FUSION

***FU**sion **S**tud**I**es of pr**O**ton boron*
***N**eutron-less reaction in laser-generated plasma*

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on behalf of the whole collaboration

http://fusion.lns.infn.it/

Which is the framework?

The Inertial Confinement Fusion

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The Inertial Confinement Fusion

What is FUSION?

INFN project approved by the **INFN Committee V** (2023-2025)

10 INFN Sections, 15.3 FTE

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FUSION: **FU**sion **S**tud**I**es of pr**O**ton boron Neutron-less reaction in laser-generated plasma

Why FUSION?

Study of the p(11B, α)2α
in a plasma environment

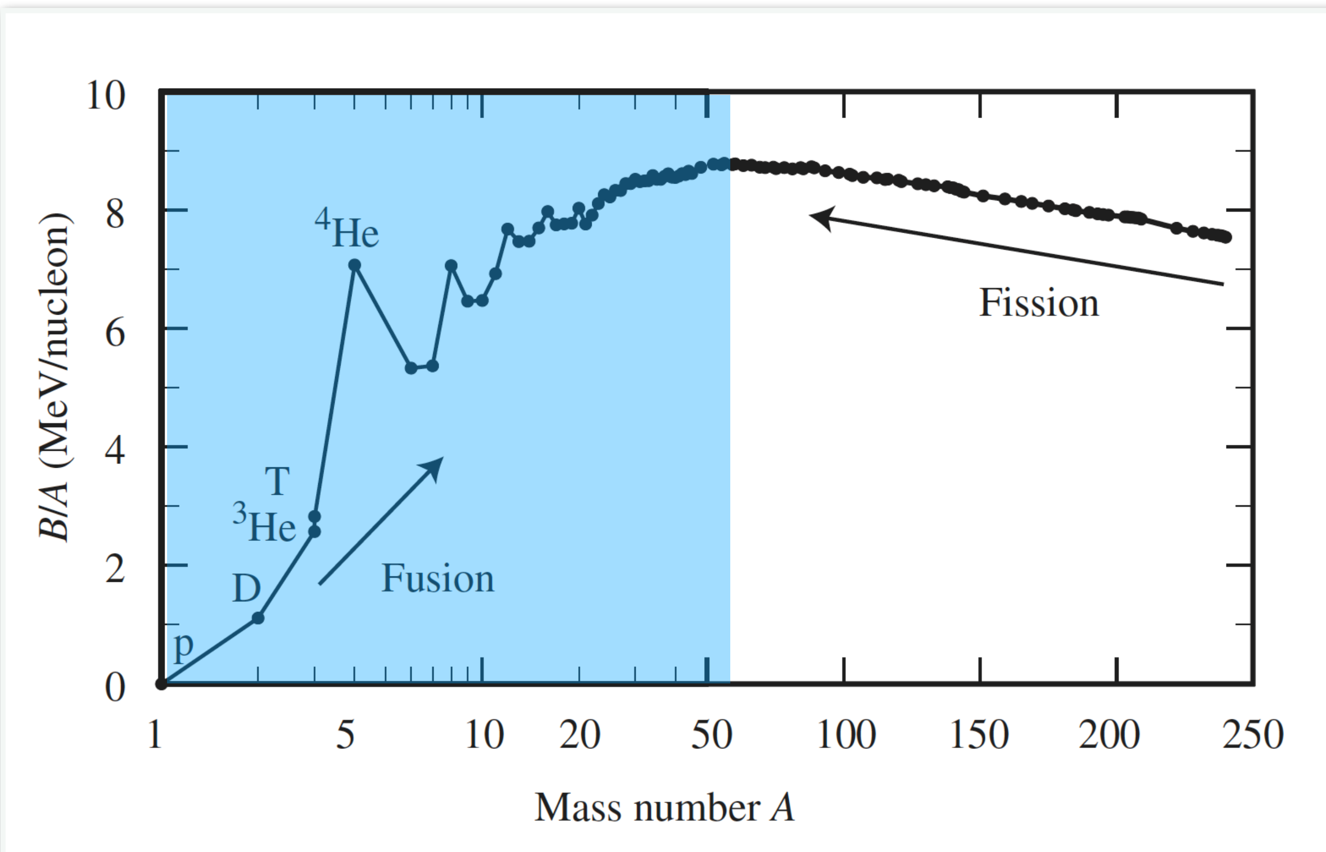
for **energy**

for the development of **new alpha sources**

for the general **understanding** of fusion nuclear reaction in plasmas

Nuclear fusion and approaches

Nuclei fusion produce exothermic reactions: released energy proportional to the mass difference (binding energy)



—**magnetic** confinement

An energy source (i.e. a laser) release energy in a small capsule forming a region (hot-spot) where **exothermic nuclear reaction can be triggered**

Nuclear fusion and approaches

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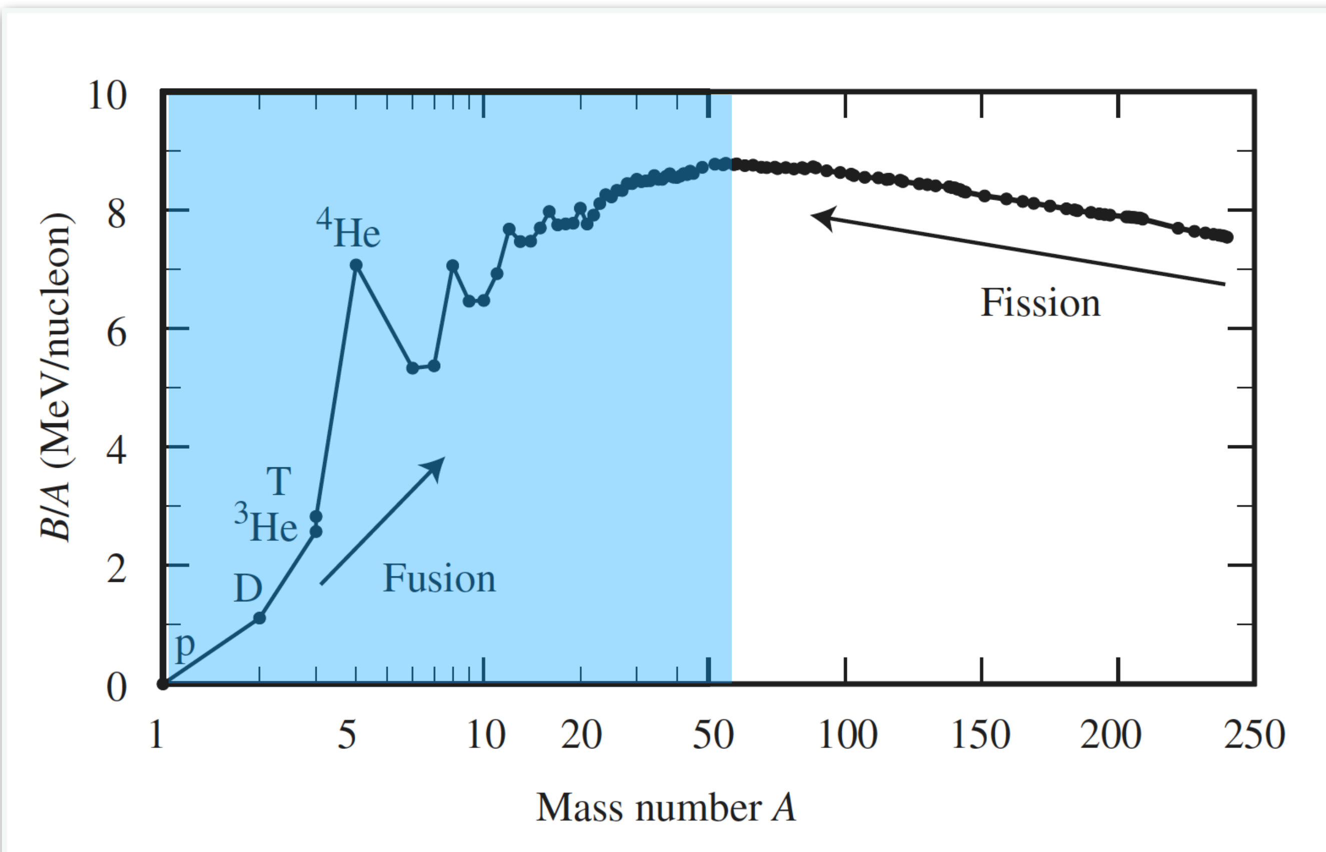
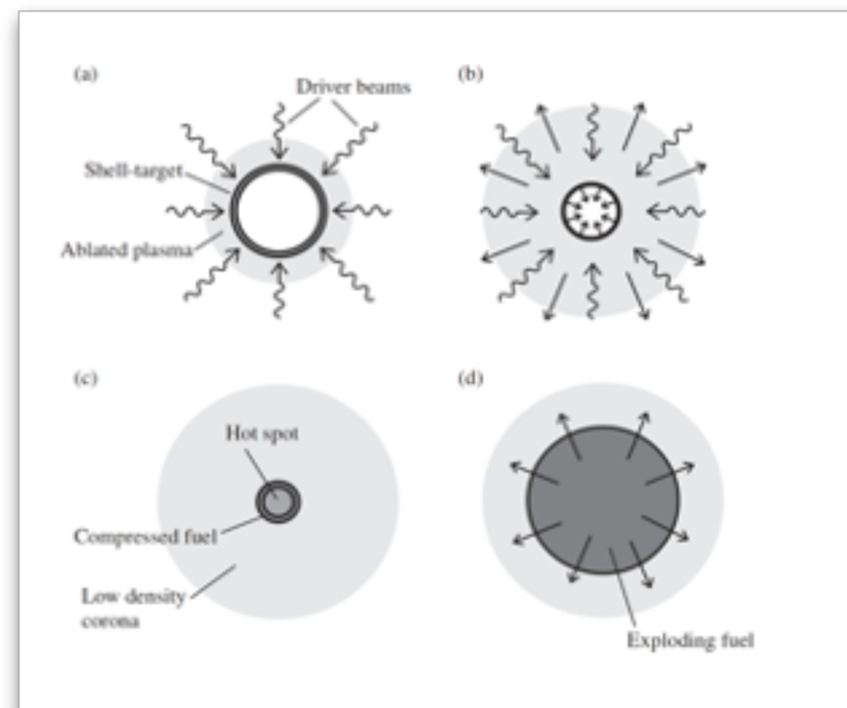


—**magnetic** confinement

—**inertial** confinement



S Atzeni, J Meyer-Ter-Vehn, <<Inertial Fusion>>, Oxford Science Publications (2004)

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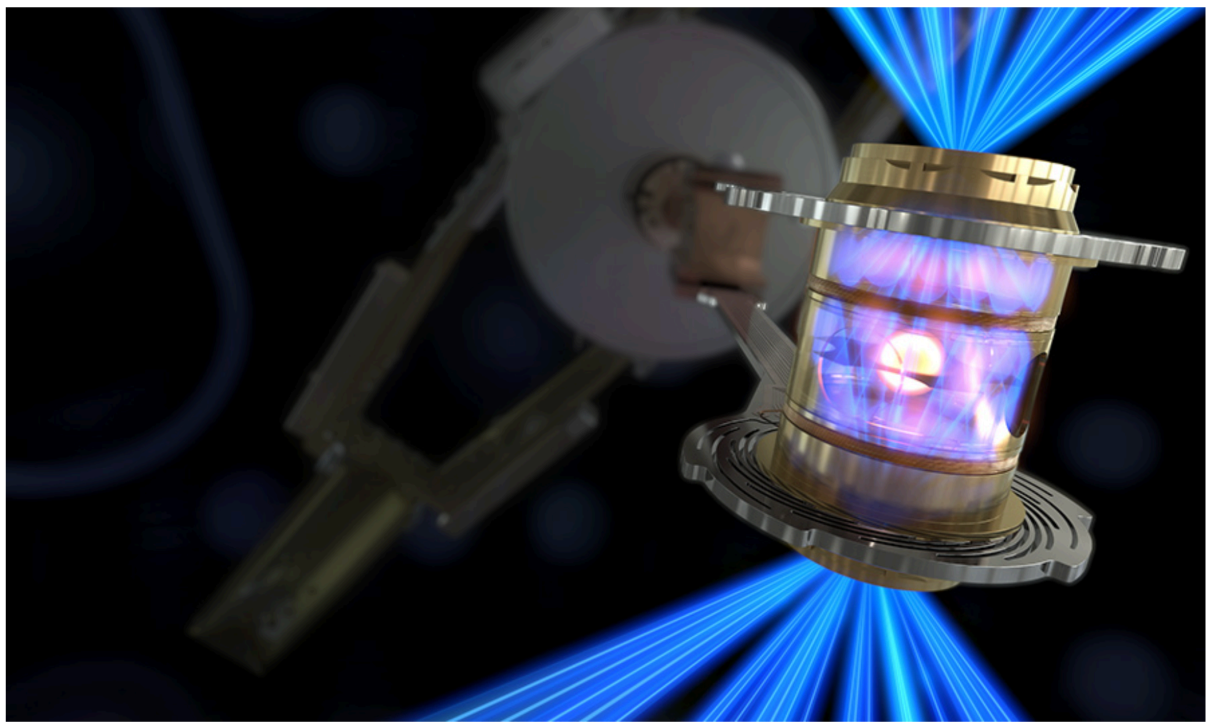
Nuclear fusion and approaches



In the indirect-drive method used at the National Ignition Facility, a UV laser is fired at a cylinder called a hohlraum rather than at the hydrogen fuel. The hohlraum then emits x rays, which compress the fuel inside. Credit: Lawrence Livermore National Laboratory

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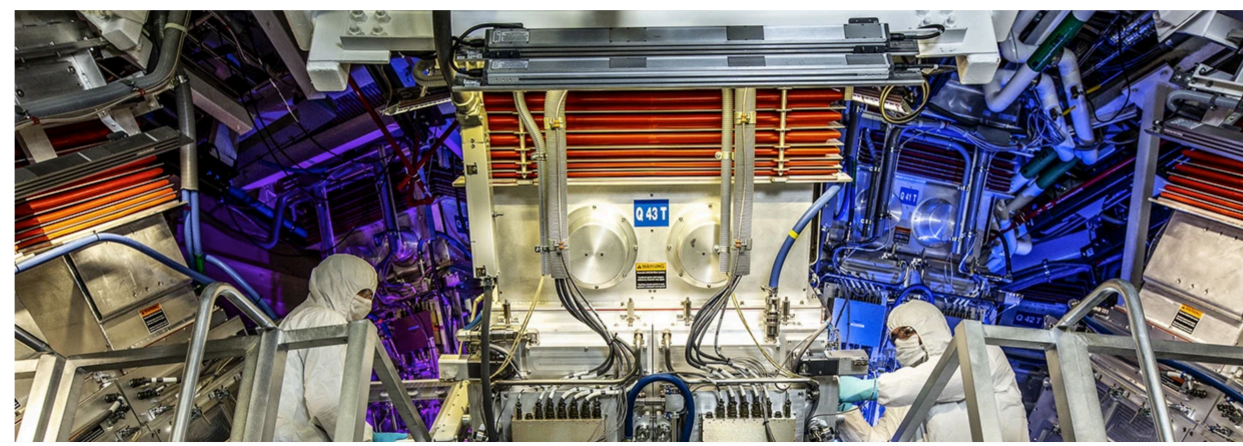
NEWS EXPLAINER | 13 December 2022

Nuclear-fusion lab achieves 'ignition': what does it mean?

Researchers at the US National Ignition Facility created a reaction that made more energy than they put in.

Jeff Tollefson & Elizabeth Gibney



Corrected 17 February 2023. See full text.

NEWS

wealthy institutions, Freelon says. "Who's going to lose out are going to be grad students, people without institutional affiliations, people whose institutions are lower wealth." Even if researchers ultimately retain access to Twitter's data, the uncertainty caused by the API announcement highlights larger issues, they say. Because social media influences society as a whole, social media companies should not be able to control research on the impact of their products, argues Philipp Lorenz-Spreen of the Max Planck Institute for Human Development, who studies social media networks. "We do not depend on the oil industry to be able to measure CO_2, but we are dependent on Facebook to measure polarization on Facebook," he says. "That is a bad situation."

In Europe, the Digital Services Act, whose rules will apply from early 2024 on, seeks to address this issue. One provision allows national authorities to compel access to so-

ENERGY

Laser fusion success sparks hope of new route to fusion power

Startups lay plans for power plants that would trigger tiny, rapid-fire fusion blasts

By **Daniel Clery**

Last year, when the National Ignition Facility (NIF) fired its 192 laser beams at a gold cylinder enclosing a tiny sphere of hydrogen isotopes, it did more than spark a historic fusion reaction. The shot—the first to produce more energy than the lasers delivered—also triggered a burst of optimism among some fusion scientists that the same general ap-

Others are far more cautious. "We don't know how to build a power plant," says Tammy Ma, who heads the inertial fusion energy effort at Lawrence Livermore National Laboratory, the home of NIF. Late last month, the Department of Energy (DOE) published a report outlining a long program of research that it would need to do to develop power plants based on ICF..

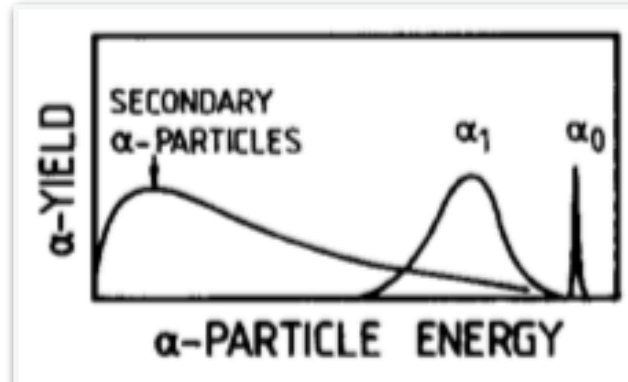
Although the December 2022 shot at NIF produced a record-breaking 3.15 megajoules

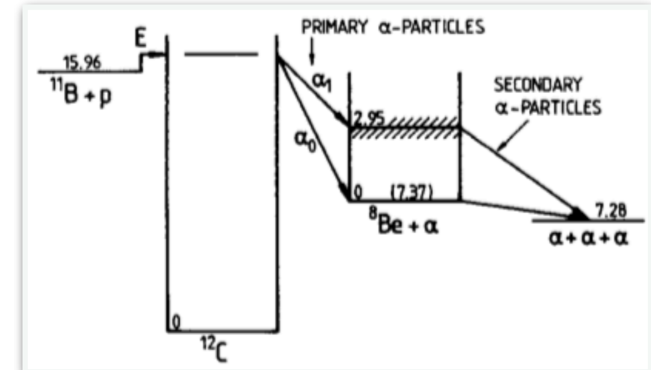
December 5th 2022

About 3.15 Mega-joules of fusion energy from the 2.05 MJ

The INFN FUSION project: the $p(^{11}B, \alpha)2\alpha$ fusion reaction in a laser generated plasma

The p(^{11}B, α)2α





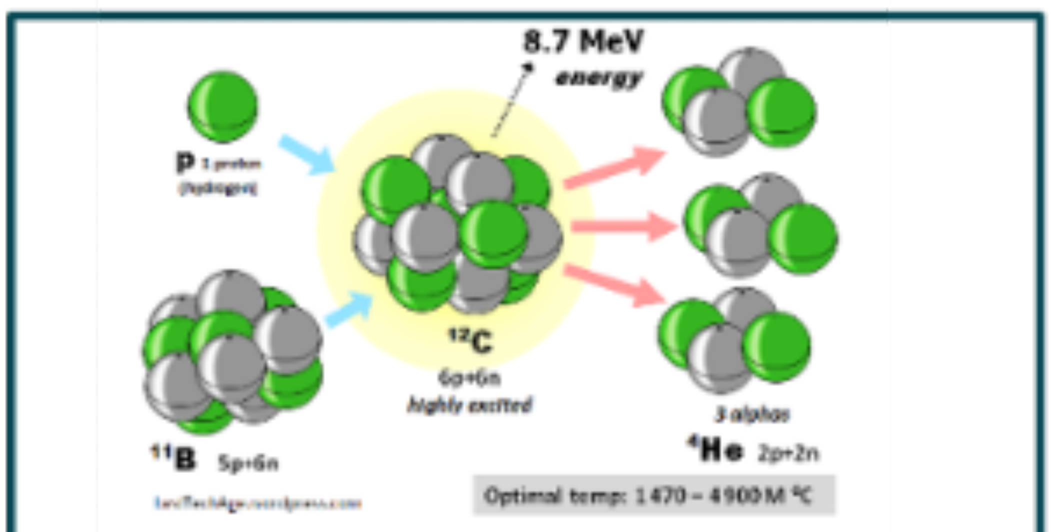
The **p-^{11}B is another reaction of interest for future ICF schemes**: even if it is energetically less favourable it shows enormous advantages

p(^{11}B, α)2α Q_{reac} = 8.9 MeV

Table 1.1 Some important fusion reactions and parameters of the cross-section factorization 1.21.

	Q (MeV)	$\langle Q_\nu \rangle$ (MeV)	$S(0)$ (keV barn)	$\epsilon_G^{1/2}$ (keV$^{1/2}$)
Main controlled fusion fuels				
$D + T \rightarrow \alpha + n$	17.59		1.2×10^4	34.38
$D + D \rightarrow T + p$	4.04		56	31.40
$D + D \rightarrow {}^3He + n$	3.27		54	31.40
$D + D \rightarrow \alpha + \gamma$	23.85		4.2×10^{-3}	31.40
$T + T \rightarrow \alpha + 2n$	11.33		138	38.45
Advanced fusion fuels				
$D + {}^3He \rightarrow \alpha + p$	18.35		5.9×10^3	68.75
$p + {}^6Li \rightarrow \alpha + {}^3He$	4.02		5.5×10^3	87.20
$p + {}^7Li \rightarrow 2\alpha$	17.35		80	88.11
$p + {}^{11}B \rightarrow 3\alpha$	8.68		2×10^5	150.3
The p–p cycle				
$p + p \rightarrow D + e^+ + \nu$	1.44	0.27	4.0×10^{-22}	22.20
$D + p \rightarrow {}^3He + \gamma$	5.49		2.5×10^{-4}	25.64
${}^3He + {}^3He \rightarrow \alpha + 2p$	12.86		5.4×10^3	153.8
CNO cycle				
$p + {}^{12}C \rightarrow {}^{13}N + \gamma$	1.94		1.34	181.0
$[{}^{13}N \rightarrow {}^{13}C + e^+ + \nu + \gamma]$	2.22	0.71	—	—
$p + {}^{13}C \rightarrow {}^{14}N + \gamma$	7.55		7.6	181.5
$p + {}^{14}N \rightarrow {}^{15}O + \gamma$	7.29		3.5	212.3
$[{}^{15}O \rightarrow {}^{15}N + e^+ + \nu + \gamma]$	2.76	1.00	—	—
$p + {}^{15}N \rightarrow {}^{12}C + \alpha$	4.97		6.75×10^4	212.8
Carbon burn				
${}^{12}C + {}^{12}C \rightarrow {}^{23}Na + p$	2.24			
${}^{12}C + {}^{12}C \rightarrow {}^{20}Na + \alpha$	4.62		8.83×10^{19}	2769
${}^{12}C + {}^{12}C \rightarrow {}^{24}Mg + \gamma$	13.93			

p + 11B → 3α (8.7 MeV)



S Atzeni, J Meyer-Ter-Vehn, <<Inertial Fusion>>, Oxford Science Publications (2004)

The p(^{11}B, α)2α

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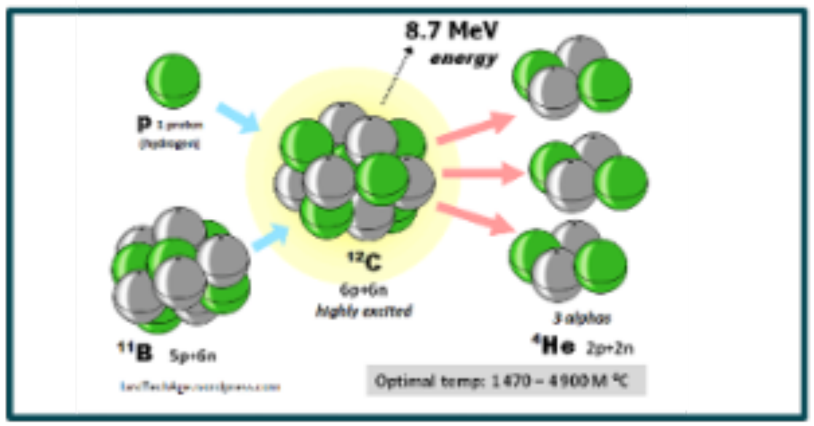
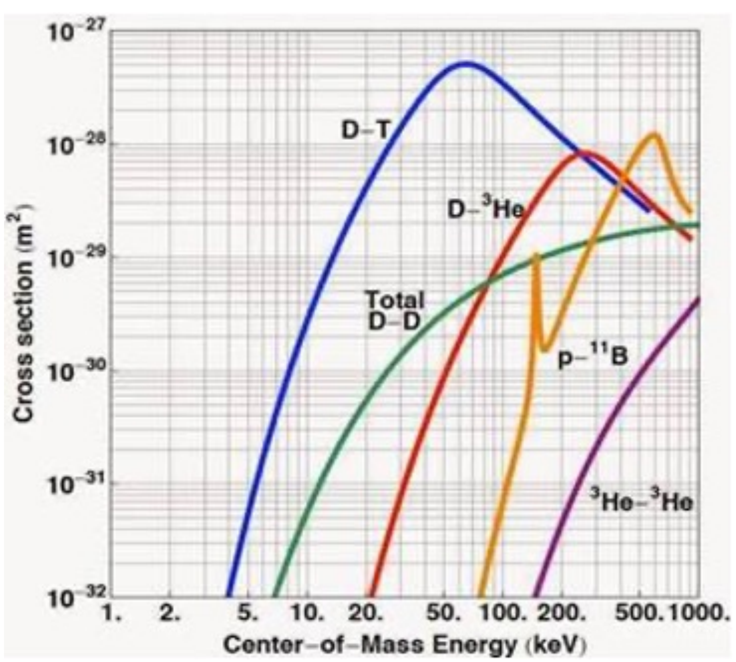




It is a **neutron-less** fusion reaction

Two resonances at about **100 keV** and **600 keV** in the system center of mass

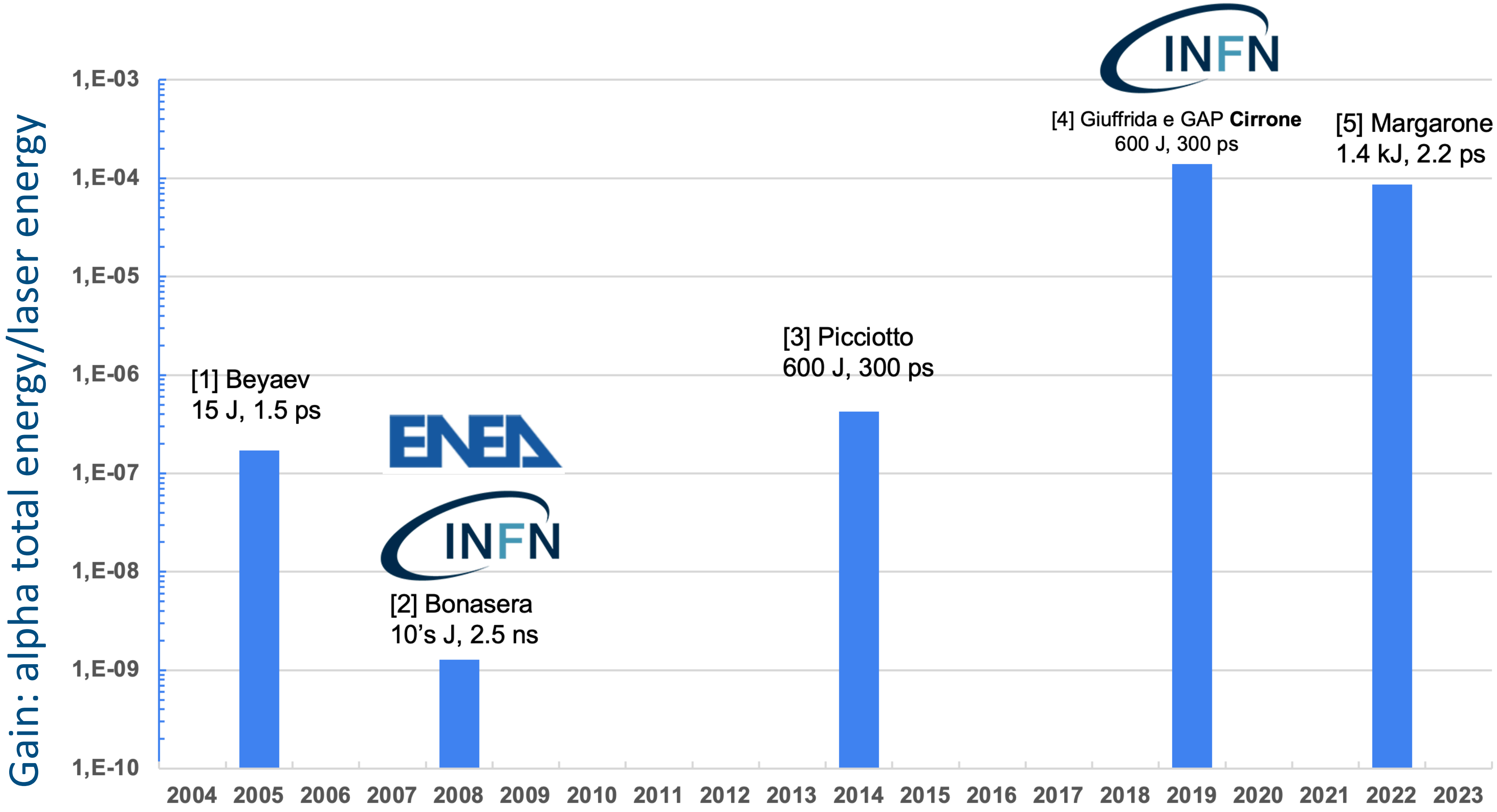
Abundant reagents

Is of interest in **astrophysical processes**

Is of interest for new schemes of α sources

Of course, this reaction must be studied **in a plasma** as that generated in a laser-matter interaction process

Why FUSION want investigate this reaction ?



[1] Belyaev VS,Matafonov AP, Vinogradov VI, Krainov VP, Lisitsa VS, Roussetski AS, et al. Phys Rev E. (2005) 72:026406.
[2] Bonasera A, Caruso A, Strangio C, Aglione M, Anzalone A, Kimura S, et al. Measuring the astrophysical S-factor in plasmas. World Scientific (2008). p. 503–7.
[3] Picciotto A, Margarone D, Velyhan A, Bellutti P, Krasa J, Szydlowsky A, et al. Phys Rev X. (2014) 4:031030.
[4] Giuffrida L, Belloni F, Margarone D, Petringa G, Milluzzo G, Scuderi […] and GAP Cirrone. Phys Rev E. (2020) 101:013204.
[5] Margarone D., Bonvalet J, Giuffrida L., Morace A., Kantarelou V., Tosca M., Applied Sciences 12, no. 3: 1444.

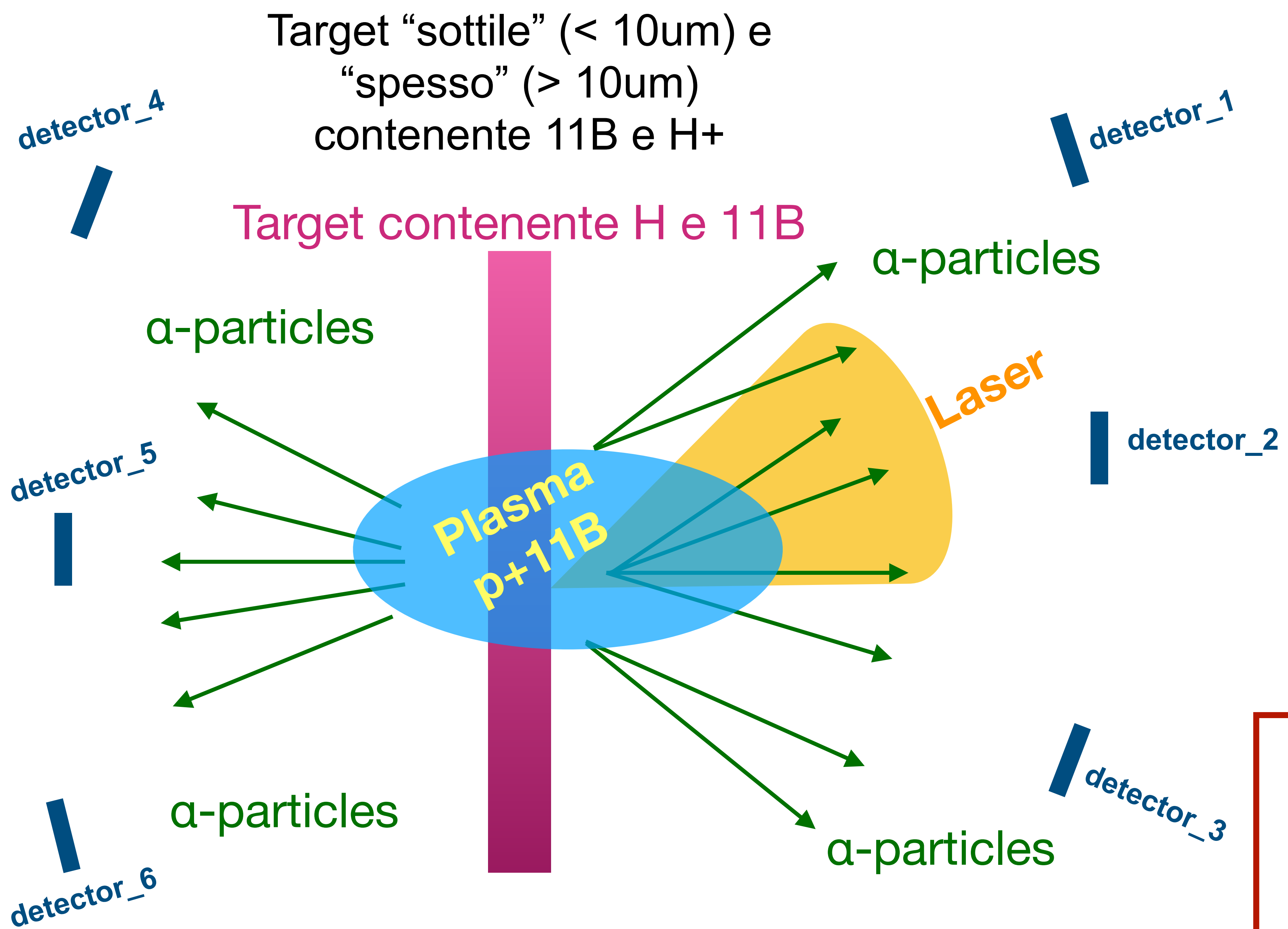
FUSION **GOAL**: increase this gain of one order of magnitude

The INFN FUSION project

INFN Unit	Local Responsible	Institution
Bologna	Dr Fabrizio Odorici	INFN of Bologna (I)
Catania	Prof Antonio Trifiro'	University of Messina (I)
Firenze	Prof Gabriele Pasquali	University of Florence (I)
Lecce	Prof Rosaria Rinaldi	University of Salento (I)
LNGS	Prof Libero Palladino	University of l'Aquila (I)
LNS	Dr Giacomo Cuttone	INFN-LNS, Catania (I)
Milano	Dr Davide Bortot	Milan Polytechnic, (I)
Roma 2	Prof Claudio Verona	University of 'Tor Vergata', Rome (I)
TIFPA	Dr Antonino Picciotto	Fondazione Bruno Kessler, Trento (I)
Torino	Dr Raffaella Testoni	Turin Polytechnic (I)

1. **New targets** and diagnostic
2. Study of the **reaction in plasma**
3. Study of the **stopping powers** of proton in a Borated plasma

Study of the reaction in plasma



Simplified scheme of the p(11B,a)2a reaction activated in plasma

GAP Cirrone (LNS), F Consoli (ENEA)

Innovative **targets** containing H and 11B

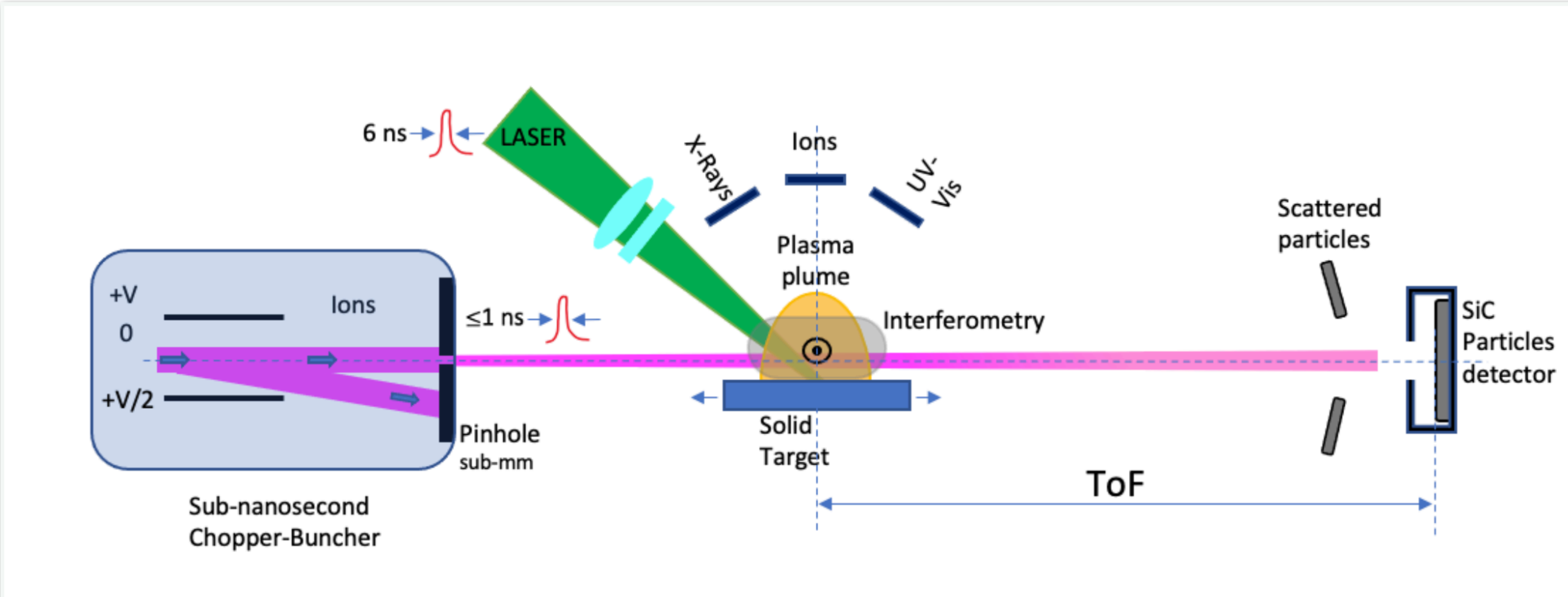
The laser interact with the target and generate a plasma

The p(11B,a)2a reaction occur in plasma and **alpha yield is measured**

Laser pulse characteristics

Duration: 300 ps
Contrast: 10E-7
Energy: up to 1000 J
Power on target: 3 TW
Intensity on target: 10^{16} W/cm2

Measurement of the stopping power in plasma



A **“Borated” plasma** is generated

Proton/ion bunches will be synchronised

Energy loss in this plasma will be characterised

S Tudisco LNS), G Pasquali (FI)

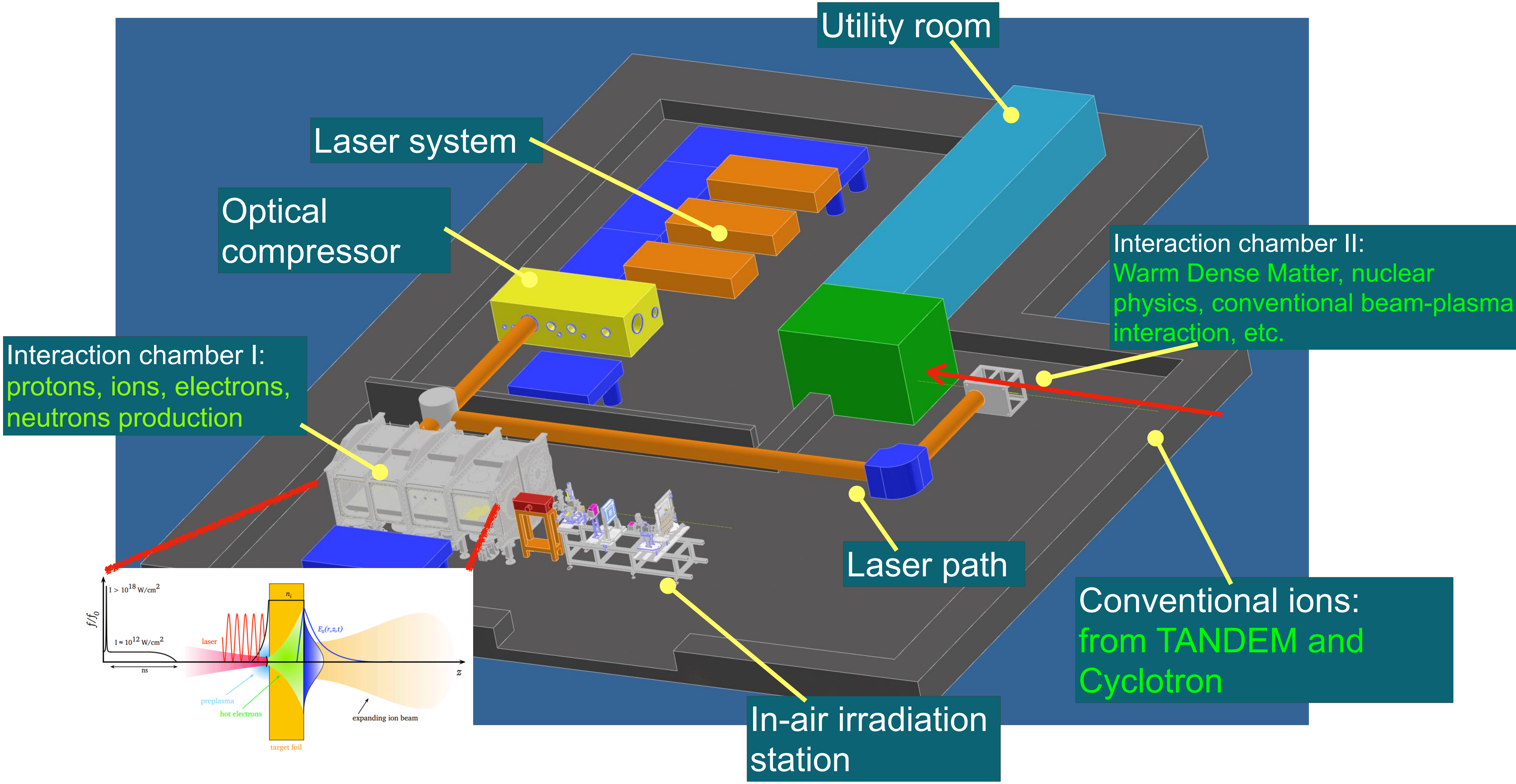
Laser pulse characteristics

Duration: 6 ns
Energy: 2 J
Power on target: 10E8
Pulse intensity: 10^{12} W/cm2

Ion-beam characteristics

Spot diameter: < 1mm
Energy: 0.5 - 3 AMeV (protons, alfa)
Bunch duration: 1 ns

I-LUCE experimental area



Protons (up to 100 MeV), ions, electrons (up to 3 GeV), neutrons and gamma production and interaction with conventional beams

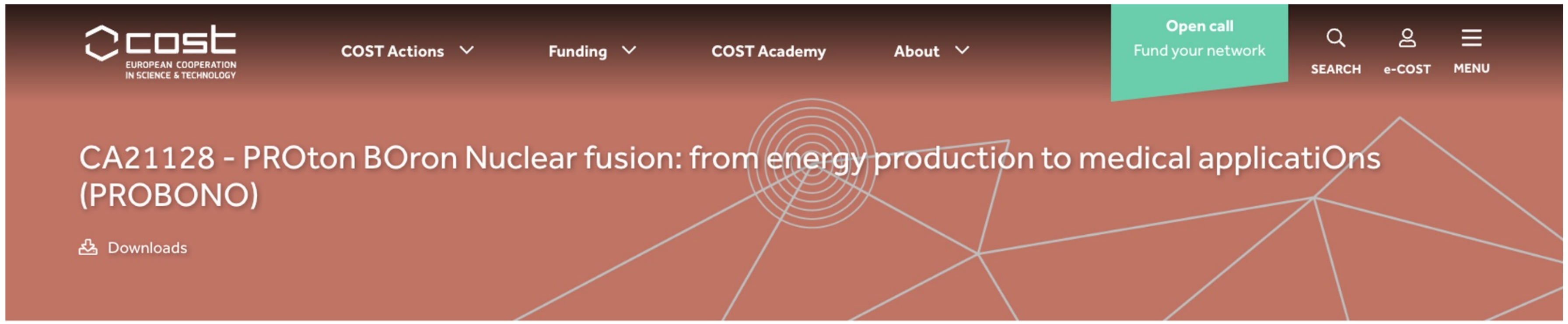
I-LUCE potential activities

- ✓ **Dosimetry and Radiobiology** of «FLASH» beams (electrons, protons, gamma)
- ✓ **Cultural Heritage:** PIXE studies with laser-driven protons
- ✓ **Space applications:** laser-driven beams could easily reproduce the space radiation quality
- ✓ **Radioisotopes production:** laser-driven beams could easily produce high intensity charged particles beams
- ✓ Imaging at the molecular level with **ultrafast X-Rays** (ex radiation chemistry of the radiolysis)
- ✓ **Neutron sources**
- ✓ **Free Electron Laser radiation**

- ✓ **Stopping powers** in plasma
- ✓ Studies on **Nuclear Reaction** in plasma with particular focus on the pB reaction* (PROBONO Cost Action)
- ✓ Materials studies
- ✓ ………… Many other physics cases

Ion-plasma interaction: UNIQUE CAPBILITY OF INFN-LNS

Cost action on the use of p-^{11}B: FUNDED!



- Formation of a critical mass and a common front for preparation of EU proposals (i.e. Horizon Europe and ERC Calls)
- More than 50 Institutions
- Dr GAP Cirrone and F Consoli Italian representative in the management Committee

ProBoNO:

Energy applications

Medical applications

Table-top sources

Radioisotopes

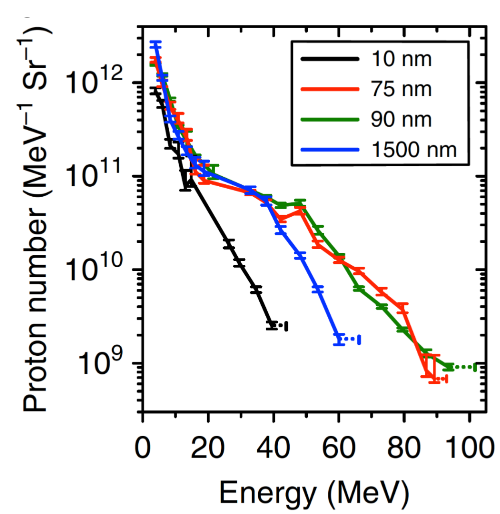
Patents:
EP2833365A1 - reaction scheme
EP3266470A1 - medical applications

Thanks for listening

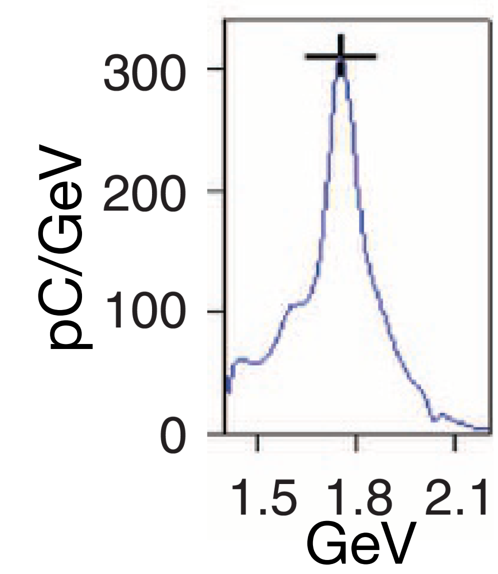
Laser and beams specifications at 350 TW

Laser Power		350 TW
Energy per pulse		>7 J
Pulse duration		≤ 25 fs
Focusing surface		36 μm² or
Max power density (at the target)		8.82·10^{20}
I*λ^2		5.64·10^{20}
Contrast ratio @100 ps (ASE)		> 10^{10}
Repetition rate		1 Hz
Protons Ions	Max energy	50 MeV
	Particle per pulse (at 30 MeV)	10^{11} MeV^{-1} Sr^{-1}
	Energy spread	100%
	Beam divergency (max)	±20°
Eletrons	Max energy	3 GeV
	Particles per pulse	10^9
	Beam divergency (max)	± 20 mad
Neutrons	Max energy	20 MeV
	Particles per pulse	10^{10}
	Energy spread	100
	Beam divergency	Isotropic
Gamma X-beams	Synchrotron radiation of the electrons inside the	
	Energy	up to 80
	Beam divergency	Directionality in the beam

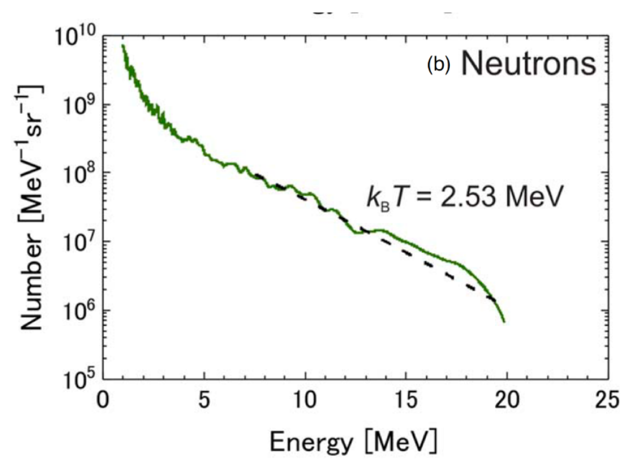
Protons spectra from A. Higginson et al. "Near-100 MeV protons via a laser-driven transparency-enhanced hybrid acceleration scheme", NATURE COMMUNICATIONS | (2018) 9:724



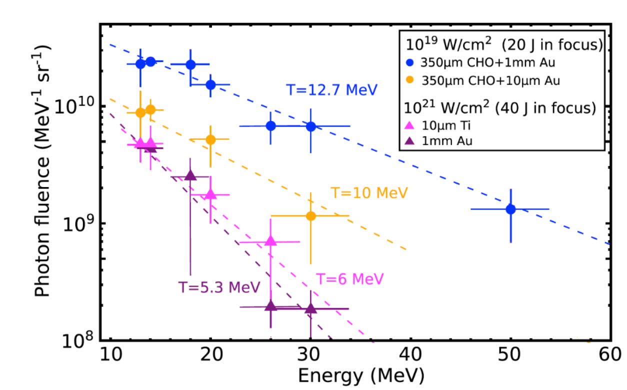
Electrons spectra from X. Wang et al. "Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV", NATURE COMMUNICATIONS, 4:1988 2018 DOI: 10.1038/ncomms2988



Neutrons spectra from A.Yogo et al. "Single shot radiography by a bright source of laser-driven thermal neutrons and x-rays", Applied Physics Express 14, 106001 (2021)



Gamma spectra from M. M. Günther et al "Forward-looking insights in laser-generated ultraintense γ-ray and neutron sources for nuclear application and science" NATURE COMMUNICATIONS | (2022) 13:170



Laser and beams specifications at 50 TW

Istituto Nazionale di Fisica Nucleare

Laser Power		≥ 50 TW
Energy per pulse		≥ 1 J
Pulse duration		≤ 23 fs
Focusing surface		36 μm²
Max power density (at the target)		$1.21 \cdot 10^{20}$
$I^* \lambda^2$		$7.72 \cdot 10^{19}$
Contrast ratio @100 ps (ASE)		$> 10^{10}$
Repetition rate		≥ 10 Hz
Protons Ions	Max energy	4 MeV
	Particle per pulse (at 2 MeV)	10^{11} MeV^{-1} Sr^{-1}
	Energy spread	100%
	Beam divergency (max)	±20°
Eletrons	Max energy	0.1 GeV
	Particles per pulse	10^{9}
	Beam divergency (max)	± 20 mad
Neutrons	Max energy	TBD
	Particles per pulse	
	Energy spread	
	Beam divergency	
Gamma X-beams	Synchrotron radiation of the electrons inside the plasma or breemsstrahlung	
	Energy	up to 20 MeV
	Beam divergency	Directionality in the beam ropabgation

Fusion studies,
nuclear studies,
radioisotopes production,
…..

Acting on the compression procedure, the pulse duration can be increased up to 1/10 ps:

==> $2.78 \cdot 10^{18}$ W/cm^2

$2.78 \cdot 10^{17}$ W/cm^2

==> $i\lambda^2 = 1.77 \cdot 10^{18}$

$i\lambda^2 = 1.77 \cdot 10^{17}$

Longer plasma expansion times:

— Decay studies
— stopping powers studies
— WDM characterisation

Power densities can be improved reducing the focusing spot:
— shorter focuing parabola
— but issues related to the: target degree, back reflection, …