Nuclear reactions in Laser-Plasmas

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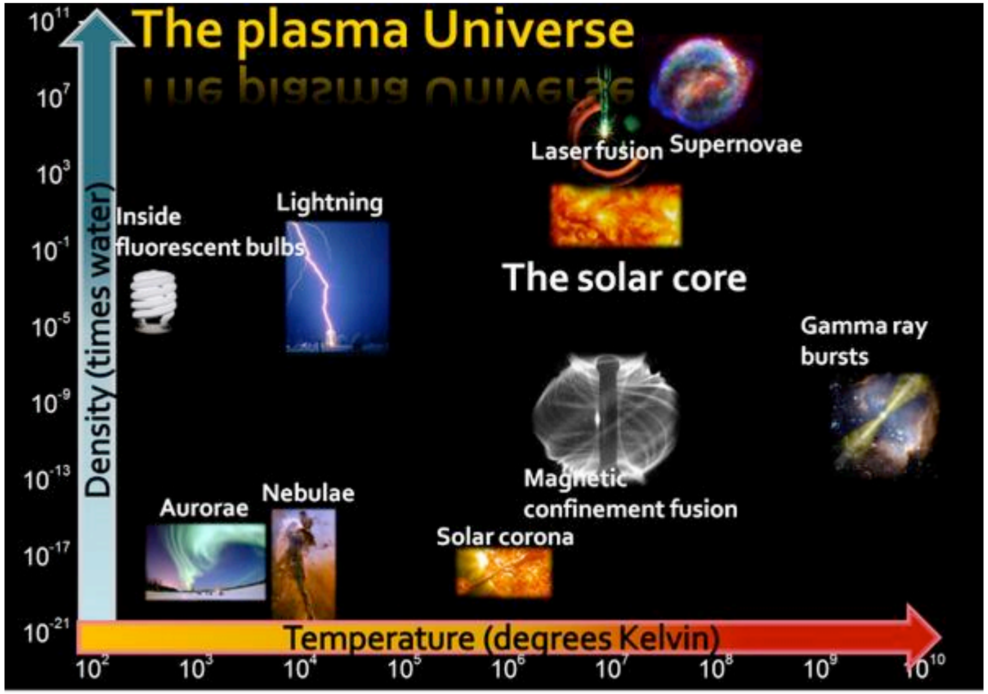
Bucharest –September 21-25, 2015

Nuclear reactions in Plasma

The visible Universe is 99.999% Plasma



Sun is about 100% plasma, as are all stars. Plasma makes up nearly 100% of the interplanetary, interstellar and intergalactic medium. The Earth's ionosphere is plasma.

The Plasma Universe is a term coined by Nobel laureate *Hannes Alfvén* to highlight the importance of plasma throughout the Universe.

Nuclear Physics ⇔ Plasma

> What is the origin of the elements in the cosmos? (big-bang)

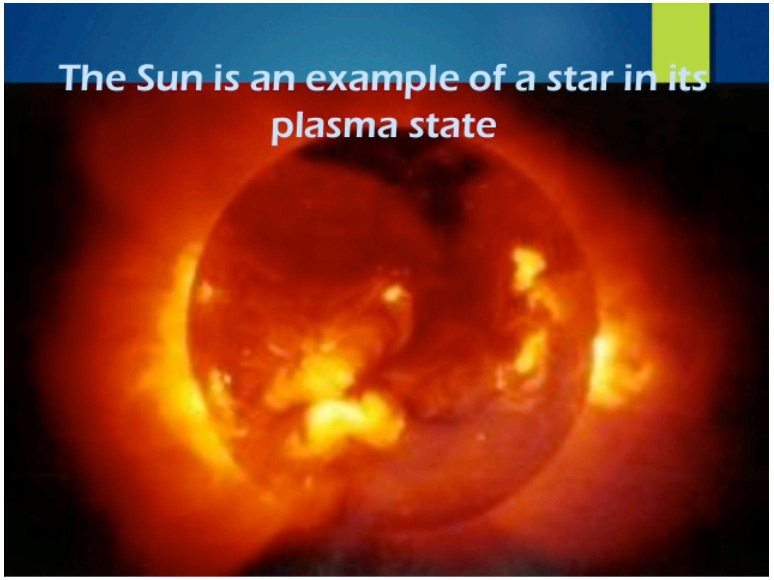
> What are the nuclear reactions that drive stars and stellar explosions?

Outline

- ✓ Plasma Physics (some basic principles)
- ✓ Thermonuclear reactions (some basic principles)
- ✓ Fundamental open questions
- ✓ How reproduce astrophysical plasmas in Lab? (Laser Plasmas)
- ✓ How extract the physical information?
- ✓ Nuclear Reaction in Laser-Plasmas @ ELI-NP
- ✓ INFN-LNS Laser activities

Plasma Physics: basic principles

Plasma is defined as a quasineutral gas of charge and neutral particles which exhibits collective behaviour.



The free charges, make the plasma highly electrically conductive that may carry, and generate magnetic fields that may cause the plasma to constrict (or pinch) into filaments, generate particle beams, emit a wide range of electromagnetic radiation (radio waves, light, microwave, x-ray, gamma and synchrotron radiation)

Quasineutrality of plasma implies that the electron density n_e is nearly equal to the ion density n_i so that $n \approx n_e \approx n_i$, where n is the common density of plasma particles called the plasma density;

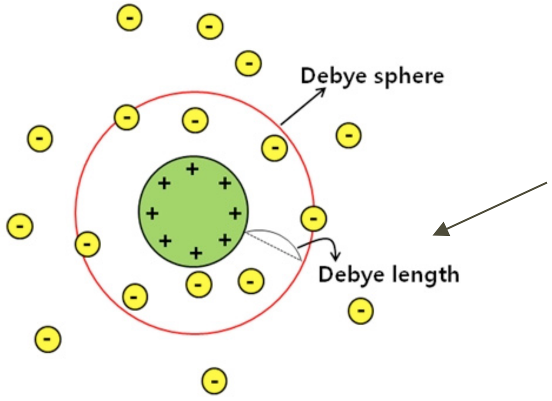
Collective behaviour implies that the motion of species depend not only on the local conditions but also on the state of the plasma far away from the point of interest.

Plasma Physics: basic principles

Quasineutrality

Plasma possesses a special ability to shield out external potentials (ϕ_0) that are applied to it within a very small region:

$$\boxed{\phi(r)=\phi_0 \exp(-r / \lambda_D)}$$



$$\lambda_D = (\varepsilon_0 k T_e / n e^2)^{1/2}$$

A charge in the plasma interacts collectively only with the charges those lie inside its Debye sphere, its effect on the other charges being effectively negligible

Collective behaviour

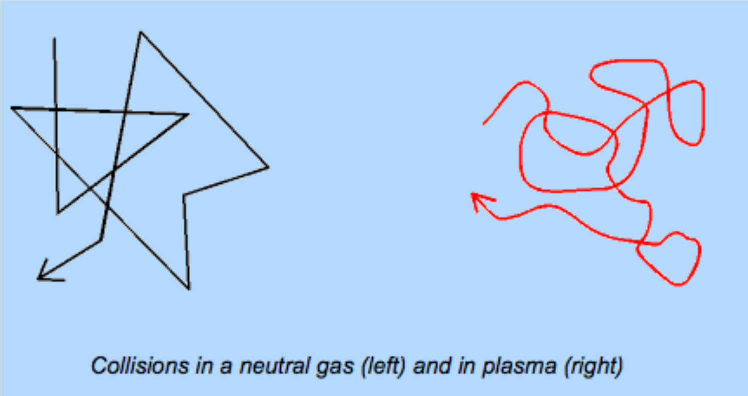
If the electrons in a quasineutral plasma are displaced from its equilibrium position an electric field will be built such that it will try to restore the neutrality of the plasma. Due to inertia, the electrons will overshoot and oscillate around their equilibrium positions with a characteristic frequency ω_p

plasma frequency $\omega_p = (n e^2 / \varepsilon_0 m_e)^{1/2}$

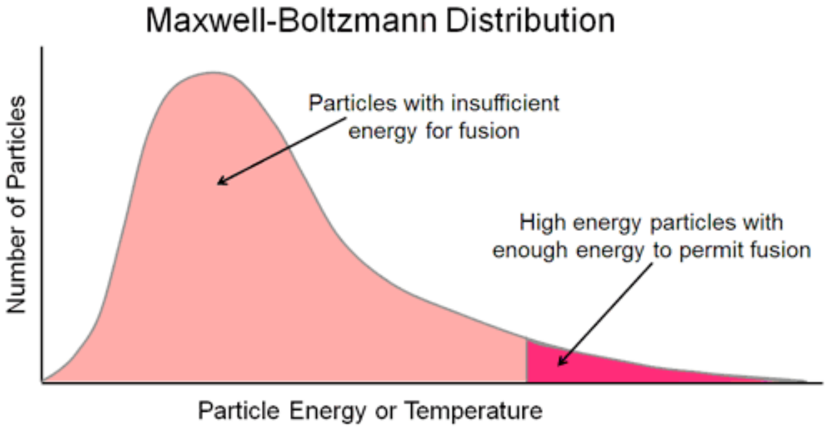
Plasma Physics: basic principles

Collisions. The character of the collisions and their mechanism is different from the collisions of neutral particles. During the collision of neutral particles there are abrupt changes in the direction of the movement, while in plasma the changes in direction, caused mostly by the interaction with the electric field (~ $1/r^2$), are smoother.

The Mean Free Path can be as the average distance during which the particles turn about 90° from the original direction.



Collisions in a neutral gas (left) and in plasma (right)



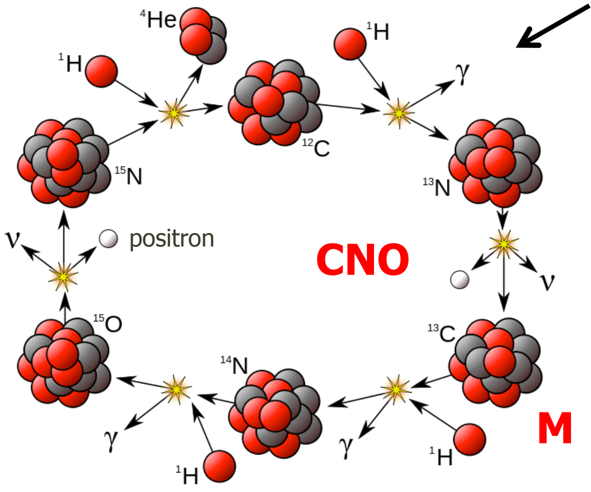
If plasma is in thermodynamic equilibrium the motion of the particles is determined by the temperature T.

Plasmas are often in a non-equilibrium state. In Laser-plasmas T depends from time and position.

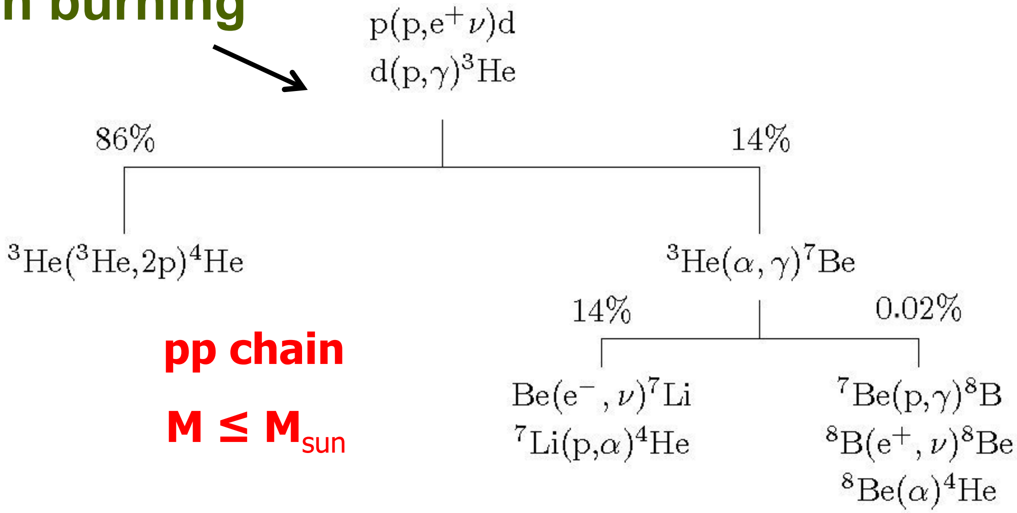
Thermonuclear reactions

Stellar Nucleosynthesis

hydrogen burning



M > M$_{sun}$



$p(p,e^{+}\nu)d$
$d(p,\gamma)^{3}He$

86%

$^{3}He(^{3}He,2p)^{4}He$

14%

$^{3}He(\alpha,\gamma)^{7}Be$

14%

$Be(e^{-},\nu)^{7}Li$
$^{7}Li(p,\alpha)^{4}He$

0.02%

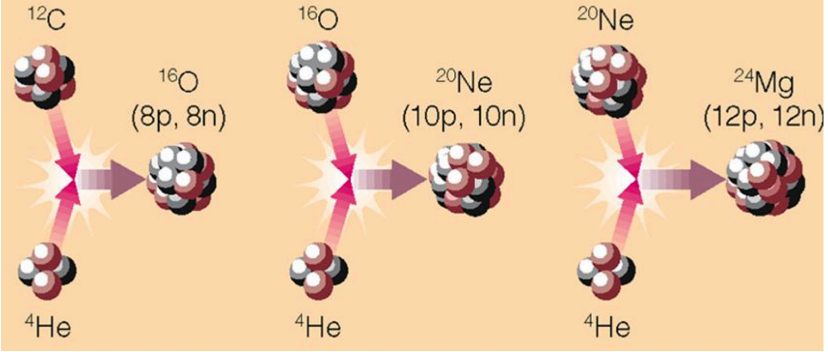
$^{7}Be(p,\gamma)^{8}B$
$^{8}B(e^{+},\nu)^{8}Be$
$^{8}Be(\alpha)^{4}He$

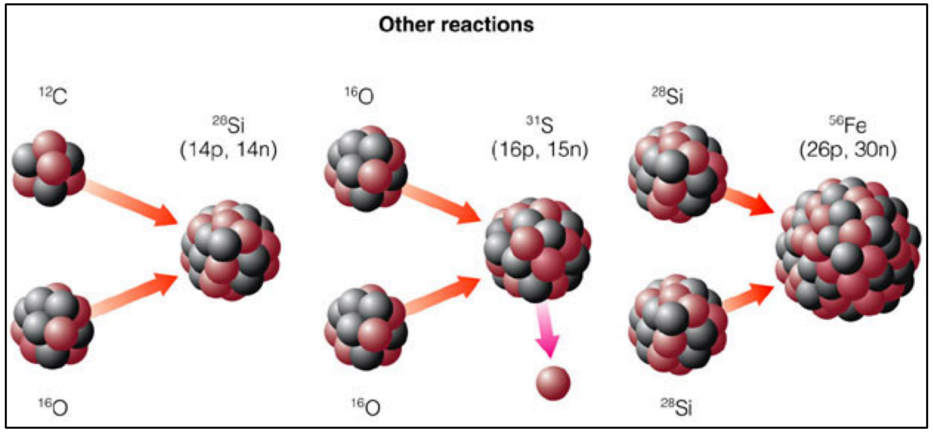
pp chain

M ≤ M$_{sun}$

Helium burning

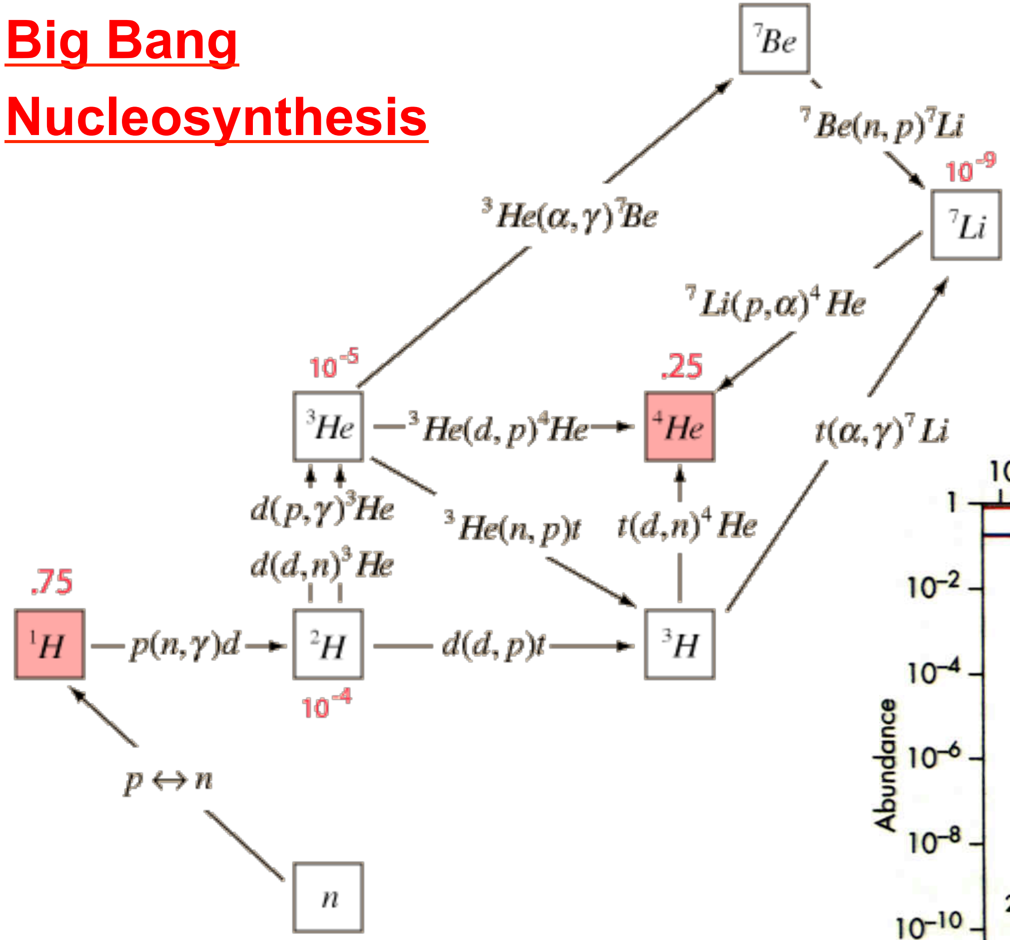
Helium capture reaction





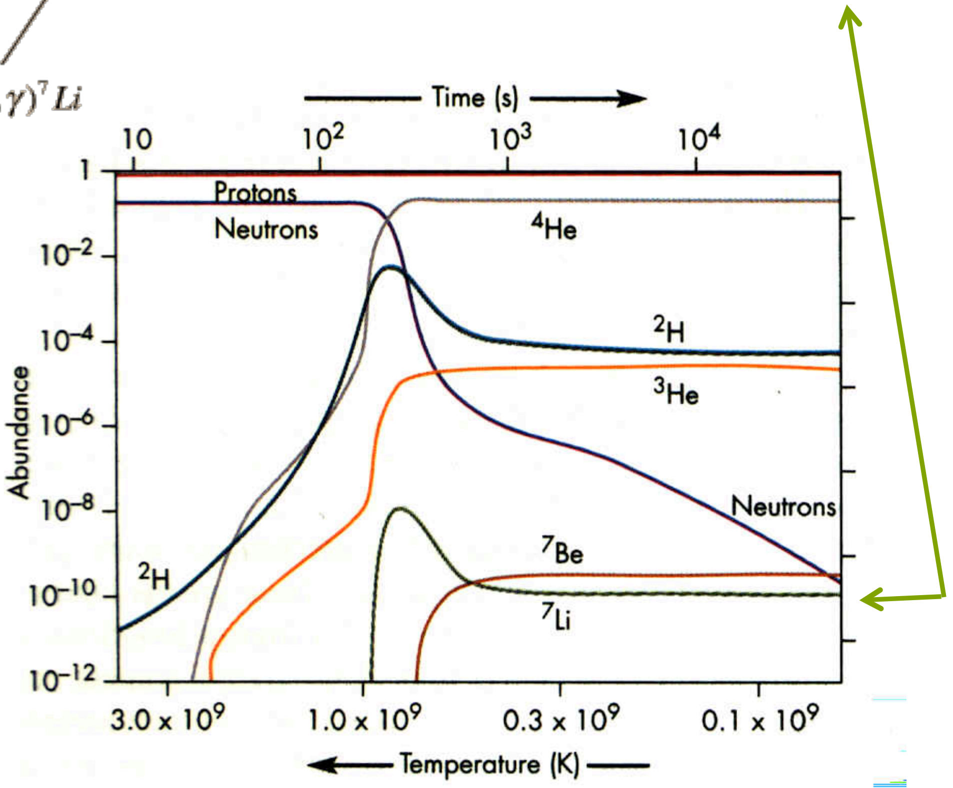
Thermonuclear reactions

Big Bang Nucleosynthesis



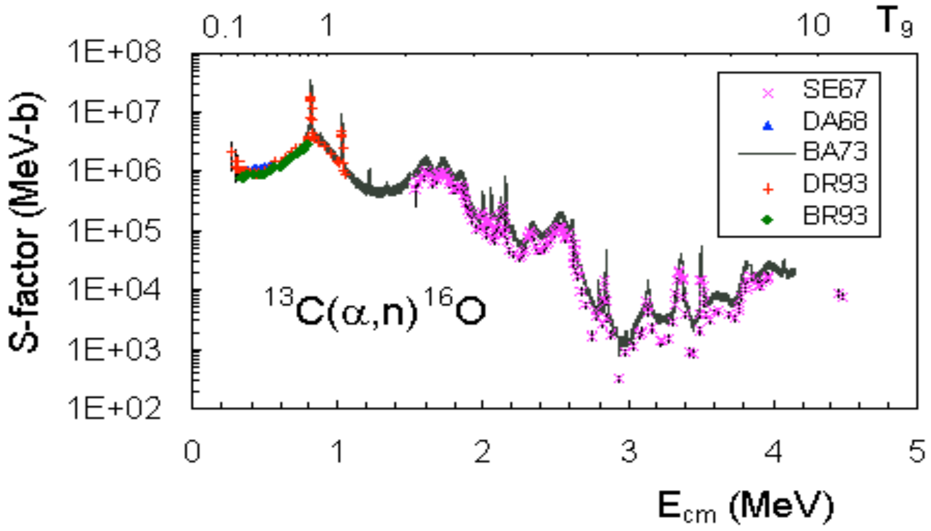
Lithium problem

Observed abundance is 1/3 of the prediction



Physics case @ ELI-NP

Stellar nucleosinthesys



$^{13}C(^{4}He,n)^{16}O$

Important in the helium burning process in advanced stellar phase, is one of the most interesting neutron sources

can be activated at the base of AGB (Asymptotic giant branch) stars, “slow-process” i.e. the neutron induced reactions responsible of the heavy elements production

Gaining knowledge, for the first time in plasma, especially in the region below 270 keV where no experimental data are available it will be possible to evaluate more carefully the available neutron flux for the following s-process nucleosynthesis.

B. Meyer, Annu. Rev. Astron. Astrophys., 32, 153

Physics case @ ELI-NP

Primordial nucleosinthesys

^{7}Li(d,n)^{4}He-^{4}He

Recently addressed by Coc et al. Astrophysical Journal, 744 (2010) 158

seems to be one of the most important reactions affecting the primordial CNO abundances produced during the early stage of universe

Very few experimental data exist !!!
astrophysicist assume constant the S-factor
ranging between two extreme hypotheses from 5 to 150 MeV x b

Coc et al. Astrophysical Journal, 744 (2010) 158

Thermonuclear reactions: basic principles

The rate *r* for a given reaction depends on the number density of the reactants, N_a and N_X

$$r_{aX} = (1+\delta_{aX})^{-1}\, N_a N_X \underbrace{\int_0^\infty \sigma(v)\, v\, \phi(v)\, dv}_{\langle \sigma v \rangle}$$

δ_{aX} is the Kronecker delta,
σ the cross section
$\phi(v)$ the Maxwellian distribution

In the center of mass frame:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{kT}\right)^{3/2} \int_0^\infty \sigma(E) E e^{-E/kT} dE$$

For charged particles the cross section itself depends on three factors:

- The probability of overcoming the coulomb barrier → $=\exp(-2\pi\eta)$ $\quad \eta = \frac{Z_1 Z_2 e^2}{\hbar}\sqrt{\frac{\mu}{2E}}$
- The probability of a quantum-mechanical interaction → $=1/E$
- Astrophysical factor, S(E)

nuclear origin
<u>WEAK</u> energy
dependence

$$\boxed{\sigma(\mathrm{E}) = \frac{S(E)}{E}\exp(-2\pi\eta)}$$

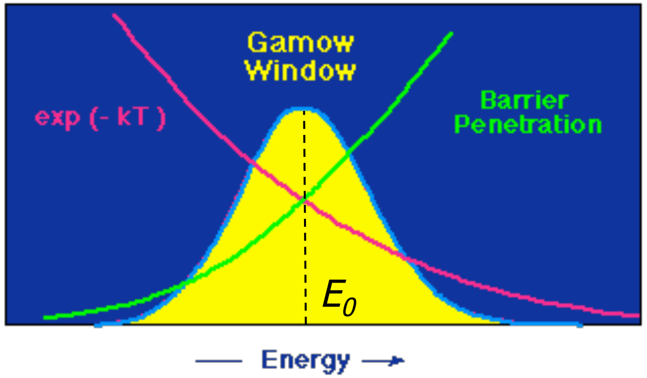
Thermonuclear reactions: basic concepts

Cross section exponential drop towards at low energies due to Coulomb barrier

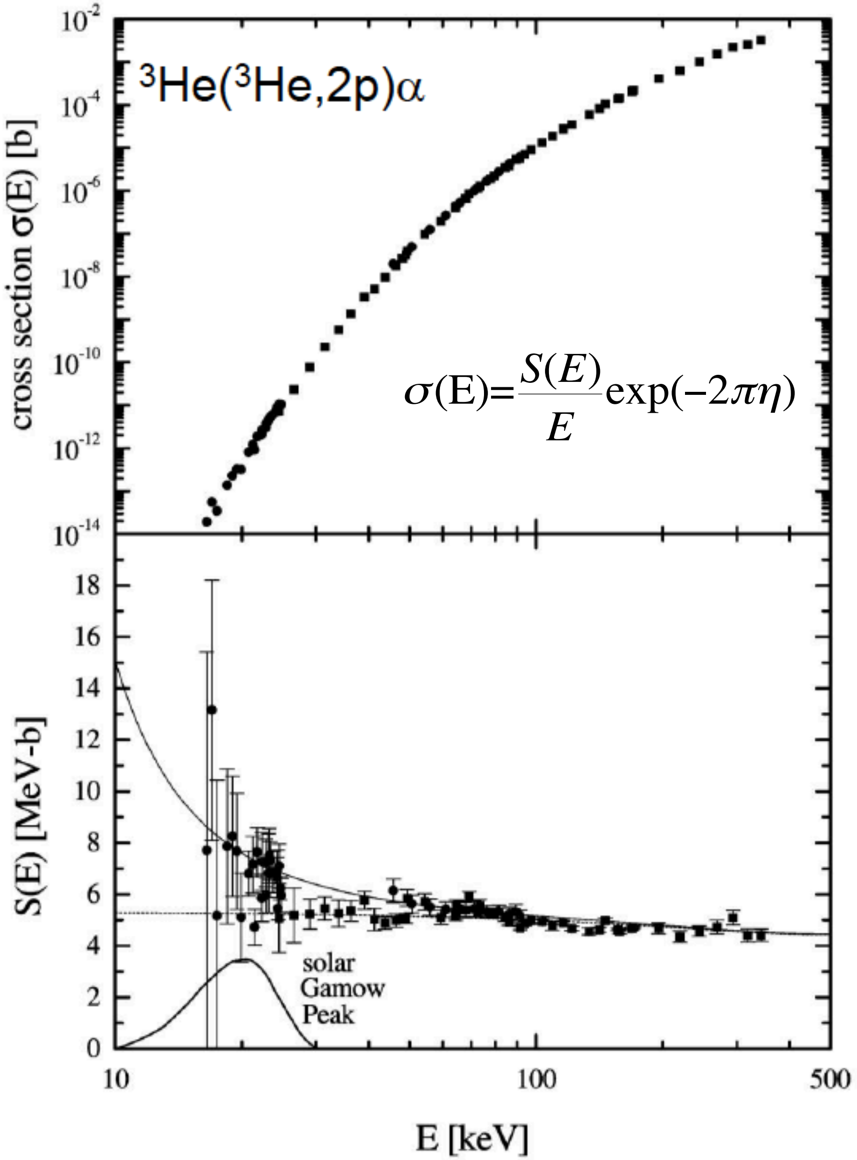
$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} \left(\frac{1}{kT}\right)^{\frac{3}{2}} \int_0^\infty S(E) \exp\left\{-\frac{E}{kT} - \frac{b}{E^{1/2}}\right\} dE$$

$$b = 0.99 Z_1 Z_2 A^{1/2}$$

$$E_0 = \left(\frac{bkT}{2}\right)^{2/3}$$



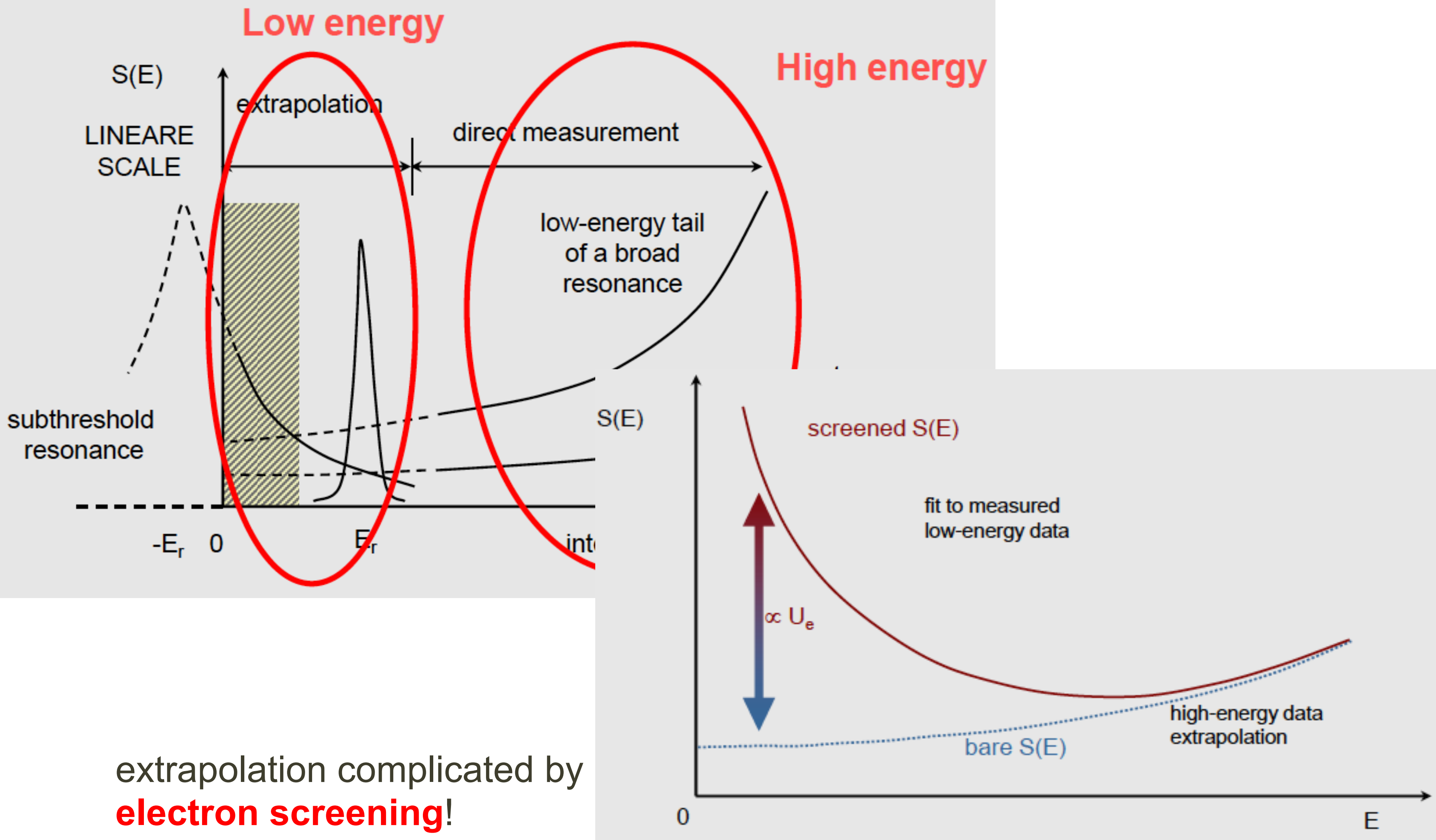
For most data an **EXTRAPOLATION** to the astrophysical important energies is MANDATORY! (exception: $^3He(^3He,2p)\alpha$)



$$\sigma(\mathrm{E}) = \frac{S(E)}{E} \exp(-2\pi\eta)$$

Thermonuclear reactions: basic concepts

Extrapolation is dangerous!



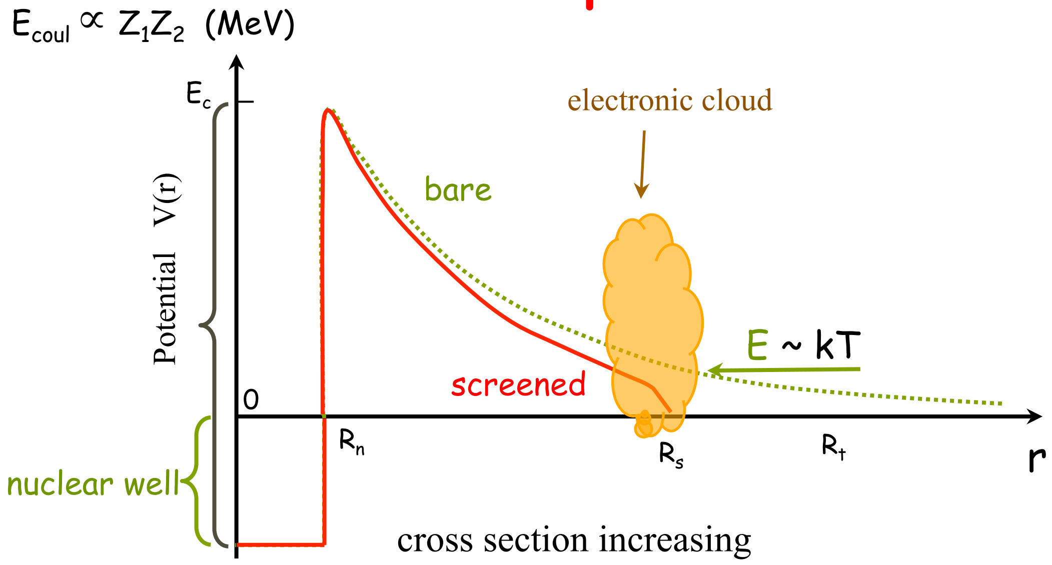
extrapolation complicated by **electron screening**!

Electron Screening puzzle

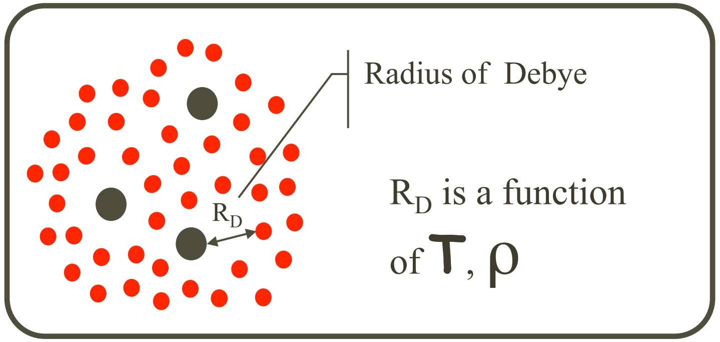
At low energy due to the presence of the electrons:

$$f_s = \frac{\sigma_s(E)}{\sigma_b(E)} = \frac{S_s(E)}{S_b(E)}$$

Coulomb potential



In a **PLASMA** ions are in sea of free electrons (Debye shielding)



Salpeter approach: $V(r) = \frac{e^2 Z_i}{r} \exp\left(-\frac{r}{R_D}\right)$

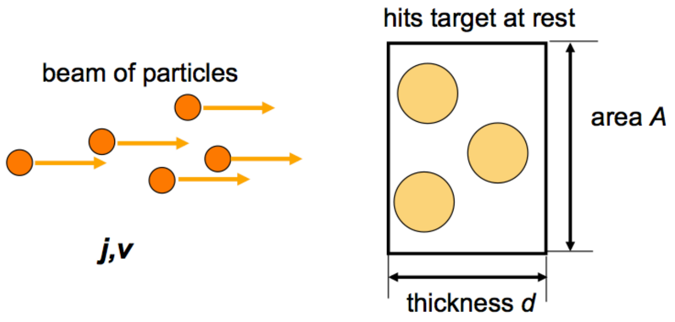
$$\boxed{f_{scr} = \exp\left(\frac{Z_1 Z_2 e^2}{kT \lambda_D}\right)}$$

Salpeter formula

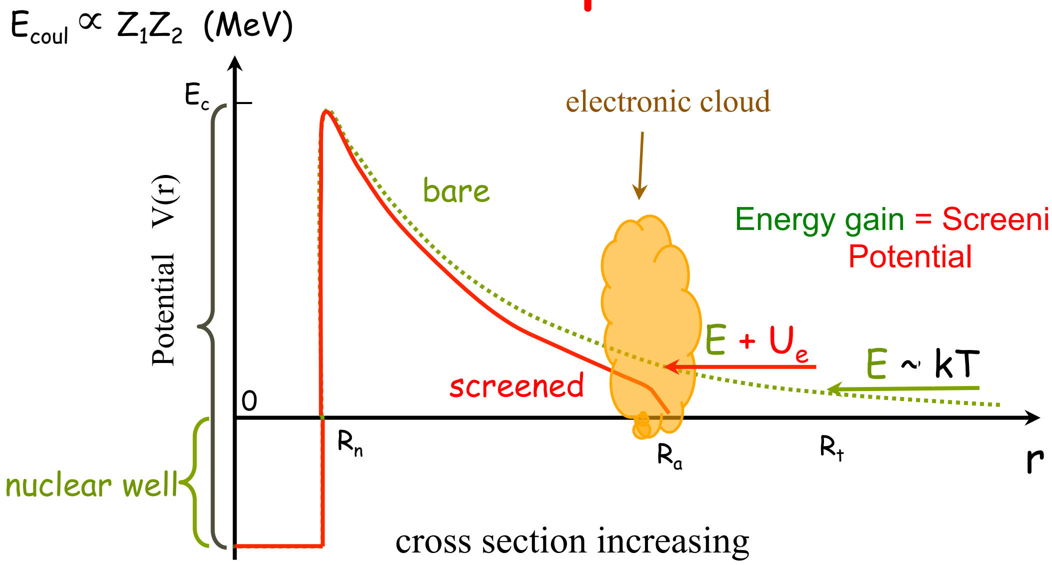
E.E. Salpeter, Australian Journal of Physics 7(3) (1954) 373

Electron Screening puzzle

In laboratory



Coulomb potential



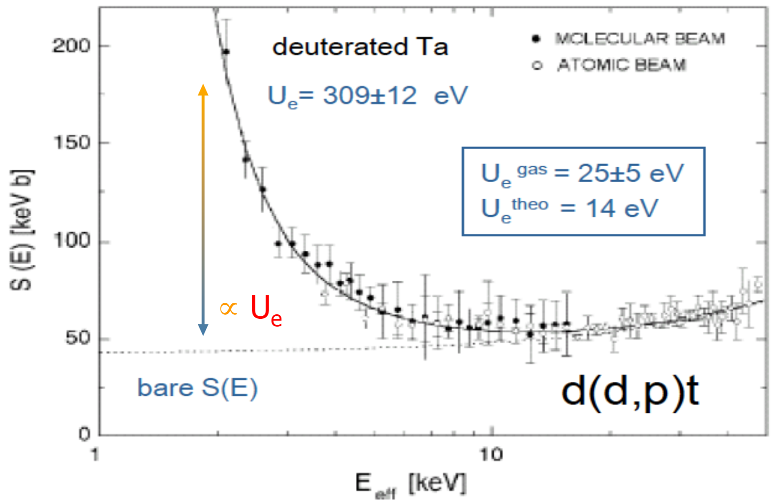
cross section increasing

$\sigma_s(E) \neq \sigma_s^p(E)$ ➡ $f_{lab} \neq f_{plasma}$

screening in laboratory ➡ screening in plasma

$$f_{lab} \propto \exp \pi\eta \frac{U_e}{E}$$

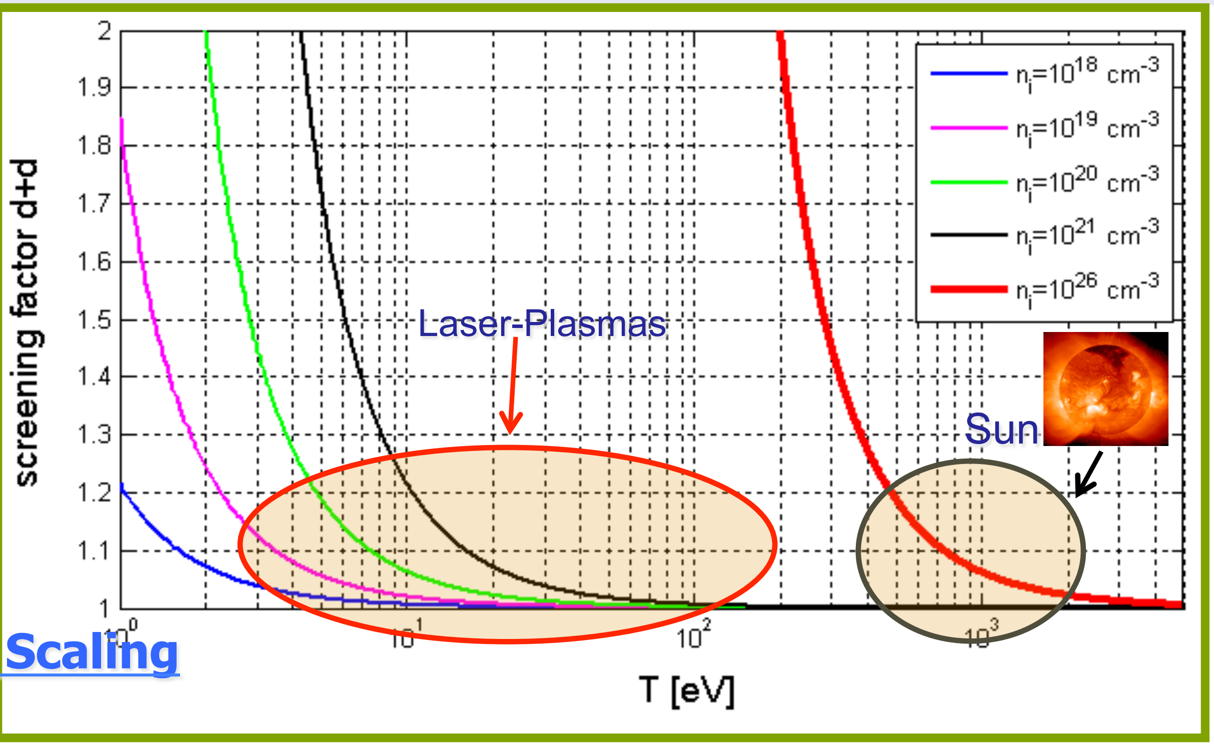
$$U_e \sim Z_1Z_2e^2/R_a$$



Raiola F. et al. EPJ A13 (2002) 377-382

Electron Screening puzzle

$$f_{scr} = \exp\left(\frac{Z_1 Z_2 e^2}{kT\lambda_D}\right)$$

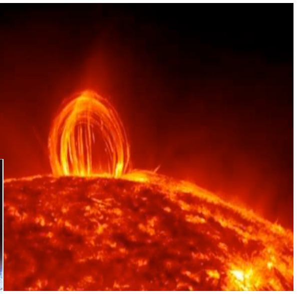


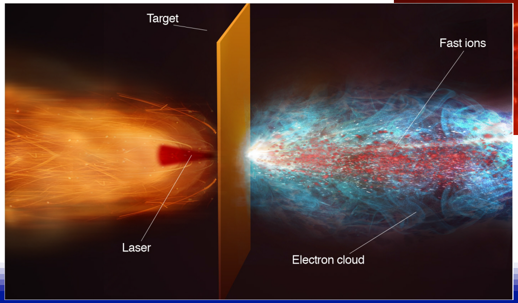
Plasma Scaling

Hydro-magnetic equilibrium

$$\frac{\text{Particle pressure}}{\text{Magnetic field pressure}} = \beta = \frac{nkT}{B^2/2\mu_0}$$

$\beta>1$
- Plasma instability
- Magnetic reconnections
- …



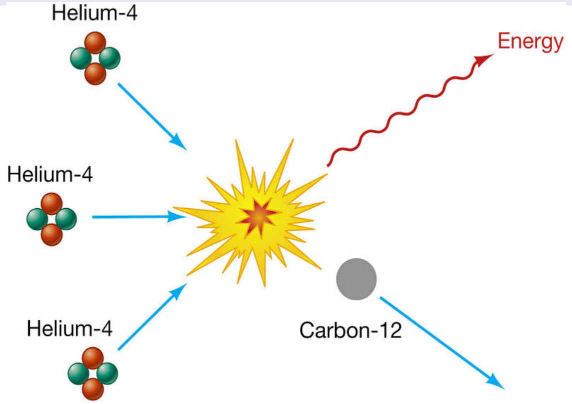


TNSA, Laser acceleration

S. Ivanovski et al. Rad. Eff. end Def. in Sol. 165 (2010) 457

Further Fundamental open questions

- ✓ Bahcall and Fowler in 1969 discussed also a possible relevant contribution of nuclear reactions between excited nuclei…(^{19}F states)
- ✓ The Plasma medium can influence the nuclear states (life time, strength etc.) and structure
- ✓ Triple alpha scattering (Carbon Hoyle state) →



Such aspects can't be studied through "conventional" Nuclear Physics experiments (ions beams on targets)

Modelling

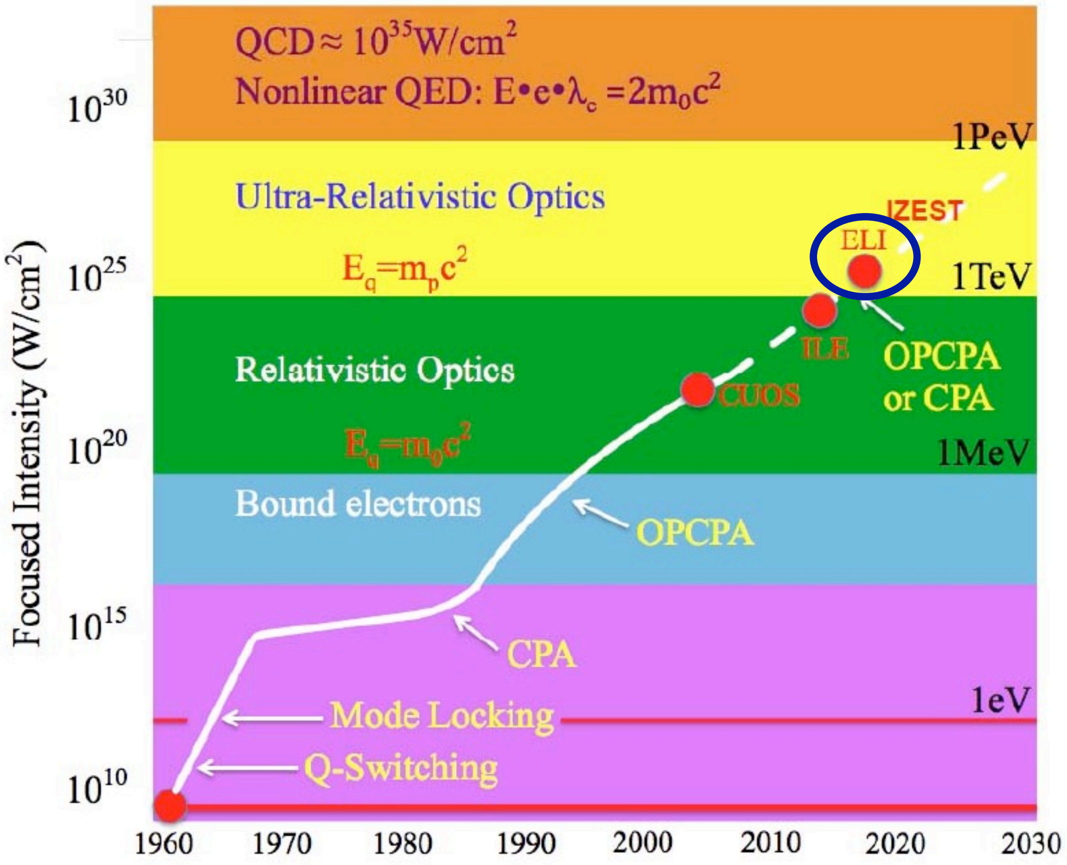
Astrophysical and Cosmological Modelling is based on cross sections data measured in lab in "conventional" way.

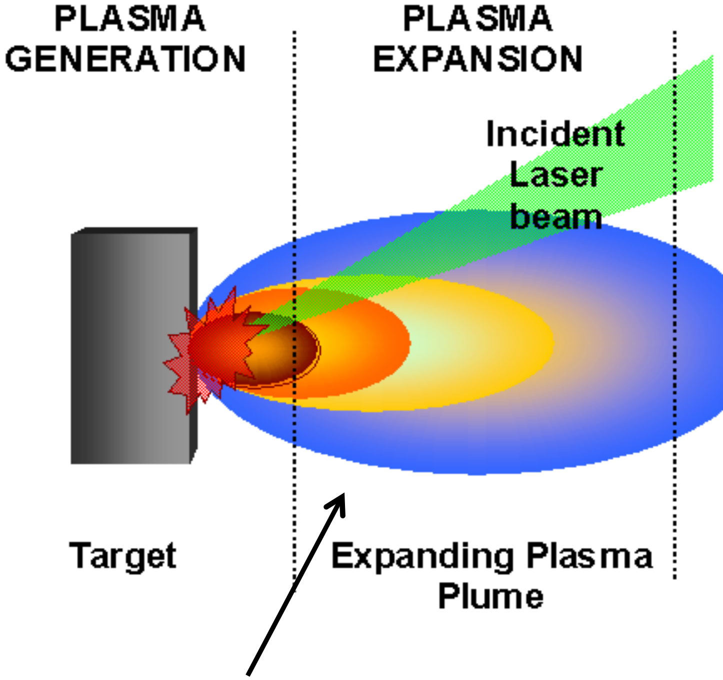
measure cross sections or rates in astrophysical conditions, is an important physics goal

- ✓ How reproduce an astrophysical plasma in Lab?
- ✓ How extract the physical information?

N.A. Bahcall and W.A. Fowler Astro. Jou. 157 (1969) 645
G. Gosselin et al. Phys. Rev. C 76, 044611 (2007)
R. Raduta et al. PLB 705, 65 (2011)

Laser Plasmas





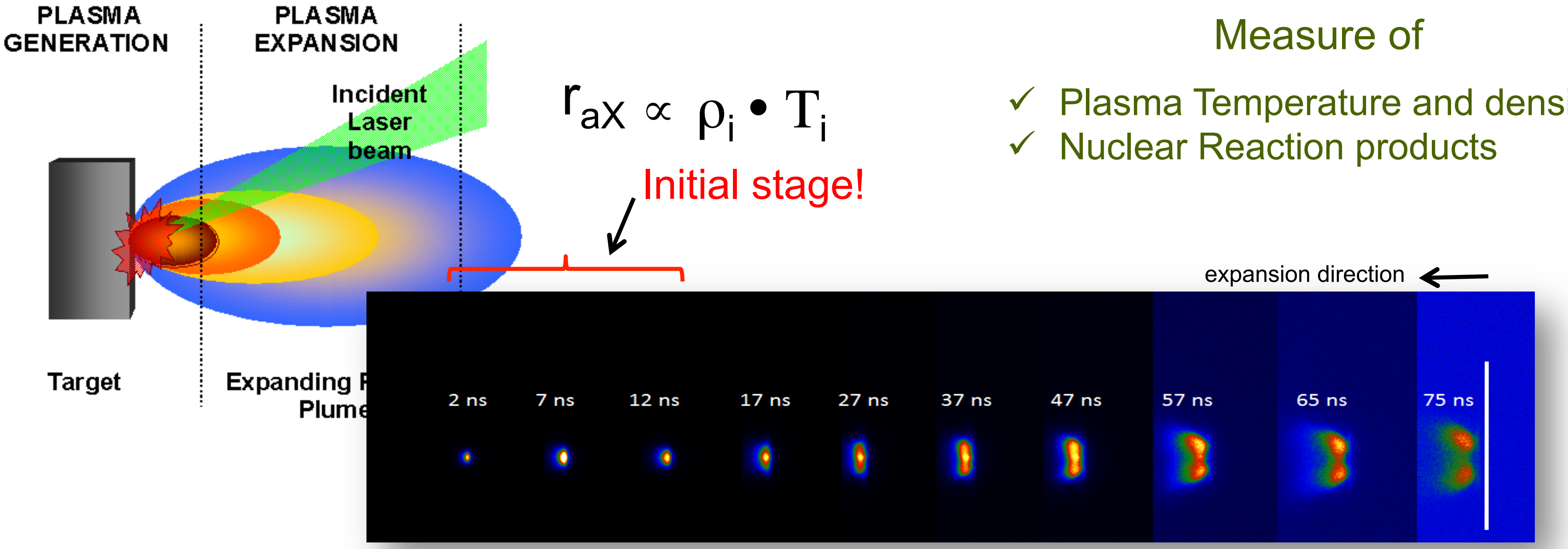
T = T(x,y,z,t)

ρ = ρ (x,y,z,t)

How extract the physical information?

$$r_{aX} = (1+\delta_{aX})^{-1}\ N_a N_X \boxed{\int_0^\infty \sigma(v)\, v\, \phi(v)\, dv} \leftarrow \langle \sigma v \rangle$$

How extract the physical information?



$r_{aX} \propto \rho_i \bullet T_i$

Initial stage!

Optical imaging from ICCD

Measure of

- ✓ Plasma Temperature and density
- ✓ Nuclear Reaction products

Techniques

Temperature

Optical imaging and spectroscopy

X-ray imaging and spectroscopy

Density

Interferometry and Shadowgraphy

Optical imaging and spectroscopy

X-ray imaging and spectroscopy

Nuclear products

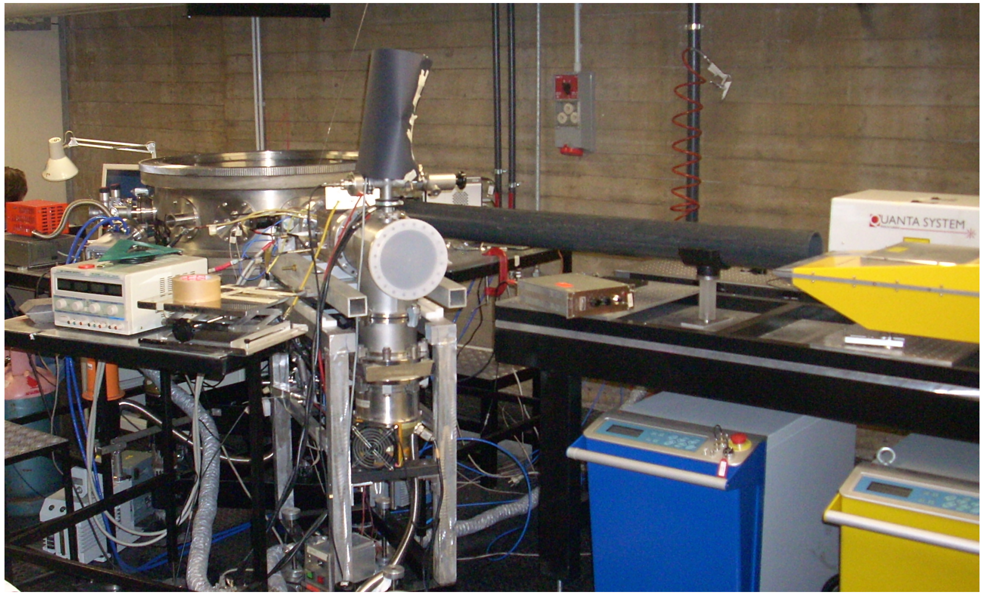
CR 39, Lanex, etc.

P. Hough_et al. Appl. Surf. Sci. 255 (2009) 5167

Principles of Plasma Spttroscopy HR Griem CAMBRIDGE press

Laser Activities @ LNS

LENS-Lab



Main activity:

R&D and test of Plasma diagnostics
R&D on detectors
Accessible nuclear studies

Equipment:

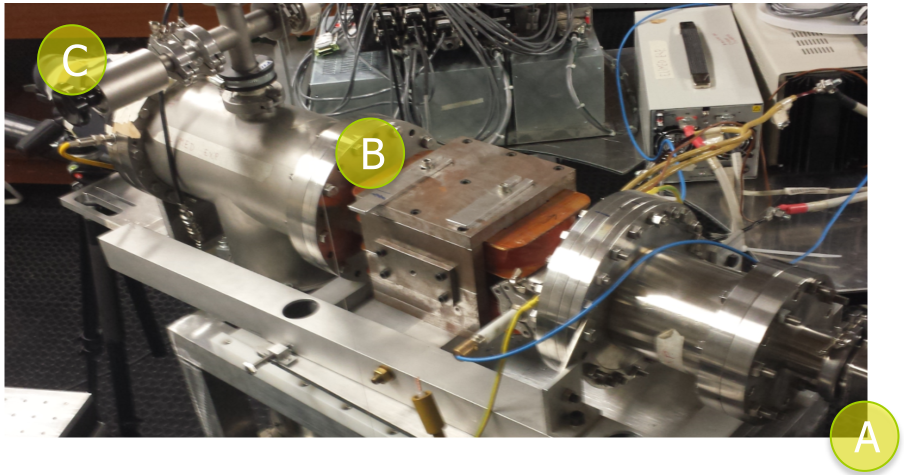
LASER:
Two Nd:YAG Lasers of 0.7 and 2.2 J
pulse-duration of 6 ns
rep. Rate of 30 and 10 Hz

PLASMA:
CCD and spectrometer for X-ray detection
ICCD and optical spectrometer
Langumuir probe
TPS – Thomson spectrometer

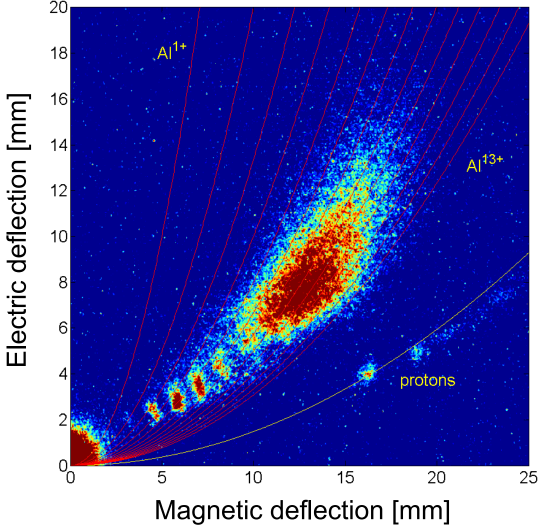
Particle detectors:
Track det.: CR39, Lanex, Gaf cromich
Diamonds detectors, SiC
SiPM and Scintillators

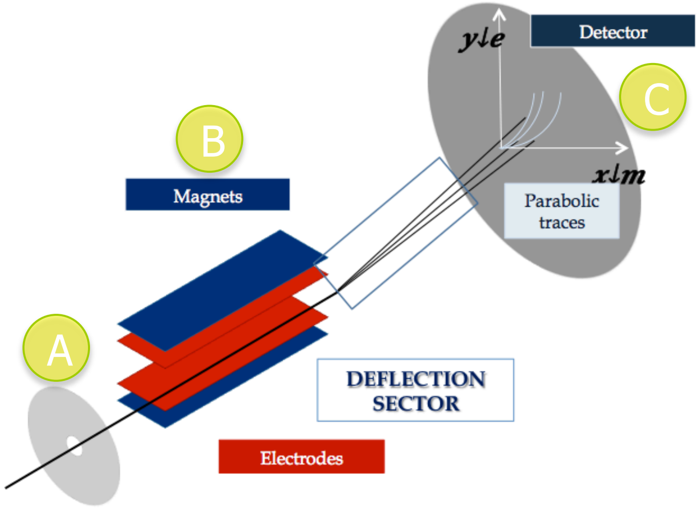
Laser Activities @ LNS

Designed to detect up 10 MeV of protons

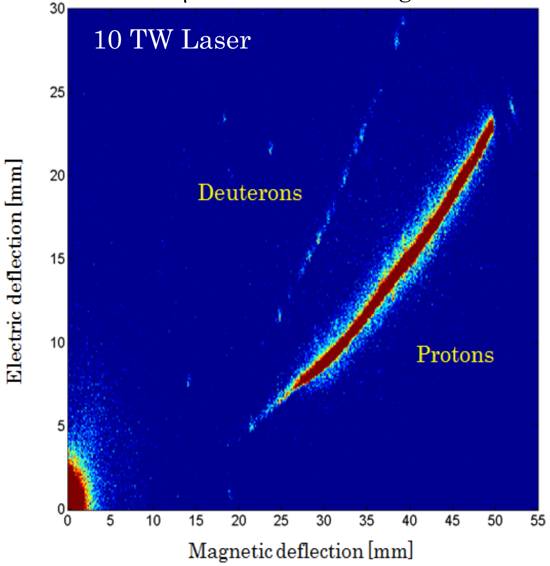


From 2 mm thick Al target at LENS

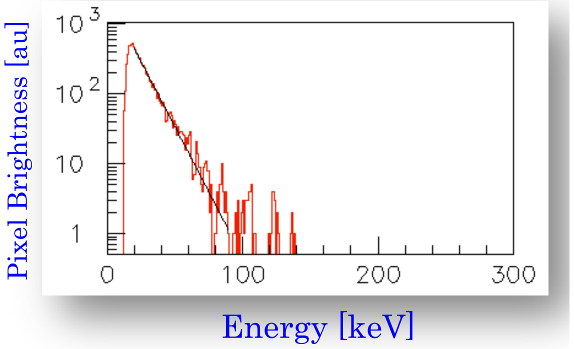




From 10 μm thick CD2 target at ILIL



Spectrum of Al^{10+} and linear fit.



INO
Istituto Nazionale
di Ottica

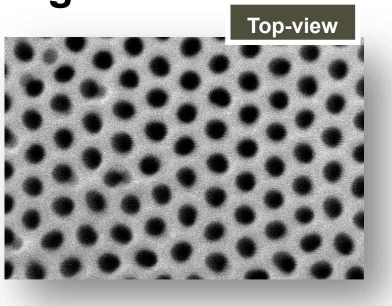
F. Schillaci et al. JINST, vol. 9, T10003, 2014

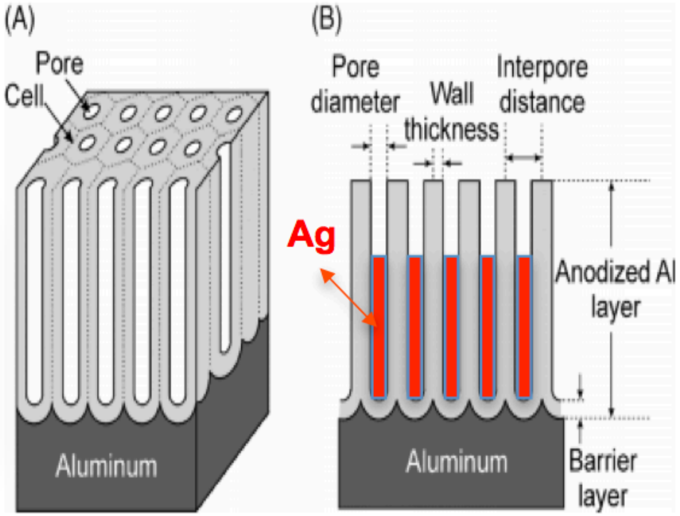
Laser Activities @ LNS

Nanostructured targets @ INFN-Bologna

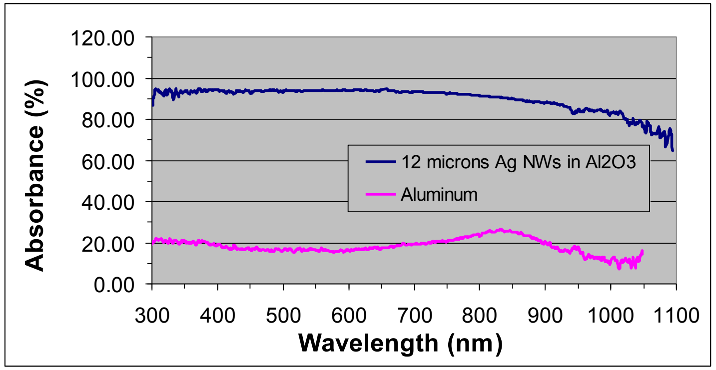
Iperpure Aluminum was electrochemically anodized into porous alumina (Al_2O_3) with self-organized regular honeycomb structure

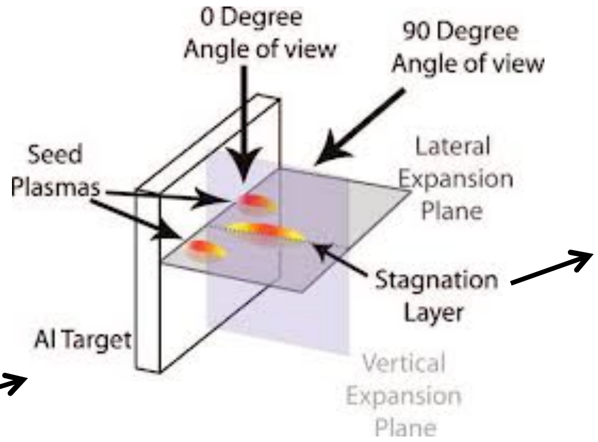
Silver NanoWires were electrochemically deposited in the alumina pores, to fill about 2/3 of the channel length





- pitch: 40 ÷ 400 nm
- pore diameter: 20 ÷ 200 nm





- High temperature Plasma
- Slow expansion

Goal

- **Generate plasma stagnation**
- **Fill alumina pores with deuterium (CD_2)**

Search events of

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n + 3.3\ MeV$$

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{1}H + ^{1}_{1}H + 4.0\ MeV$$

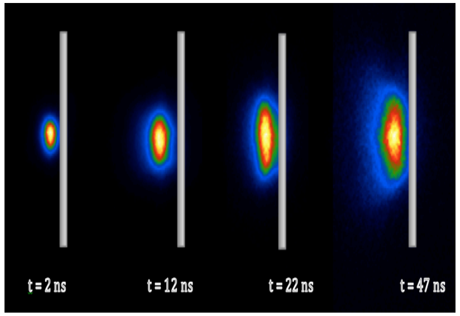
N. Gambino at al. Appl. Surf. Scie. 272 (2013) 69

Laser Activities @ LNS

Some results

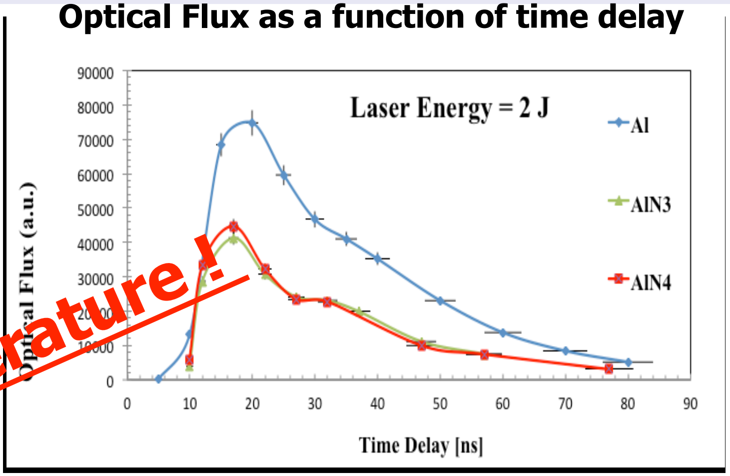
Targets Al and AlN (Nano Wires)
Length of Ag NW: 12µm →AlN3 23µm→AlN4

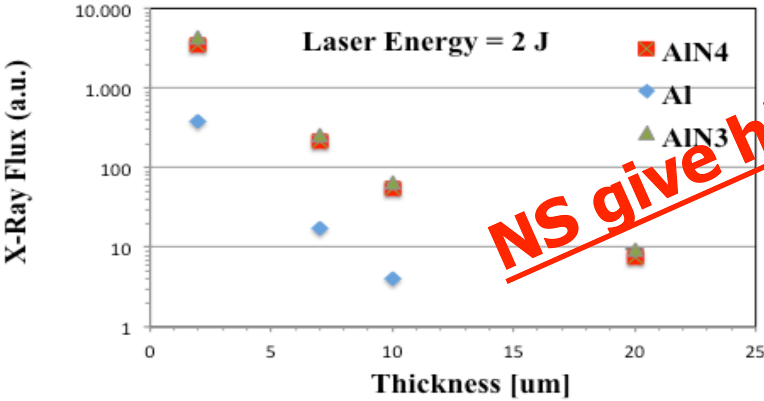
optical imaging



ICCD images

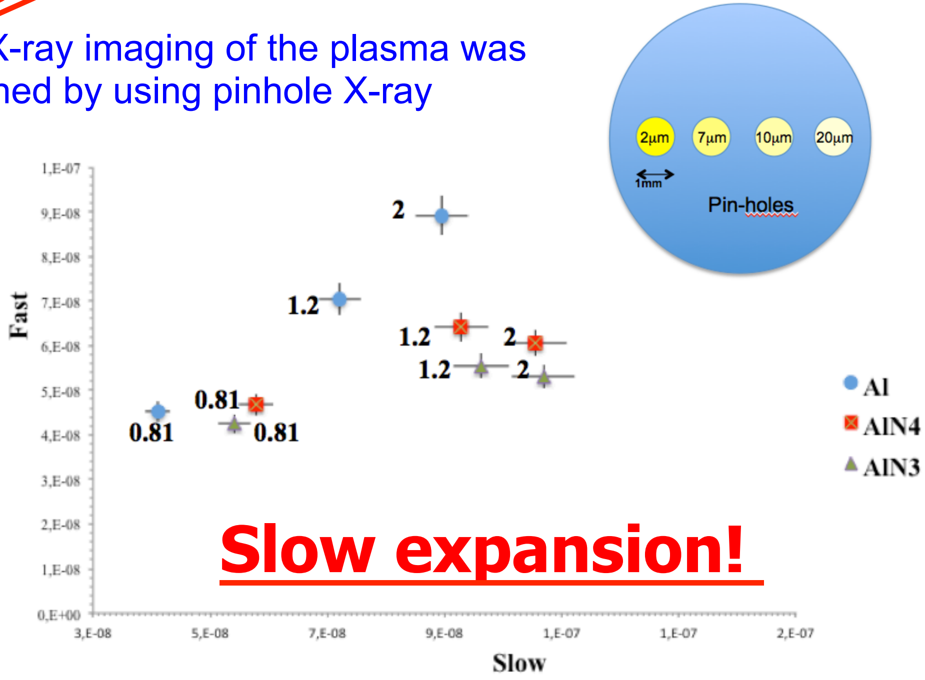
Optical Flux as a function of time delay





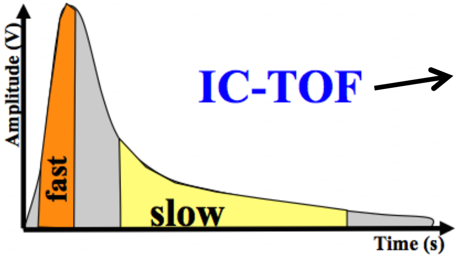
NS give highest temperature !

The X-ray imaging of the plasma was obtained by using pinhole X-ray



Slow expansion!

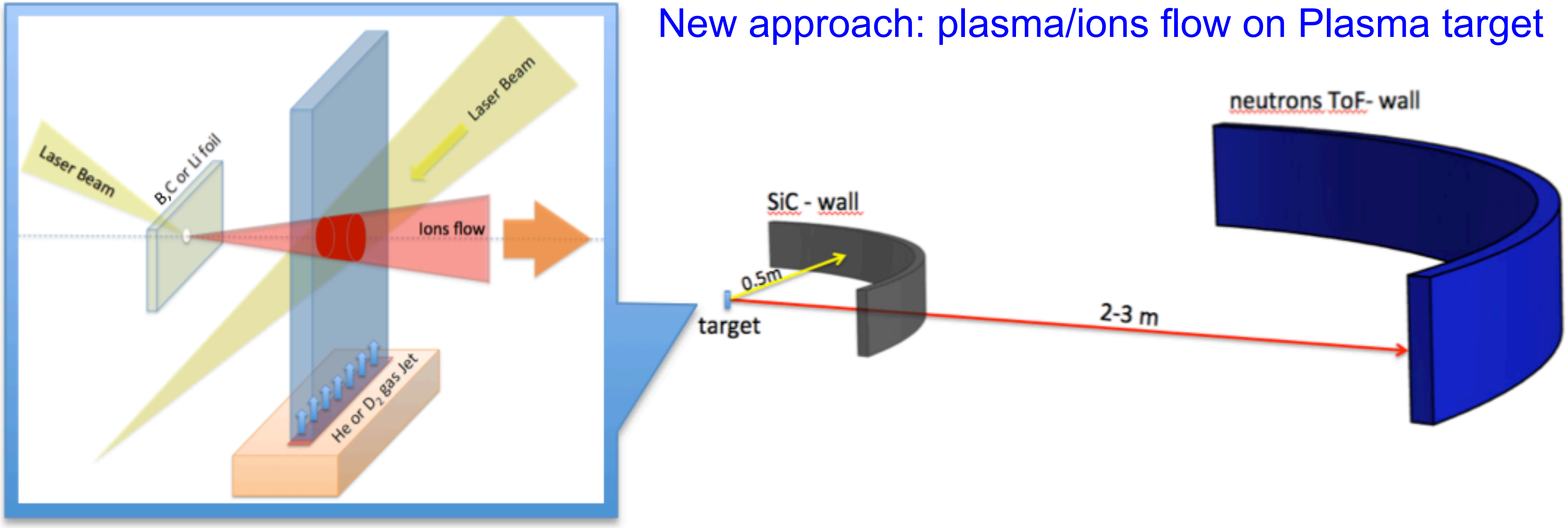
IC-TOF →



G. Lanzalone at al. In press on Rev. of Sci. Instr.

Nuclear reactions in Laser-Plasmas @ ELI-NP

New approach: plasma/ions flow on Plasma target



Gas-Jet Target: Thin Mode (few mms)

minimize “plasma-plasma friction”, the energy dissipation of the fast flowing plasma colliding with the gas-jet plasma, in order to work in a more “conventional” nuclear physics experimental scheme (projectiles on a rest target).

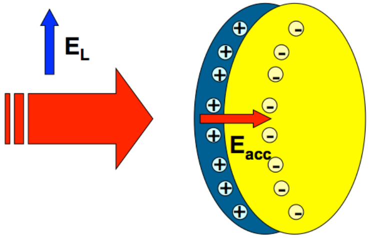
Main advantages:

- ✓ Preferred direction of the nuclear collisions
- ✓ Use of plasma target (ρ, T under control)
- ✓ Direct measurement of the Cross-Sections

Nuclear reactions in Laser-Plasmas @ ELI-NP

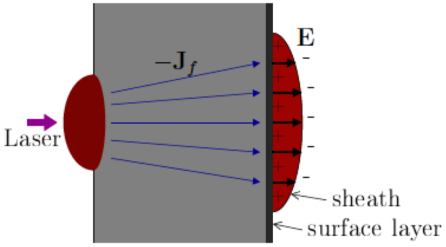
Plasma/ions flow

10 - 100 fs high-intensity laser pulse causes strong charge separation

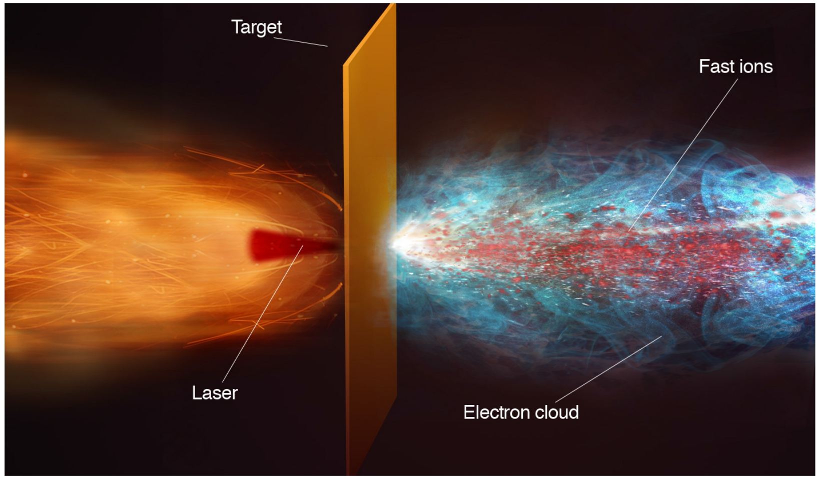


huge quasi-stationary electric (and magnetic) fields are produced
$E_L \approx E_{acc} \approx$ tens GV/cm ⇒ efficient charged particle acceleration

Target Normal Sheath Acceleration (TNSA)



$\mathbf{J}_f$: fast electron current

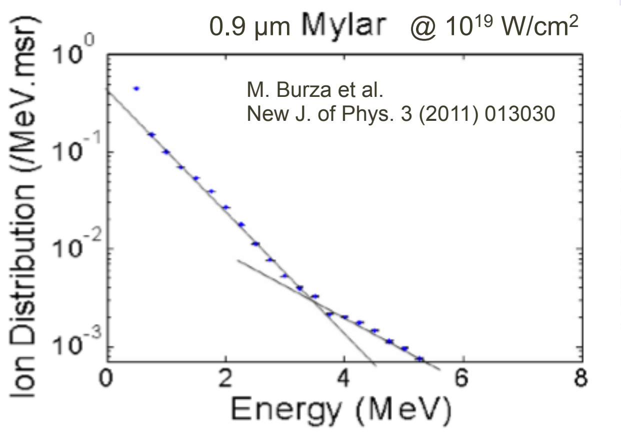


“fast” electrons leaving the rear surface of the target generating the ions acceleration

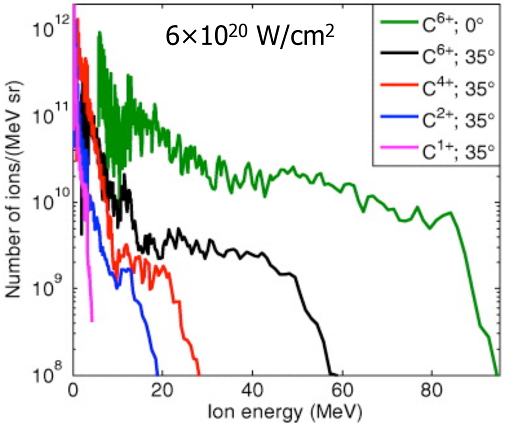
A. Macchi et el. Rev of Mod. Phys, 85 (2013) 75

Nuclear reactions in Laser-Plasmas @ ELI-NP

TNSA Energy spectra
Boltzmann-like distributions


0.9 µm Mylar @ 10^{19} W/cm^2

M. Burza et al.
New J. of Phys. 3 (2011) 013030


6×10^{20} W/cm^2

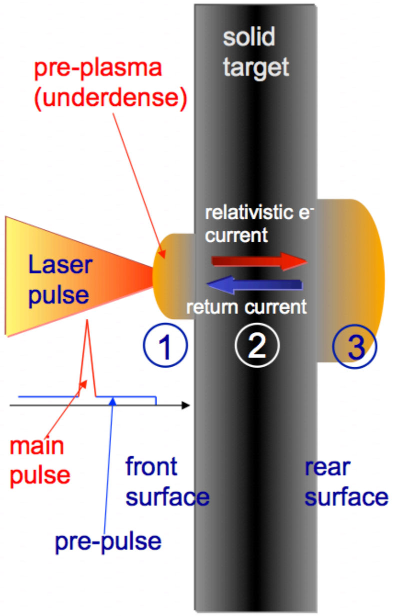
D.C. Carrol et al.
New J. of Phys. 12
(2010) 045020

SOME CRUCIAL ISSUES:

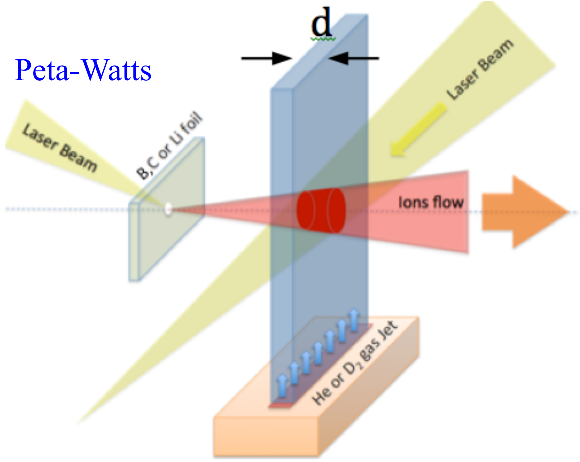
1 laser pulse-front surface interaction
- role of pulse properties
  (intensity, energy, prepulse, polarization)
- role of target properties
  (density, profile, thickness, mass)

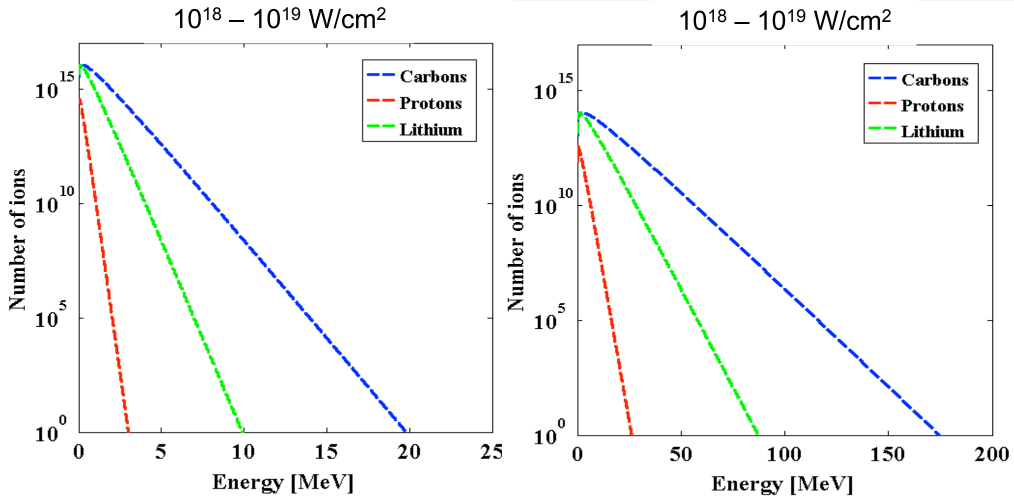
2 electron propagation in the target
- role of electron properties
  (max. energy, spectrum, temperature)
- role of target properties
- role of return current

3 effective charge separation
- generation of intense electric fields
- resulting ion acceleration

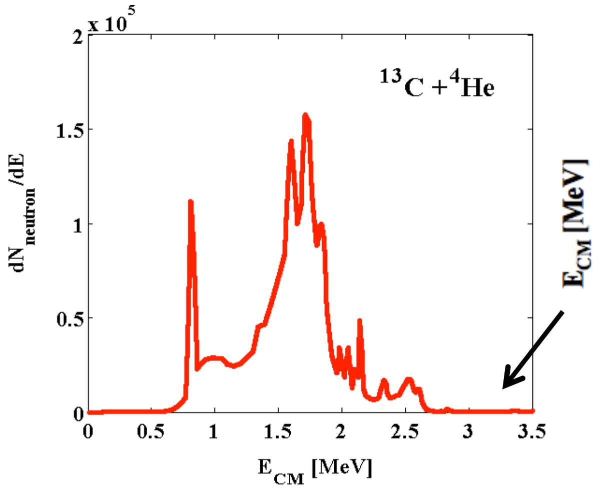


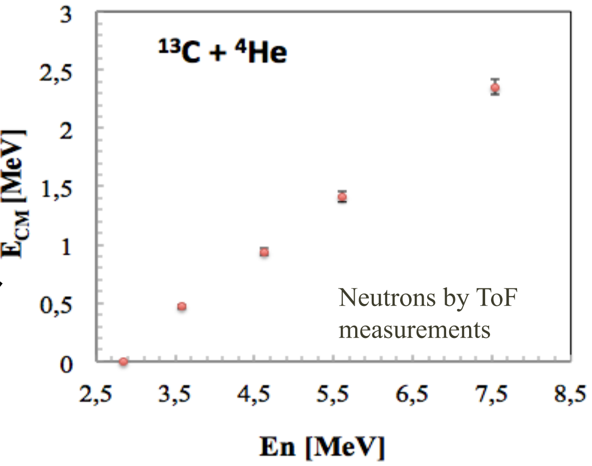
Nuclear reactions in Laser-Plasmas @ ELI-NP

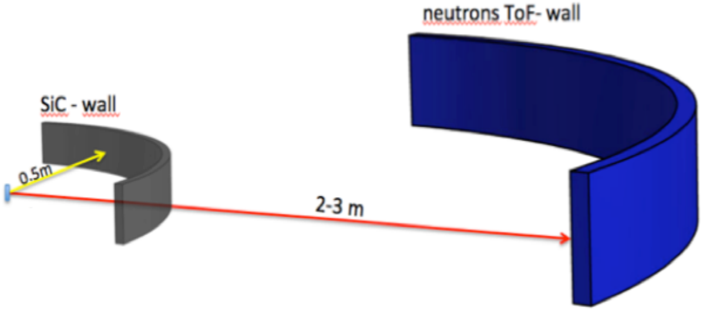




Tuning power density and target parameters => adjust the ions energy distribution





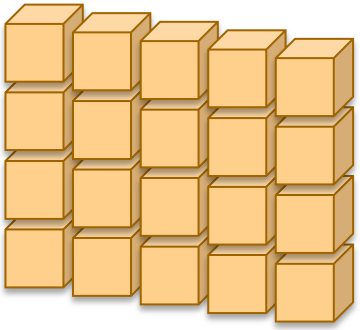


Two body kinematics (Energy, angles) => E_{CM}

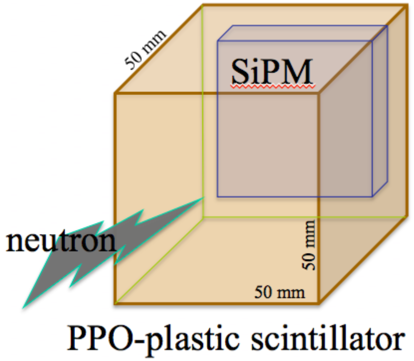
Tuning => Zoom in the region of low CM energies
Low cross-section=> Rep. rate experiments

Nuclear reactions in Laser-Plasmas @ ELI-NP

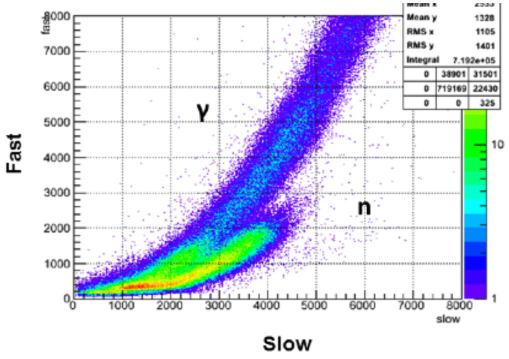
Neutrons ToF Wall



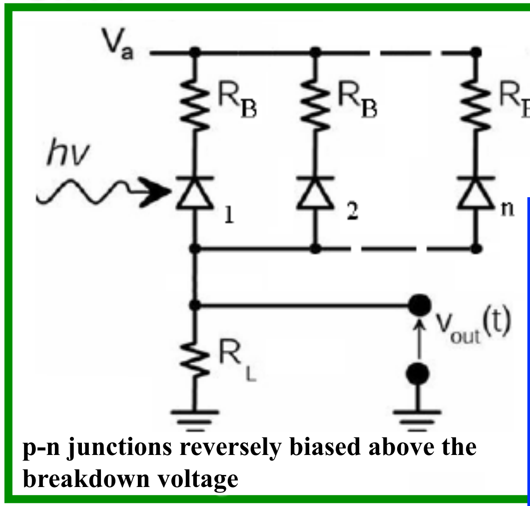
New plastic scintillators with n/γ pulse shape discrimination



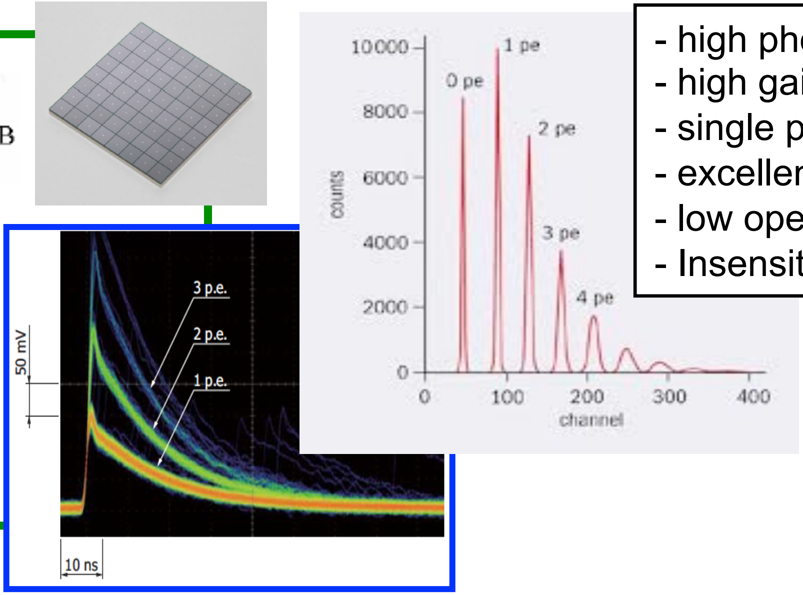
Polysiloxane based scintillator with 8% PPO and 0.02% LV



SiPM



p-n junctions reversely biased above the breakdown voltage



- high photo-detection efficiency
- high gain
- single photon sensibility
- excellent timing performance
- low operative voltage
- Insensitivity electric and magnetic fields

N. Zaitseva et al. NIM A 668 (2012) 88
G.F. Dalla Betta, C. Da Via, et al, JINST 7(2012) c10006

S. Privitera et al. Sensors 2008, 8(8) 4636

Nuclear reactions in Laser-Plasmas @ ELI-NP

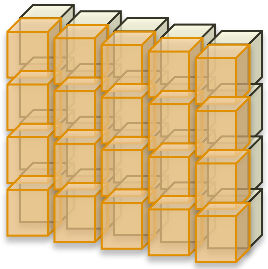
SiC-Wall

Silicon **C**arbide Detectors
for **I**ntense
Luminosity **I**nvestigations
and **A**pplications

- ✓ 1 cm^2 ΔE-E telescope
- ✓ thickness of ΔE stage 100 μm
- ✓ thickness of E stage 500-1000 μm
- ✓ hard to the radiation damage
- ✓ good energy resolution (1 %)

RD50 - CERN

Property	**Diamond**	**GaN**	**4H SiC**	**Si**
E_g [eV]	**5.5**	**3.39**	**3.26**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**≥15**	**25**	**13-20**



SiCILIA Goal
A demostrator of 40
elements with own
read-out electronics

Wide bandgap (3.3eV)
⇒ lower leakage current than silicon insensible to vis. rad.

Signal (**for MIP !**):

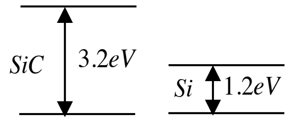
Diamond	36 e/μm
SiC	51 e/μm
Si	89 e/μm

⇒ more charge than diamond Si/SiC≈2

Higher displacement threshold than silicon
⇒ radiation harder than silicon

Leakage current

$I_L = I_{diff} + I_{gen}$



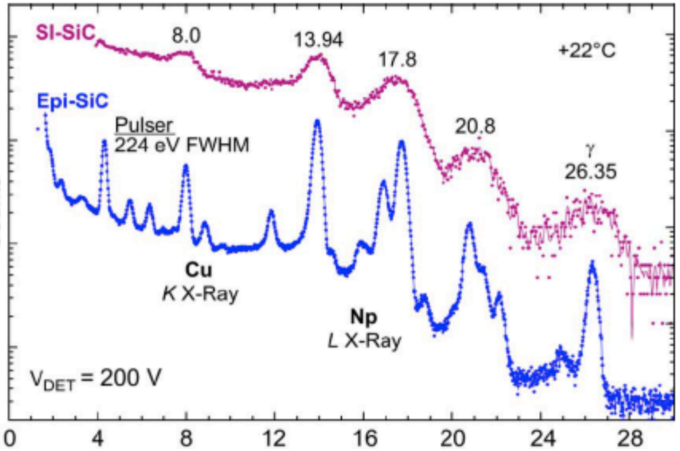
$$\boxed{I_{gen}^{(SiC)} \approx 10^{-5} I_{gen}^{(Si)}}$$

M.Moll , NIM in Physics Research A 511 (2003) 97–105

LNS Laser Activities

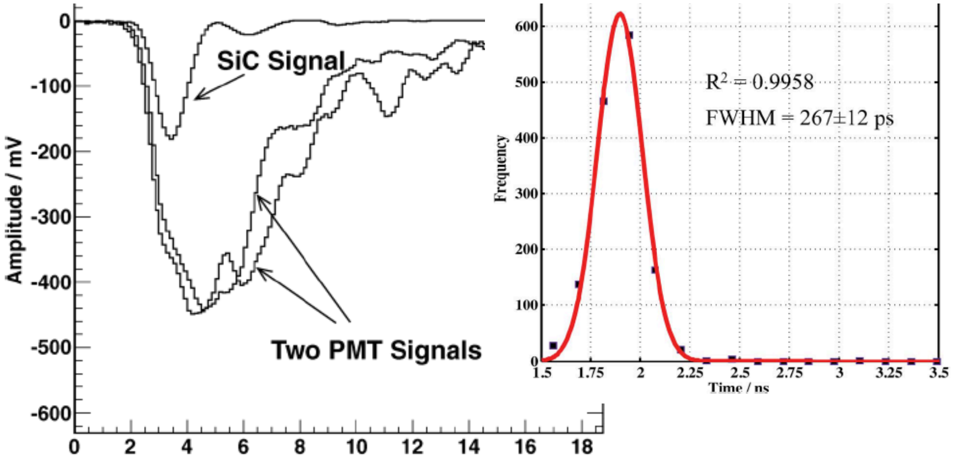
SiC Performance

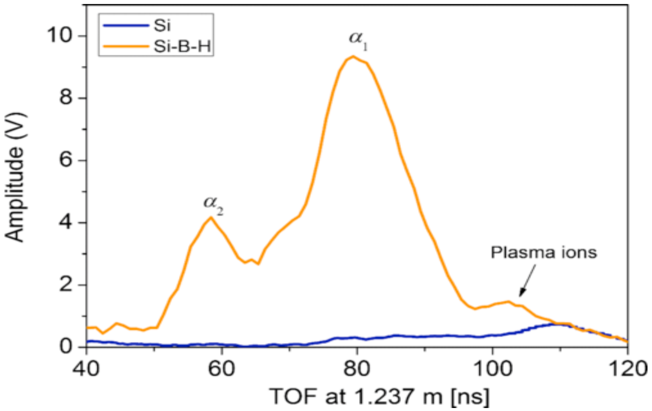
- ✓ Low leakage current ➔ high energy resolution ➔ X-rays detection
- ✓ Timing ➔ sub-nanoseconds ➔ToF application
- ✓ Insensible to visible light ➔ neutrons and charged particles detection in plasmas



G. Bertuccio et al. IEEE Trans. Nucl. Scie. 60, 2, 2013

Xiaodong Zhang IEEE Trans. Nucl. Scie. VOL. 60, 3, 2013





A. Picciotto et al. Phys. Rev. X 4, 031030 (2014)

TOF distribution measured by the SiC detector for the Si-H-B (orange curve) and Si (blue curve) targets

LNS Laser Activities

R&D on Laser ions acceleration

NRLP => ELI-NP

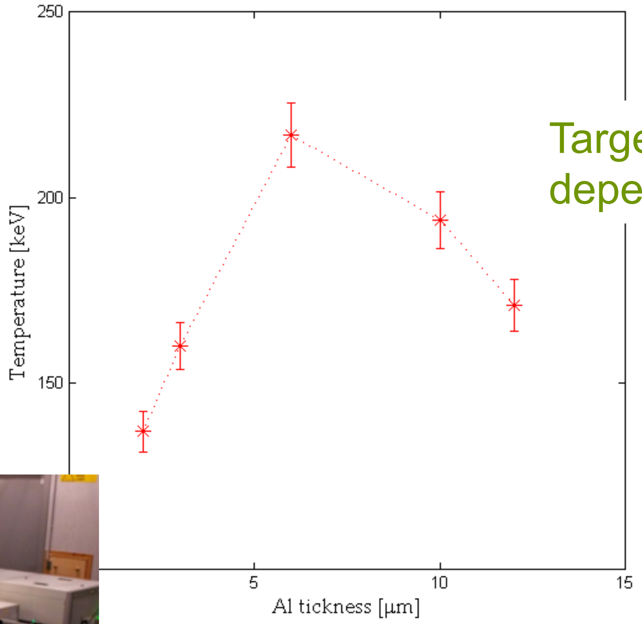
ELIMED => ELI-Beamlines

ELI-Beamlines MEDical and multidisciplinary applications

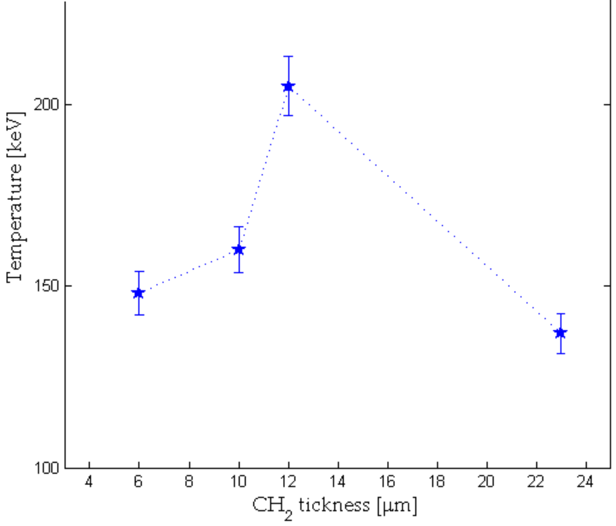
TNSA

Ions energy spectra

T from Boltzmann-like fit

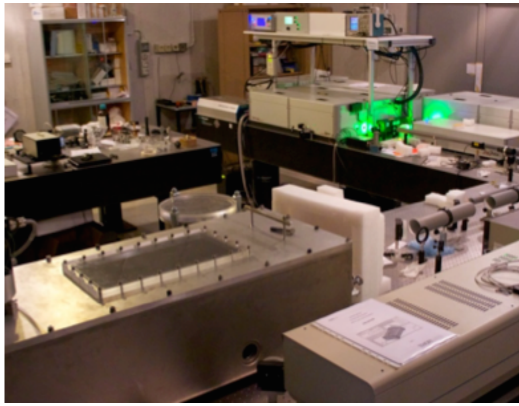


Target thickness dependence



INO-CNR
Istituto Nazionale di Ottica

10 TW Laser @ ILIL

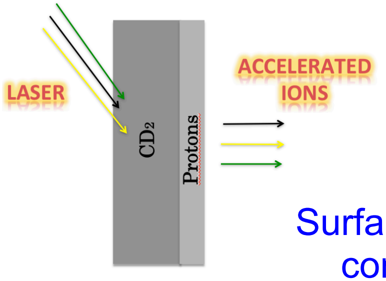


LNS Laser Activities

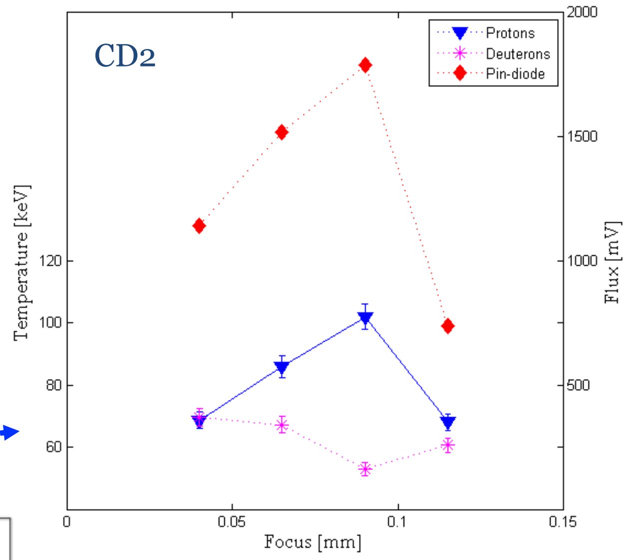
TNSA

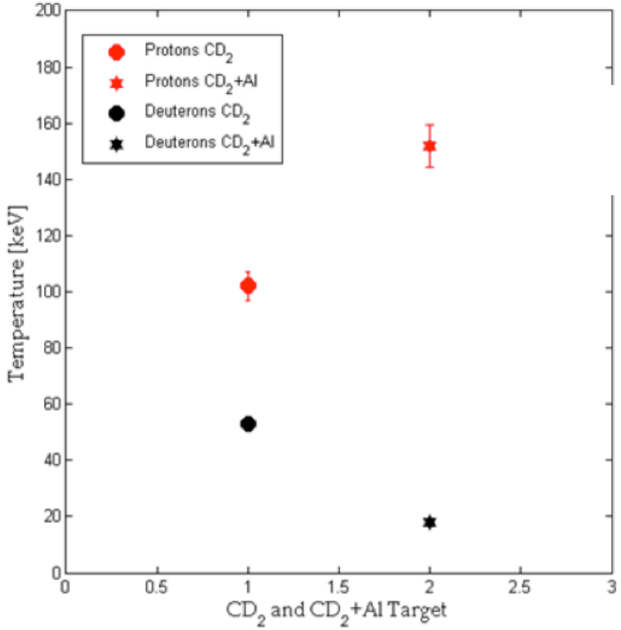
Ions energy spectra

T from Boltzmann-like fit

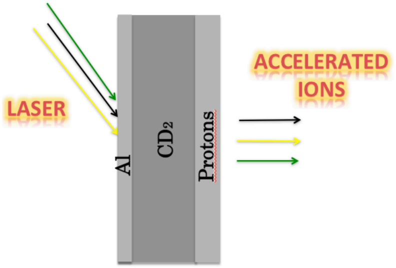


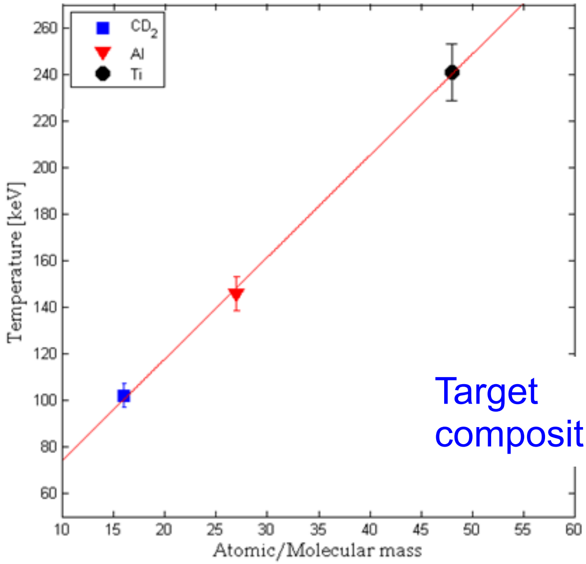
Surface%Volume contribution ⋯→





Target structure



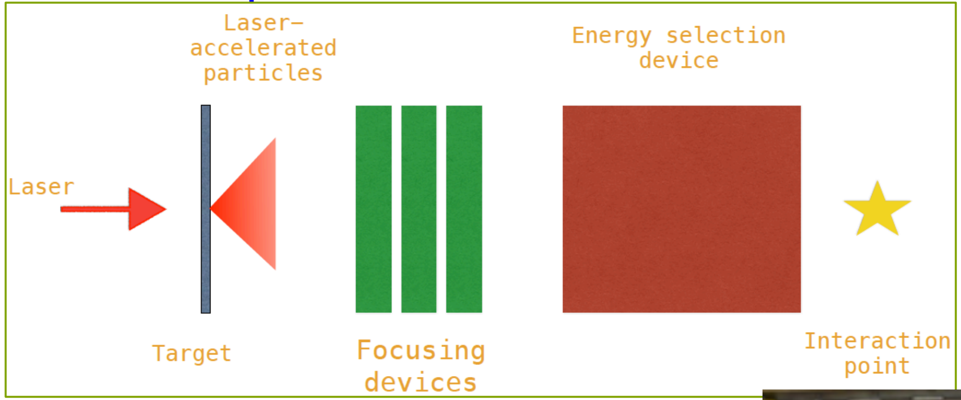


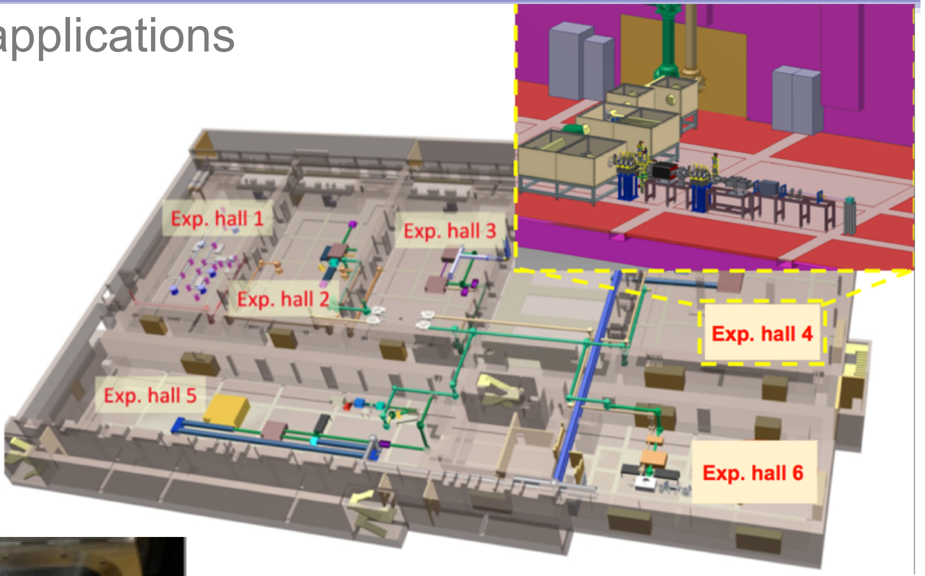
Target composition

LNS Laser Activities

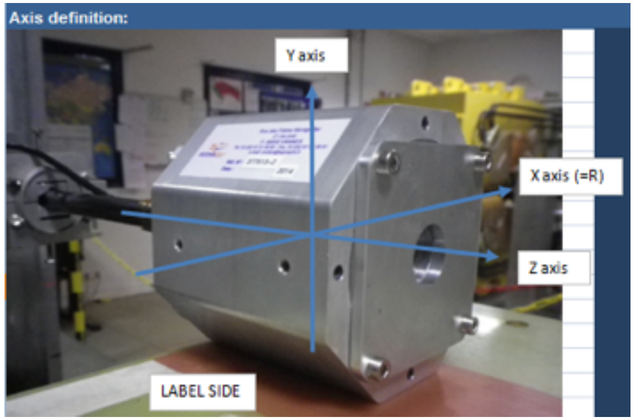
ELI-Beamlines MEDical and multidisciplinary applications

ELIMED concept

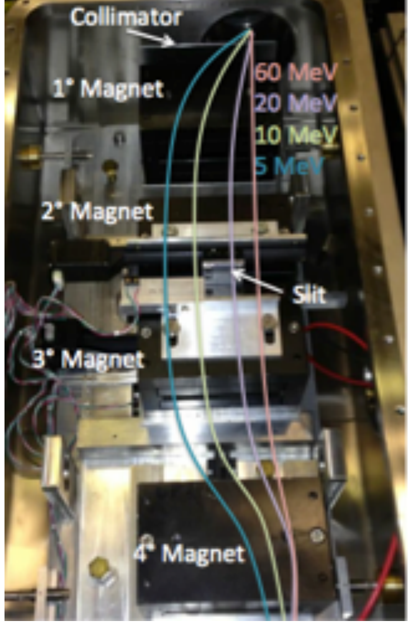


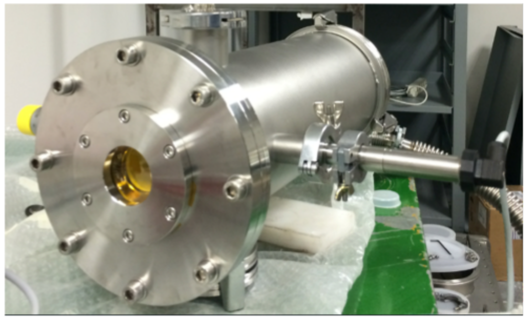


Preliminary prototypes for the beam transport (up to 30 MeV)



Prototypes for beam focusing





Dosimetry - FC

Prototypes for the energy selection

Collaboration

Università
degli Studi di Catania

INFN
Istituto Nazionale
di Fisica Nucleare

IFIN-HH

UNIVERSITATEA
DIN BUCUREŞTI
FONDATA IN 1864

Consiglio Nazionale delle Ricerche
Istituto per la Microelettronica e Microsistemi

INO
Istituto Nazionale
di Ottica

cnrs
dépasser les frontières
IN2P3
Les deux infinis

cea

UNIVERSITÉ DE
BORDEAUX

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK