLENGES TO TAKE UP

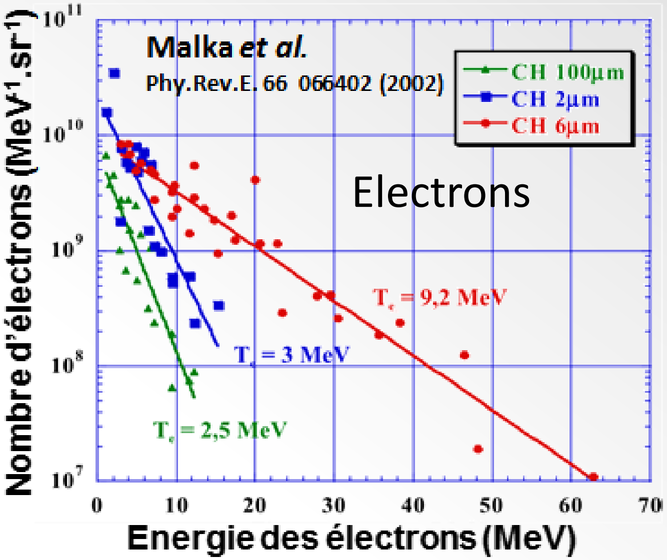
- The detection in high power laser environment
- High repetition rate lasers

The detection in high power laser environment

2.10^{19}W/cm²

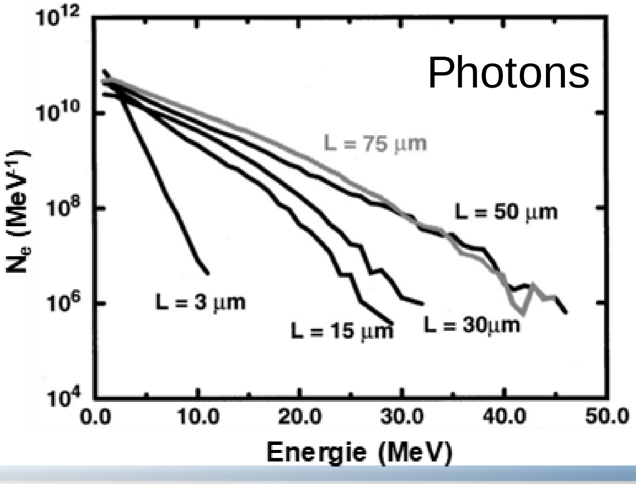


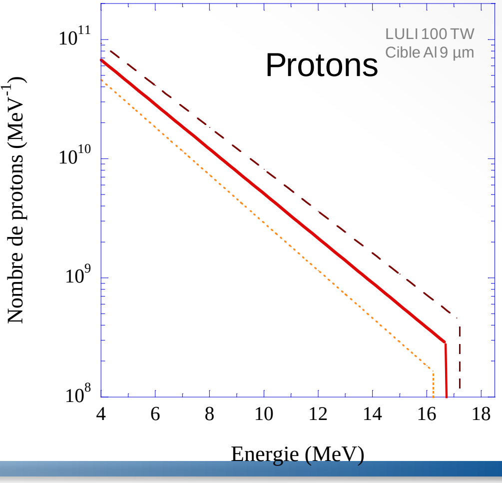
A. Macchi et al., Rev Mod Phys, vol 85, april–june 2013



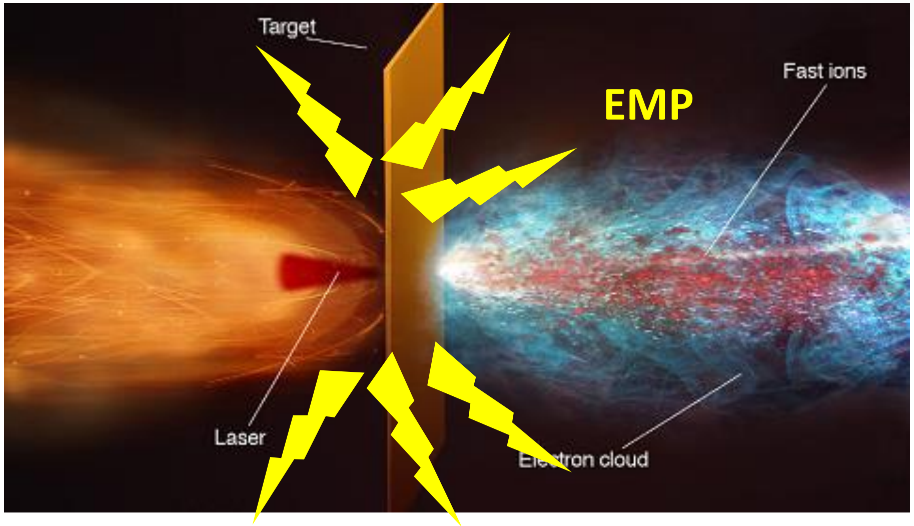
- ✓ **Physical signals in detectors :**

E ~ 0.1 J (~10^{12} MeV) in few ns
P ~ 100 MW
Φ ~10^{8} W/cm²

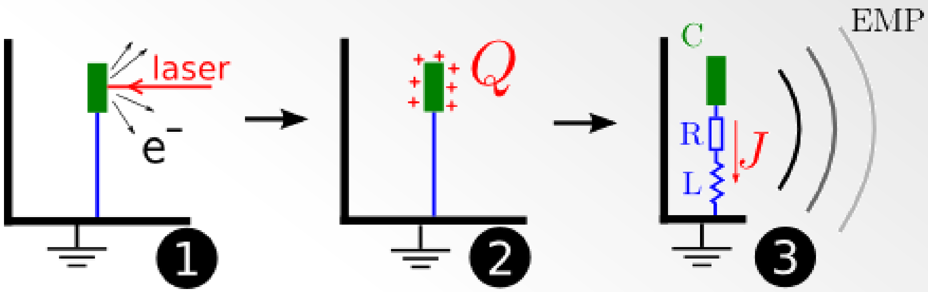


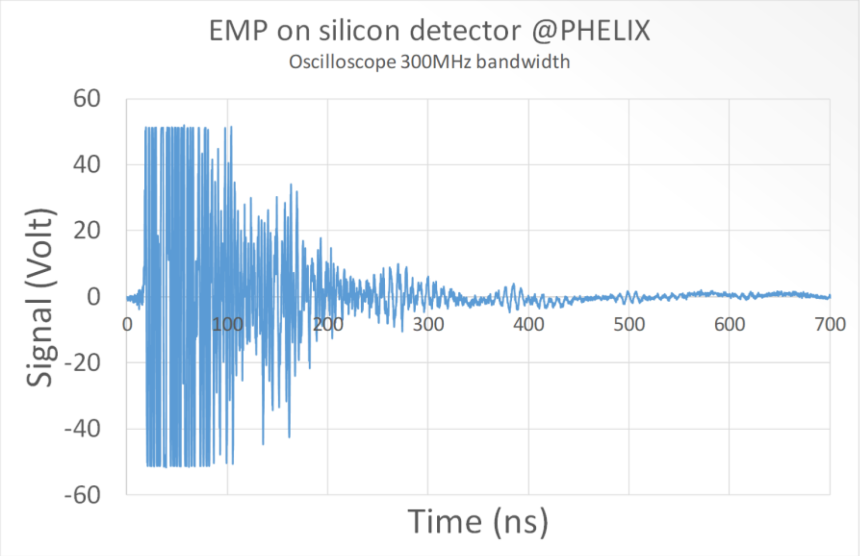


The detection in high power laser environment



J.-L. Dubois, et al., Phys. Rev. E 89, 013102 (2014).



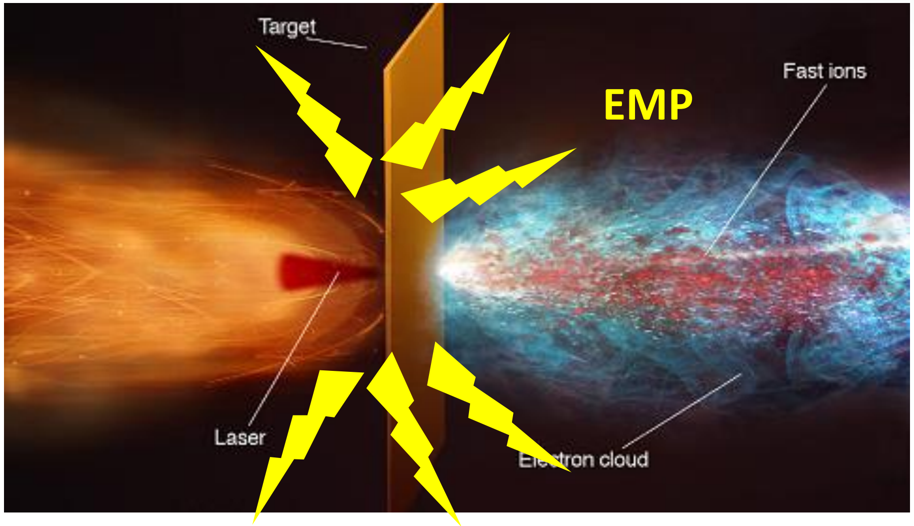


- ✓ **Physical signals in detectors :**

E ~ 0.1 J (~10^{12} MeV) in few ns
P ~ 100 MW
Φ ~10^{8} W/cm²

- ✓ **Electro Magnetic Pulse (EMP) Susceptibility**

The detection in high power laser environment



- ✓ **Physical signals in detectors :**

E ~ 0.1 J (~10^{12} MeV) in few ns
P ~ 100 MW
Φ ~10^{8} W/cm²

➡ **Use passive detectors**

- ✓ **Electro Magnetic Pulse (EMP) Susceptibility**

CR39

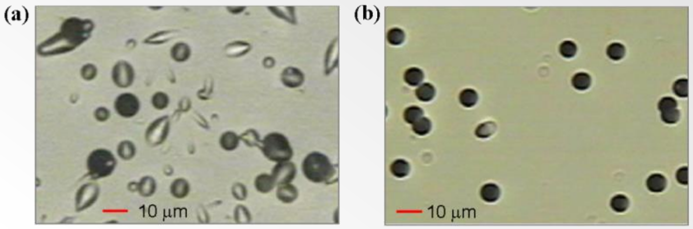
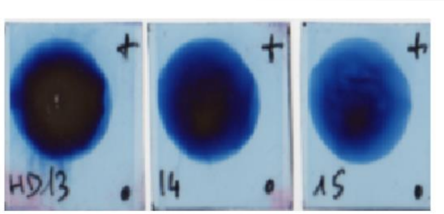


Fig. 3. Typical pictures of etched track pits caused by two different particles. (a) 5.4-MeV α particles (b) ~0.9-MeV protons.

JY.LEE et al. ; Journal of the Korean Physical Society, Vol. 51, No. 1, July 2007

Counting the number of tracks

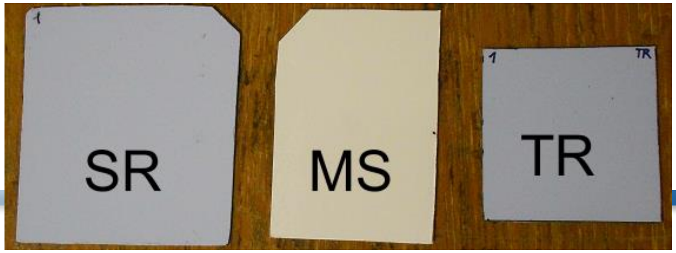
RCF



Gafchromic ©

Optical Density measurement

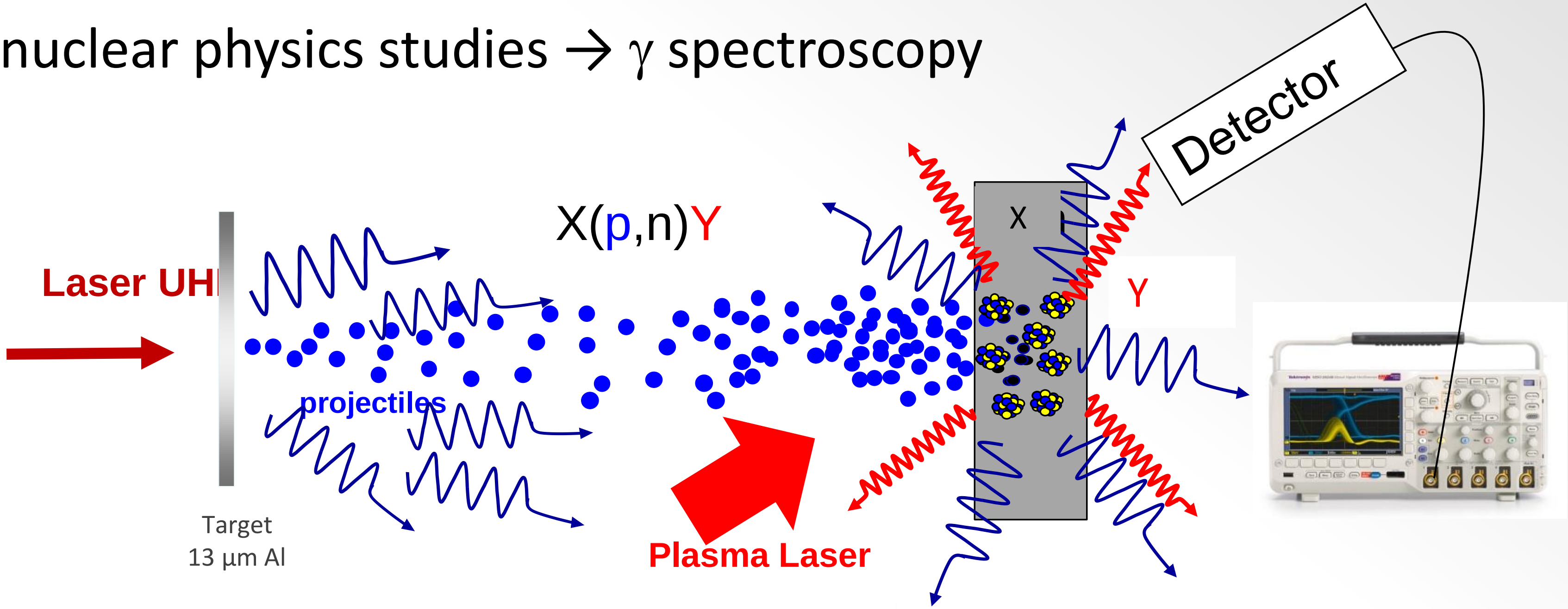
IP



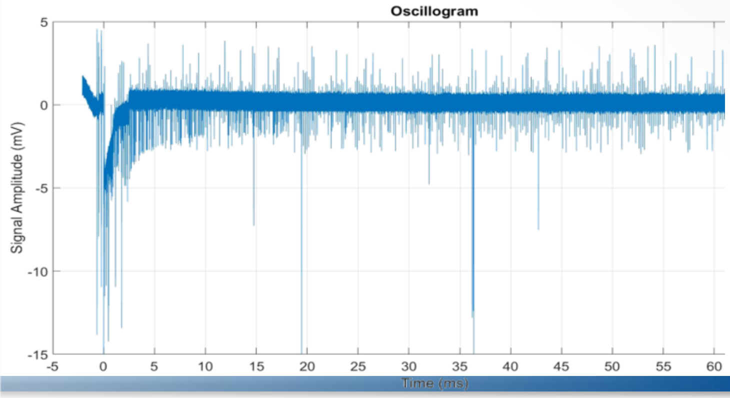
Fuji©

The detection in high power laser environment

For nuclear physics studies → γ spectroscopy



Digitalisation of all the signals :
1 Gs/s ; 14 bits ; during ~1 s



See E. Atukpor poster

The detection in high power laser environment

For nuclear physics studies → γ spectroscopy

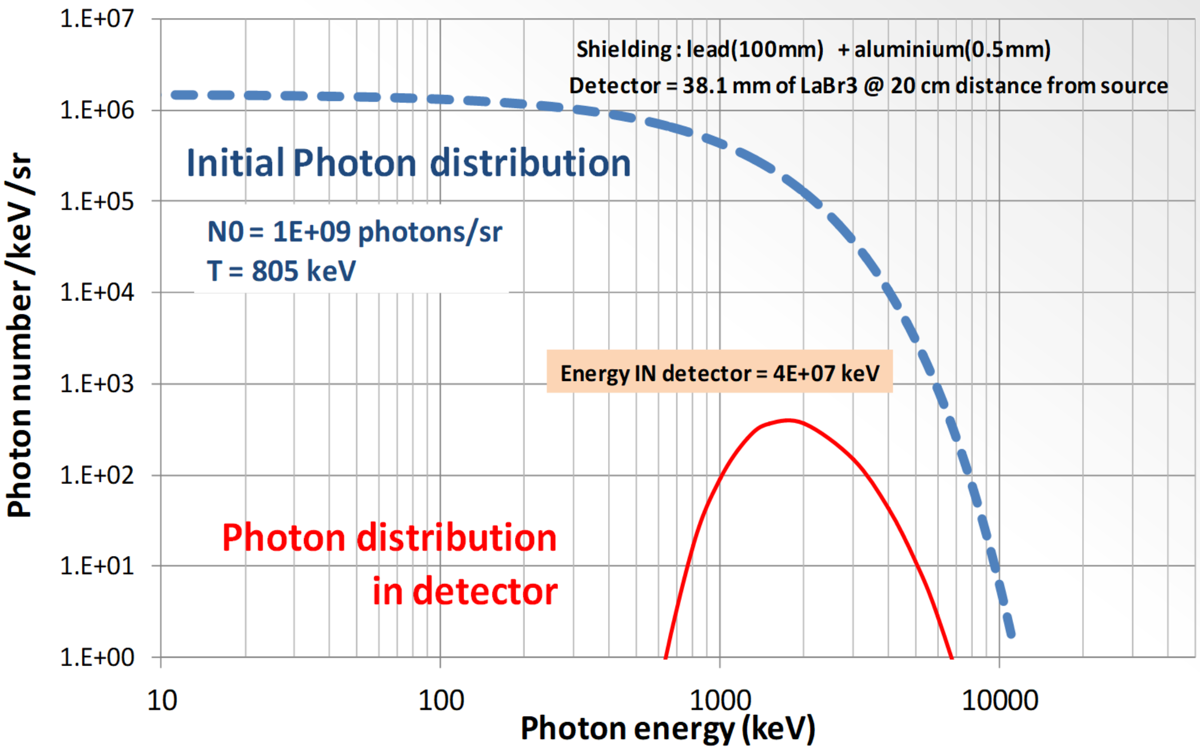
- X ray Shielding ?

✓A lot of soft X rays

✓Still 40 GeV energy deposition in $LaBr_3$ through 10 cm thick Pb shield

✓A 10µm diameter hole @20 cm let pass through 1MeV deposit in a LaBr3 detector

→ We need a sealed shielding , but not compatible with detection of few photon detection of ~100s of keV



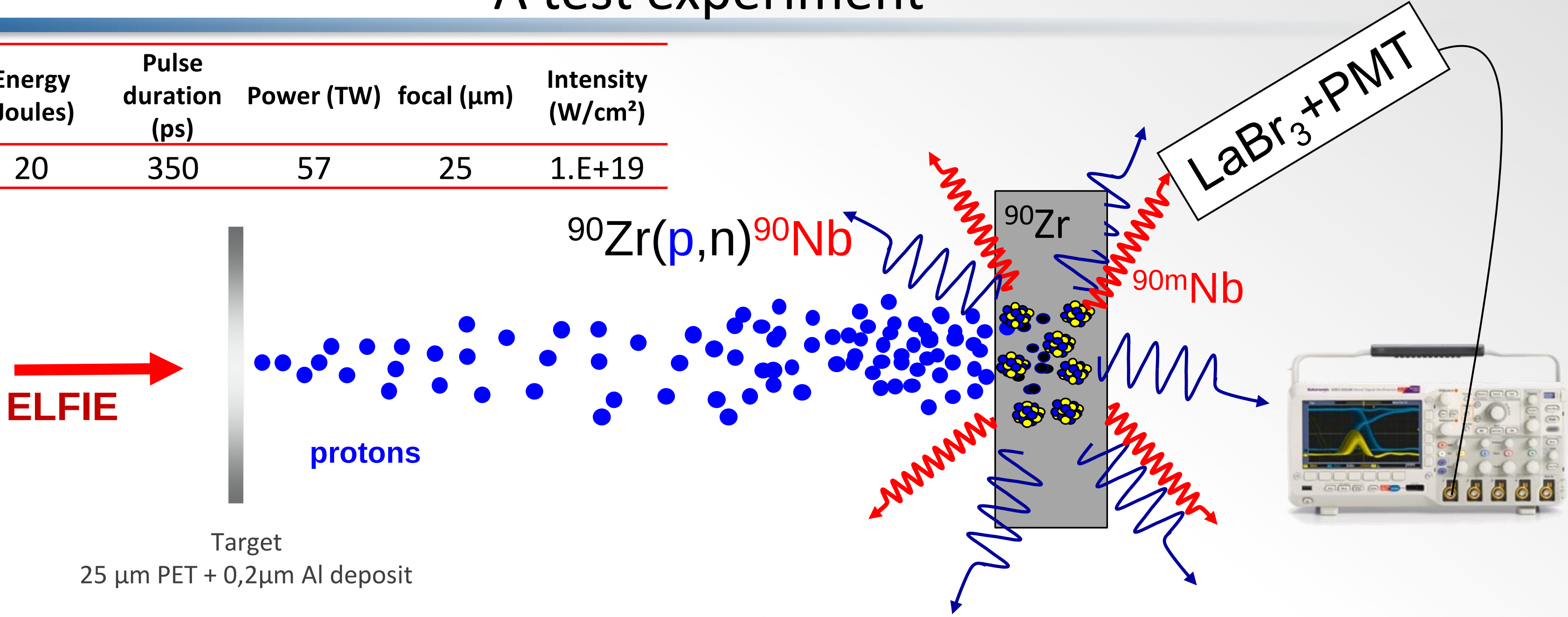
M.Tarisien, et al., IEEE Transactions on Nuclear Science, Vol 65, issue 8, p.2216-2219 (2018)

The detection in high power laser environment

A test experiment

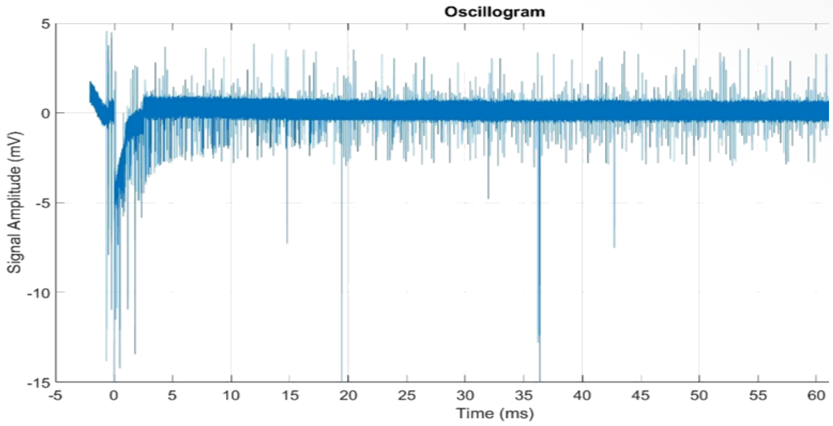
Laser	Energy (Joules)	Pulse duration (ps)	Power (TW)	focal (µm)	Intensity (W/cm²)
LULI Elfie	20	350	57	25	1.E+19

2014



Target
25 µm PET + 0,2µm Al deposit

Level Energy and Spin	Half life	γ transition Energy
0 keV ; 8+	14,6 h	/
122.37 keV ; 6+	63 µs	122.37 keV
382.01 keV ; 1+	6.19 ms	257.34 keV



F. Negoita et al., AIP Conference Proceedings 1645, 228 (2015)

The detection in high power laser environment

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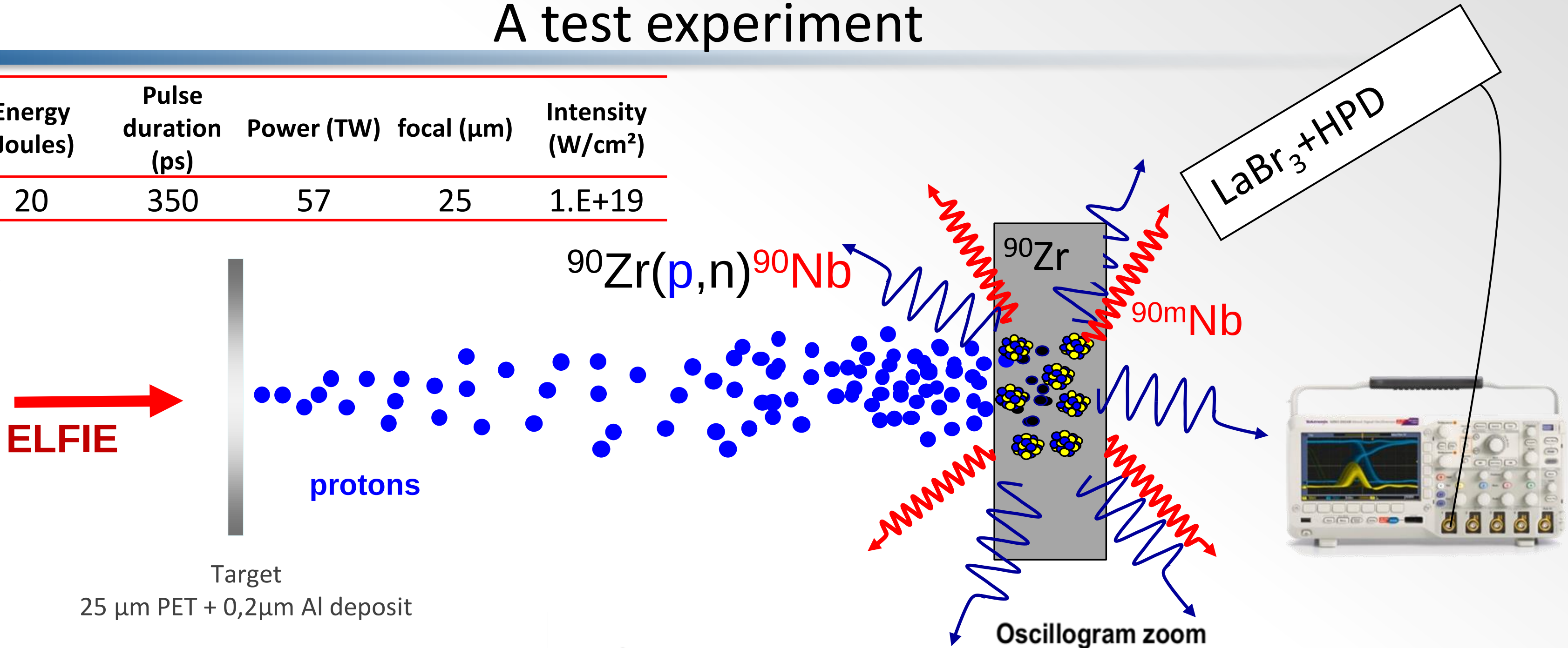
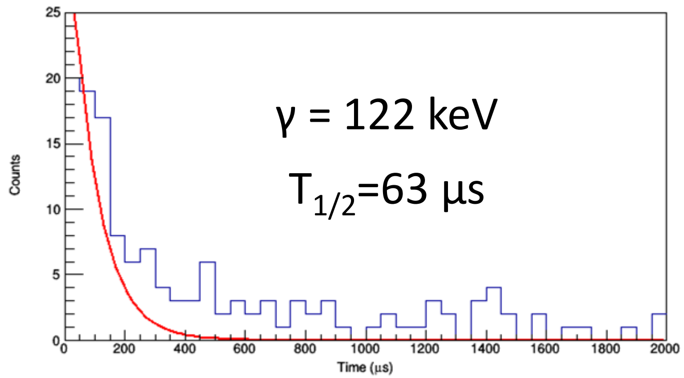
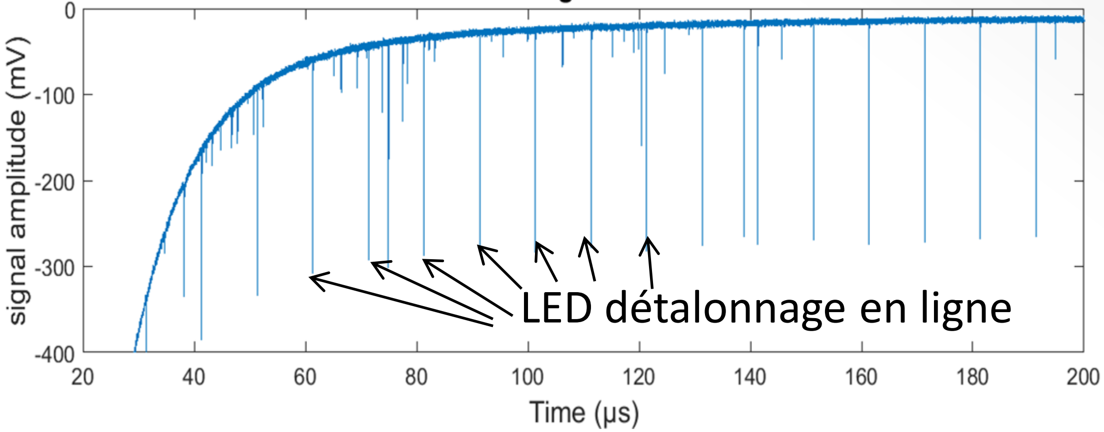


2016

Target
25 µm PET + 0,2µm Al deposit



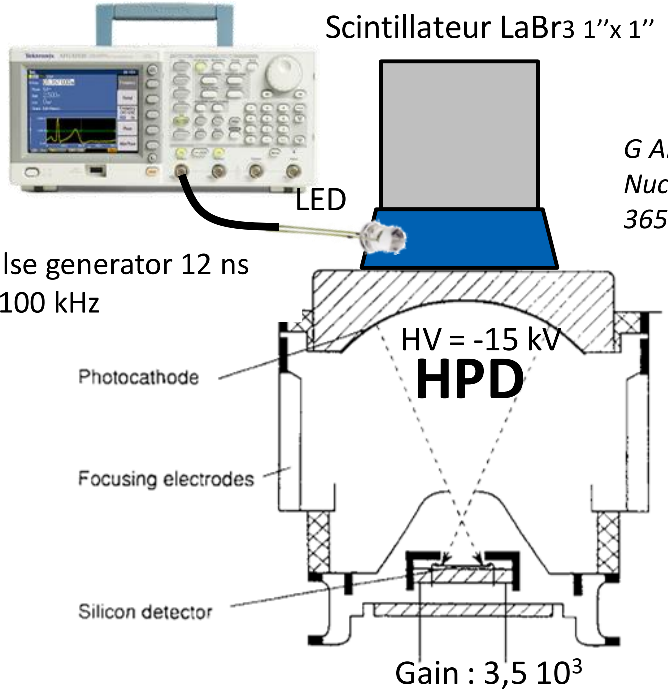
Oscillogram zoom



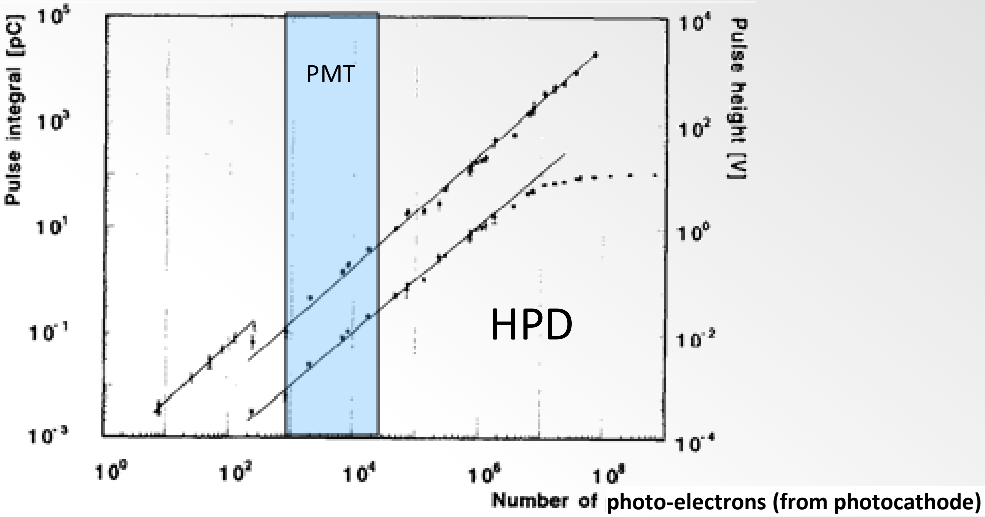
M.Tarisien, et al., IEEE Transactions on Nuclear Science, Vol 65, issue 8, p.2216-2219 (2018)

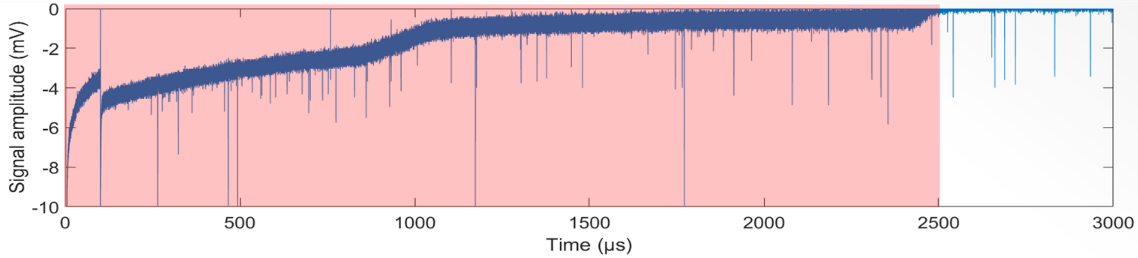
The detection in high power laser environment

A test experiment

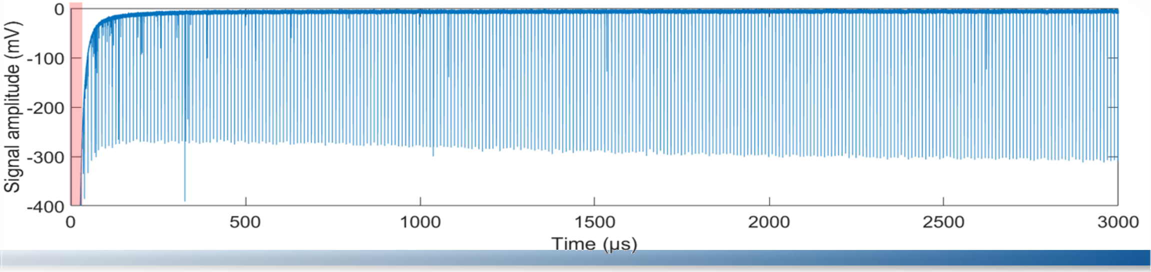


G Anzivino et al., Nucl.Instrum.Meth.A 365 (1995) 76-82





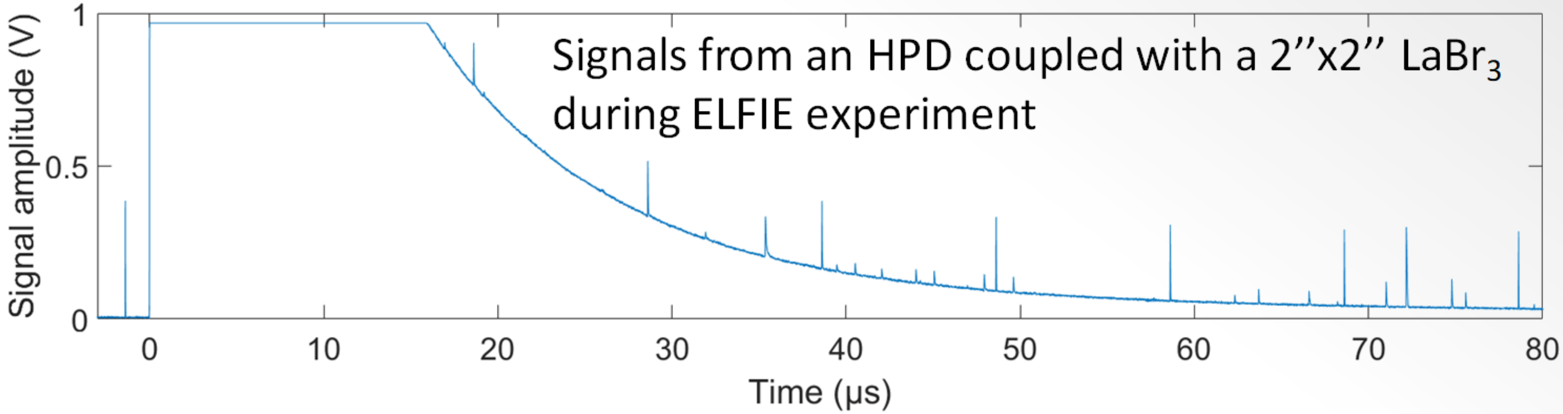
From 2500 µs recovery time to 50 µs



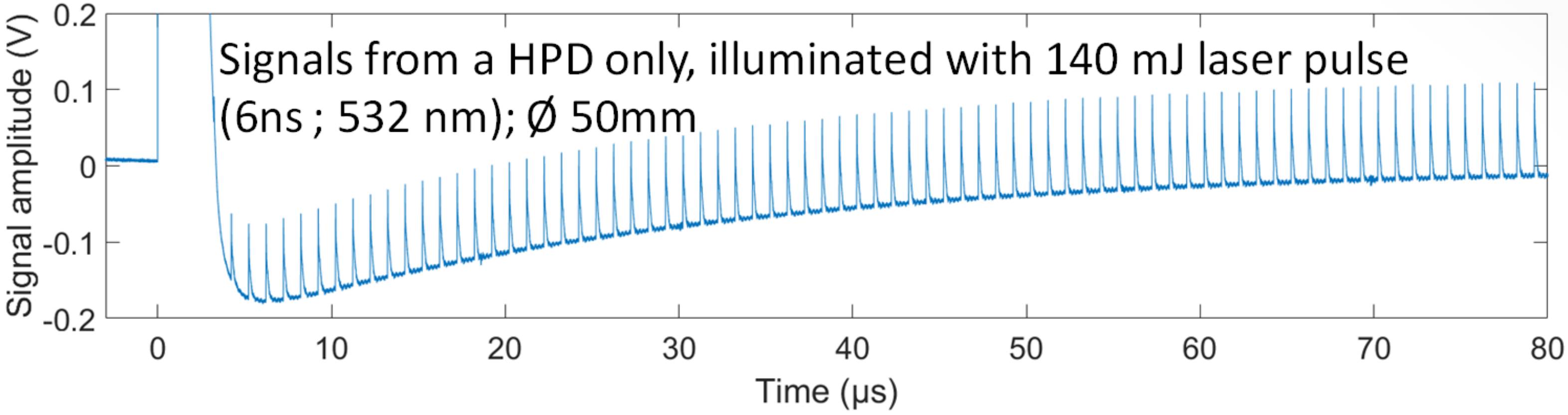
M.Tarisien, et al., IEEE Transactions on Nuclear Science, Vol 65, issue 8, p.2216-2219 (2018)

The detection in high power laser environment

Origin of long dead time?



Signals from an HPD coupled with a 2''x2'' $LaBr_3$ during ELFIE experiment



Signals from a HPD only, illuminated with 140 mJ laser pulse (6ns ; 532 nm); Ø 50mm

Afterglow is mainly responsible of long dead time

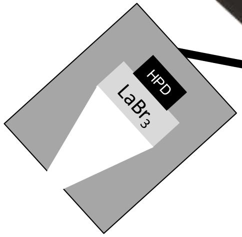
The detection in high power laser environment

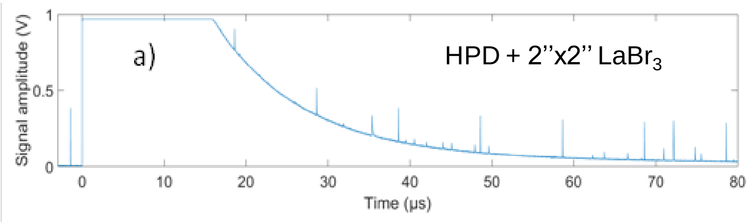
We are doing Instrumental research :

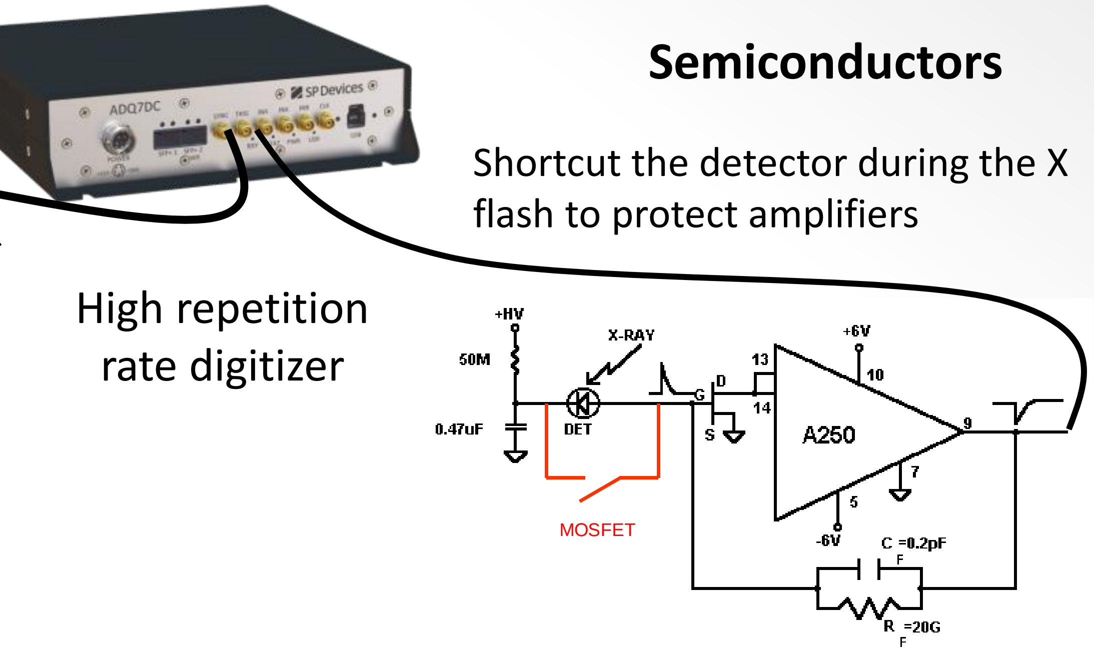
(E. Atukpor Thesis)

Scintillators

Filtering the ligth emission from the LaBr3 ou CeBr3 to remove long time component







High repetition rate digitizer

Semiconductors

Shortcut the detector during the X flash to protect amplifiers

High repetition rate lasers

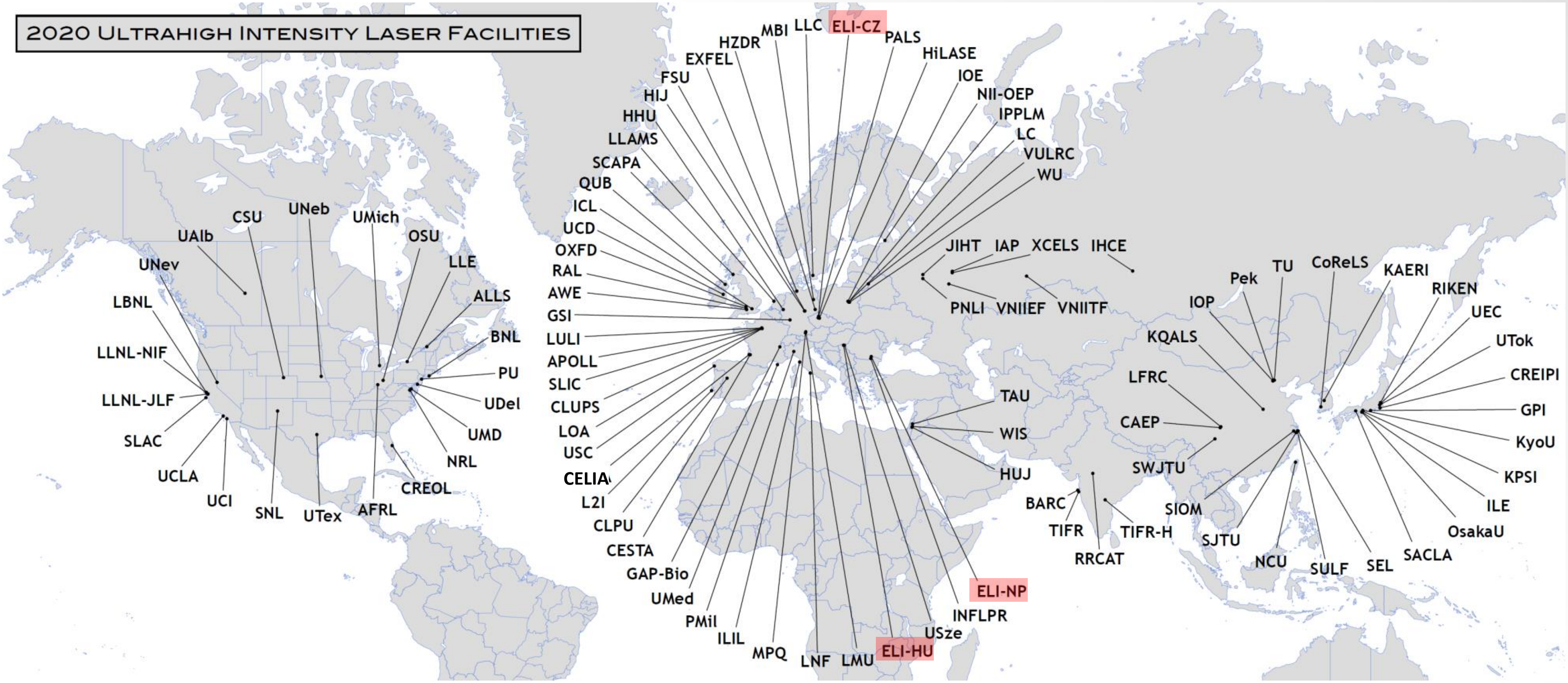
High energy and long pulse lasers for the production of hot (T~0.1-1 keV) and dense (~10^{-2} g/cm^3) plasmas

Intense lasers for particle acceleration :

- Electrons (from the 90s); E_{max}e- ~GeV currently
- Ions (from the 2000's); E_{max}protons ~100 MeV currently

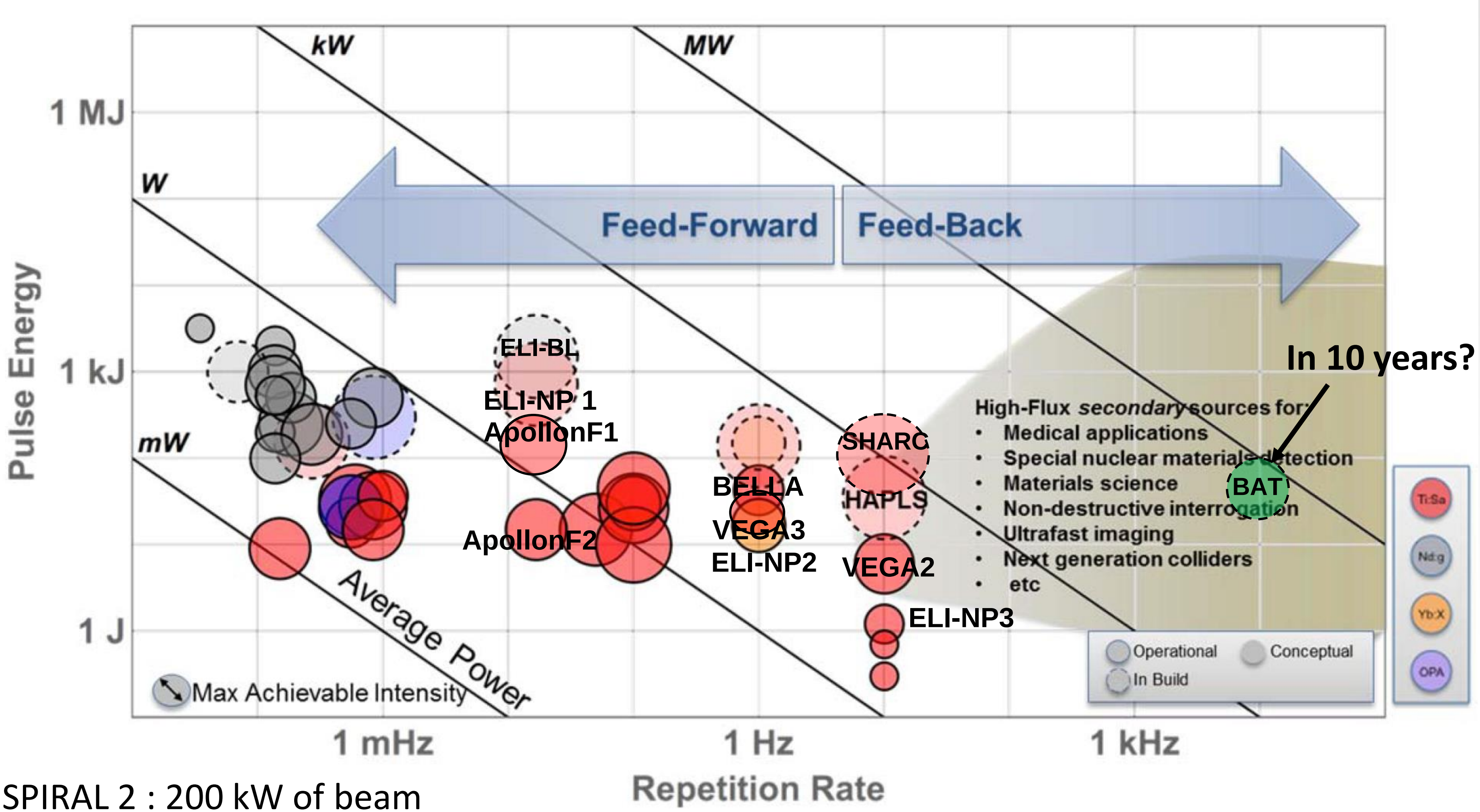
Laser	Localisation	Energie (Joules)	Durée du pulse (fs)	Puissance (TW)	Intensité (W/cm^2)	Cadence (Hz)	a0
CENBG	Bordeaux	1	9000000	1,E-04	1E+13	10	0,003
Apollon F3	**Paris-Saclay**	**200**	**1000000**	**0,2**	**1E+15**	**0,02**	0,0
PHELIX long	Darmstadt	1 000	5000000	0,2	1E+15	0,0002	0,0
ELI-BL ATON L4	**Prague**	**1 500**	**1000000**	**1,5**	**8E+15**	**0,02**	0,1
LULI 2000	Paris-Saclay	1600	1500000	1,1	1E+16	0,0001	0,0
MegaJoule	Bordeaux	1 300 000	3200000	406	6E+16	0,000006	0,2
Eclipse (upgrade)	**Bordeaux**	**1,5**	**30**	**50**	**3,E+19**	**1**	3,7
ELI-BL HAPLS	**Prague**	**30**	**30**	**1000**	**3E+20**	**10**	16,0
VEGA3	**Salamanque**	**30**	**30**	**1000**	**1E+21**	**1**	31,9
PICO 2000	Paris-Saclay	60	1000	60	5E+19	0,0003	4,6
PHELIX short	Darmstadt	130	500	260	4E+20	0,0002	18,1
Apollon F1	**Paris-Saclay**	**150**	**15**	**10000**	**1E+22**	**0,02**	76,7
TITAN	Livermore	210	5000	42	2E+19	0,0006	4,4
VULCAN	Oxford	500	500	1000	1E+21	0,0002	25,5

High repetition rate lasers



- Lasers belong to laboratories → small teams, all lasers are different; lots of competition between sites. The only real international facilities are the ELI pillars.

High repetition rate lasers



In 10 years?

SPIRAL 2 : 200 kW of beam

C.W. Siders, LLNL report n° LLNL-TR-704407, October 2016

Conclusions

- Lasers: unique tools to study nuclear properties in extreme condition: it creates both targets and projectiles

- Lots of teams working on Laser-plasma acceleration ; very few from accelerators and nuclear physics community. Accessible application is radio-isotope production

- Evaluation of nuclear excitations rates in plasma is complex
  - Description of the plasma
  - Accurate characterization of the nuclear and atomic transitions required

- ^{84m}Rb: a good candidate to evidence nuclear excitations in plasma
  - Nuclear transition characterised (2 experiments and shell model calculations)
  - Atomic physics in plasma well described and experimentally validated
  - Estimation uncertainties too high, need experimental evidence : ELI-BL with two laser beams

- The main issue remains the detection in such perturbated environment