Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Collaborations and activities of the ABC laser group

Fabrizio Consoli

FSN-FUSPHY-SDL

*fabrizio.consoli@enea.it

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The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Participation to the activities

ABC Group and collaborators:

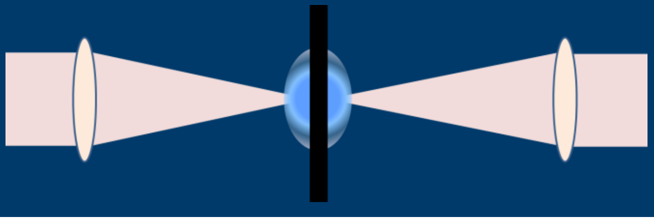
- F. Consoli, M. Cipriani, R. De Angelis, P.L. Andreoli, G. Cristofari, G. Di Giorgio, M. Salvadori, M. Scisciò

- University of Pisa: D. Giulietti

Included in the ENEA TASK- Force INER

ENEA

ABC LASER
ENEA Centro Ricerche Frascati



--- Main beams ---

Active medium	Nd:phosphate glass
Fundamental wavelength	1054 nm
Number of beams	2 (counter-propagating)
Energy	100 J per beam
Pulse duration	2.5 - 7 ns
Beam diameter	75 mm
Focusing	f/1 and f/2.5 lenses
Minimum focal spot diameter	40 μm
Maximum Intensity	2e15 W cm^{-2}
Polarization (laser output)	Linear
Polarization on target	Circular
Contrast	1e5
Beam integrator	Induced Space Incoherence


Two-beam neodymium-phosphate glass laser

--- Higher-harmonic operation ---

Frequency converter	2ω
Number of beams	- 2 at 527 nm or - 1 at 1054 nm + 1 at 527 nm
Wavelength	527 nm
Energy	- 2*40 J at 527 nm - 100 J at 1054 nm + 40 J at 527 nm or

--- Diagnostic beams ---

Beam generation	2ω conversion by KDP crystal of a portion of the main beam
Wavelength	527 nm
Number of beams	4, with different relative time delay tunable for each
Energy of each beam	~100 mJ
Delay from main beam	Customizable: 0 - 10 ns

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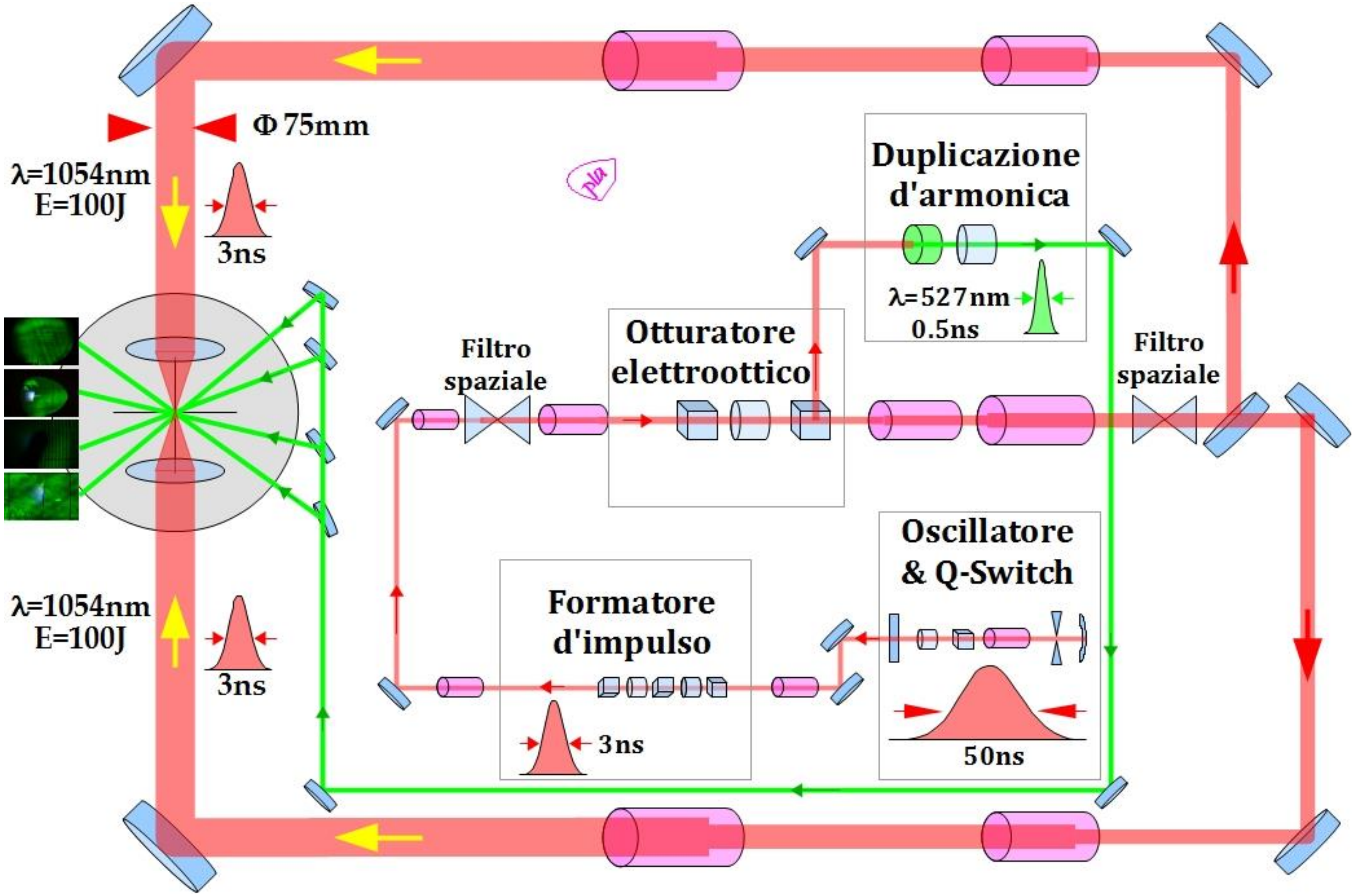
Principle scheme – ABC laser



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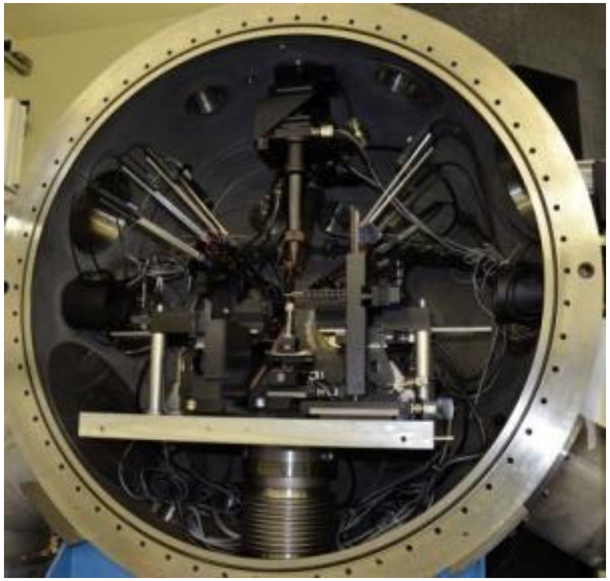
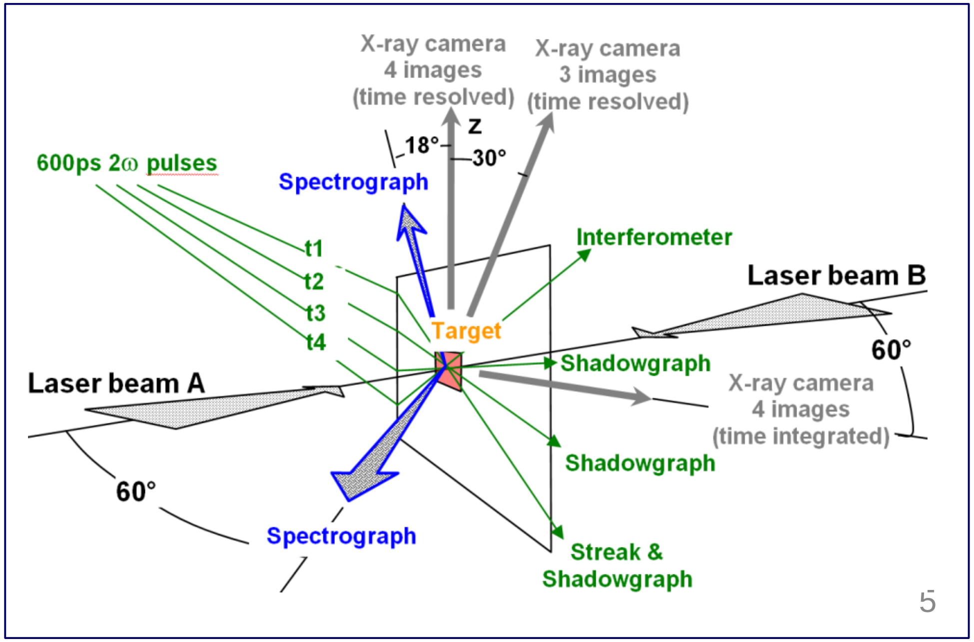
--- Interaction chamber ---

Chamber shape	Spherical
Chamber diameter	1.5 m
Target replacement	Remote handling under vacuum



--- Scheme of available permanent diagnostics, routinely used ---



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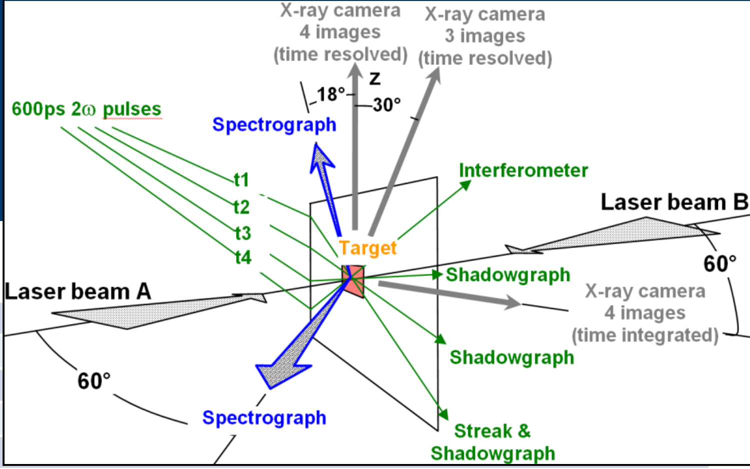

--- Available permanent diagnostics, routinely used ---

Visible interferometry	2 channels * Nomarski interferometer
Shadowgraphy	2 channels
Measurement of reflected and transmitted light	By two fast calibrated photodiodes
Visible streak cameras	2, high sensitivity, 1.5 ps time resolution
X-ray streak cameras	1 with 100 ps time resolution
X-ray diode detectors	8, each with different filter
Optical spectrometers	2 = 1 at high resolution and 1 at large spectral window
Time-Gated strip MCP	2, with 100 ps time resolution. One with 3 strips, one with 4
MCP for X-ray diagnostic imaging	1, with four pinholes with different filters
X-ray transmission grating	3 = 1 at 5000 lines per millimeter and 2 at 2000 lines per mm
Time-of-Flight Faraday cups	8, at different angles from target normal
Time-of Flight Diamond detectors	5 = 4 with high energy resolution (up to 6 MeV protons), 1 for high energy particles (up to 20 MeV protons)
Time-of-Flight Scintillator	1, BC408 fast plastic scintillator, large area (25 cm^2), equipped with fast photomultiplier
Thomson spectrometers	2 = 1 for low energy particles (5 keV-2 MeV protons); 1 for high energy ones (100 keV – 15 MeV protons). Optimized for EMP-polluted environments
Antennas for EMP measurements	1 DDOT near field probe + 2 Dipolar antennas + 1 Super-wideband antenna
CR39 detectors	Detectors of different sizes, equipment for developing and accurate readout
Imaging plate diagnostics	TR, MS, SR, ND types, with scanner and eraser
Confocal microscope for measurement of craters left on targets	1, with high optical resolution, reconstruction of 3D crater profile
Diamond Detector of large area	Polycrystalline Diamond detector with 15mm x 15 mm detection area, equipped for EMP-polluted environments

--- Diagnostics in development phase ---

Visar	Two high-dynamic range streak cameras are on site. A CW large coherence length ruby laser already acquired
Multilayer diamond structure	Multilayer structure of active fast diamond sensors equipped with different filters
Time-of Flight Scintillator	With large area and fast response. Improved sensitivity
Electron Spectrometer	Magnetostatic spectrometer for electrons in the 10-200 keV
Scattered light	An array of several optical fibers to be equipped with lenses pointing toward several directions to the target normal

Main collaborations for research activity

- Laser-generated Electromagnetic Pulses (EMPs)
- Foam materials
- Low-rate nuclear fusion reactions ($p+^{11}B$,…)
- Laser-produced radiation for applications
- Diagnostics (RF-Microwave, ions, electrons, UV, X)
- Others on Inertial Confinement Fusion
- DTT

Main collaborations for research activity

- **Laser-generated Electromagnetic Pulses (EMPs)**
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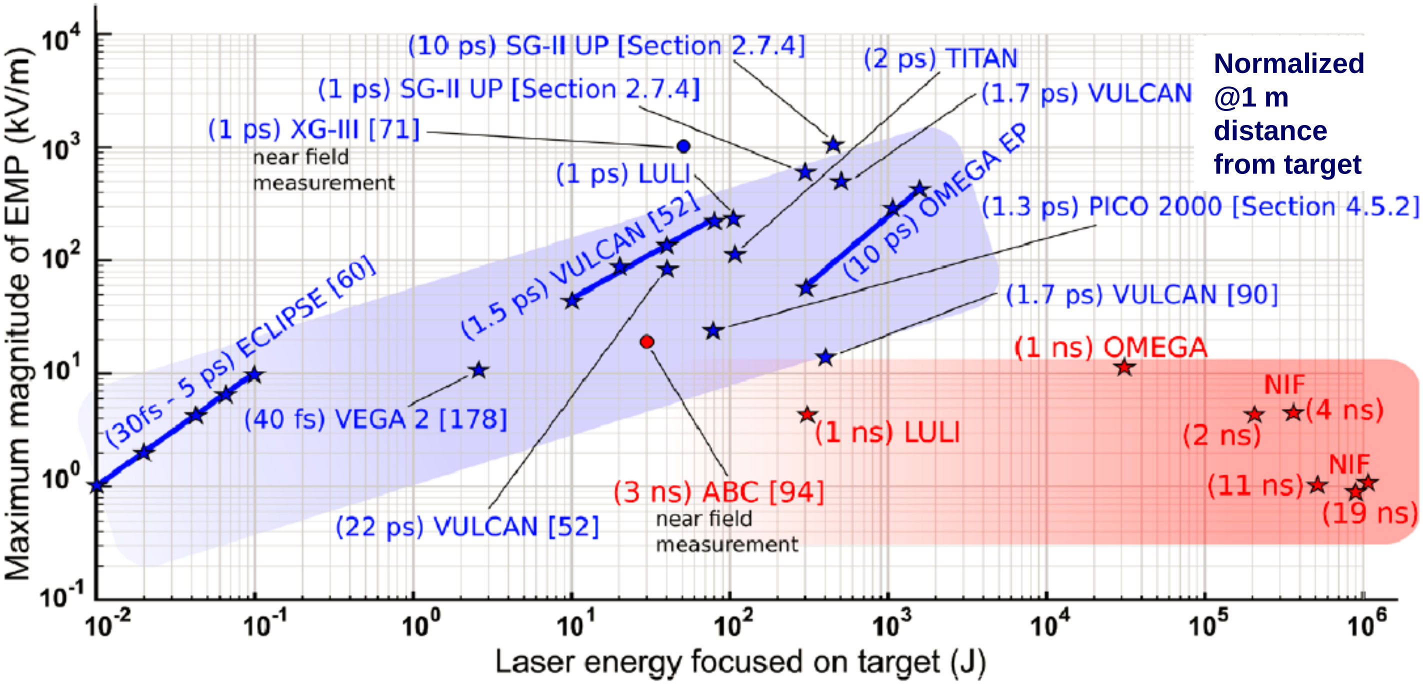
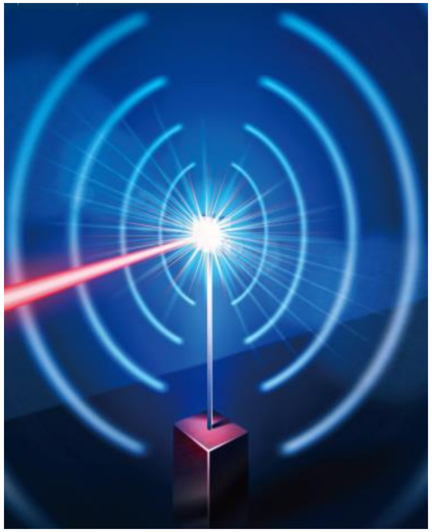
ENEA

Laser-generated electromagnetic pulses (EMPs)

- **Laser-matter interaction produces an extremely wide band of electromagnetic and particle radiation**
- **Transient electromagnetic pulses (EMPs) in the radiofrequency-microwave regime are regularly detected in laser–target interactions**
- **Remarkable intensity (up to the MV/m order and beyond) and broad frequency range from MHz to THz.**
- **EMPs scale with laser energy and mostly with laser intensity**





F. Consoli et al, High Power Laser Science and Engineering 8, e22 (2020)

Mitigation and applications

- **EMPs are recognized as a major threat to electronics, computers, diagnostics and personnel. This requires the development of effective protections.**

- **This is of primary concern for Inertial Confinement Fusion and laser-plasma accelerations facilities, especially for those at high energy, intensity and repetition rate**

- **Understanding of EMP physics opens to a wide number of significant applications for these high-intensity fields. A patent was issued by ENEA on this topic:''Method of generation of electromagnetic fields of high intensity'', (PCT/IB2020/057464).**

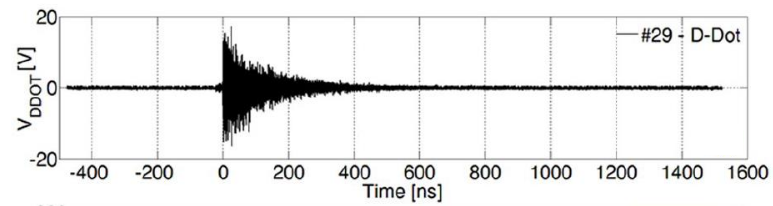
- **The main purpose of the patent is to extend the use of laser-matter interactions also as sources of RF-microwave fields of high intensity and specific properties. Applications: Inertial Confinement Fusion (Fast Ignition and Shock Ignition), material science, avionics, aerospace, medicine, biology, electromagnetic hardness of devices and materials.**

- **These fields can be quasi-stationary or pulsed fields in radiofrequency-microwave regime, can be distributed over large volumes (up to several decimeter cubes and beyond), have: high intensities (MV/m order and beyond), fast rise/fall times (ps down to fs), tailored spatial profile ('uniform', not 'uniform' and if necessary with specific profile)**

- **Recent funding (Proof Of Concept 2020.02) by the Italian Ministry of Economical Development, specifically for the development of this patent.**

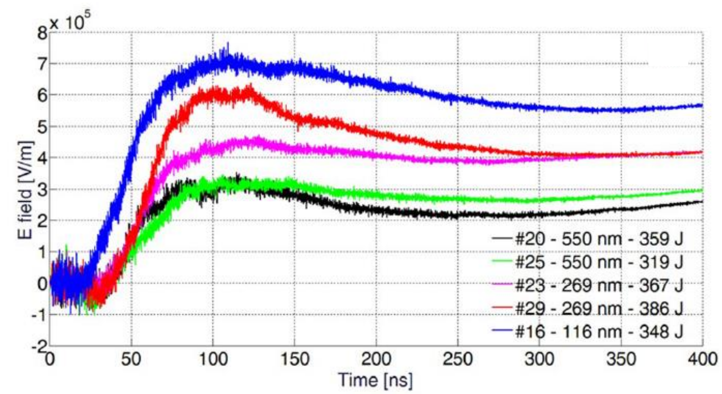
Research activities on Laser-generated Electromagnetic Pulses

- **Generation (neutralization current and other sources)**



- **Detection (conductive and dielectric probes)**

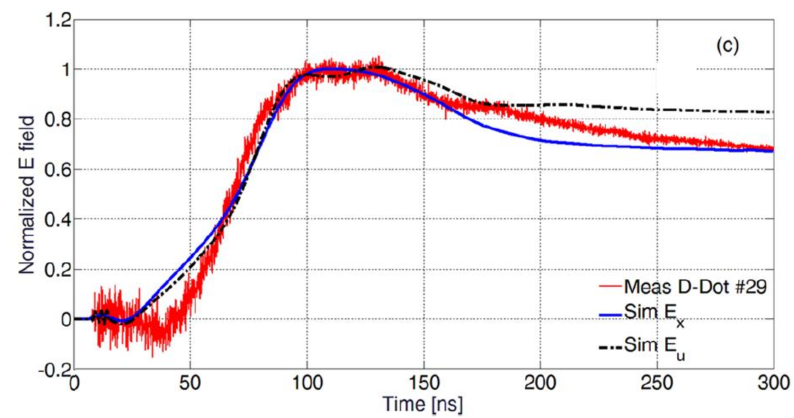
- **Mitigation and development of high sensitivity diagnostic prototypes with high robustness to EMPs**
  - **Advanced time-of-flight methodologies and detectors**
  - **Thomson spectrometers**



- **Use of laser-generated EMPs for applications**

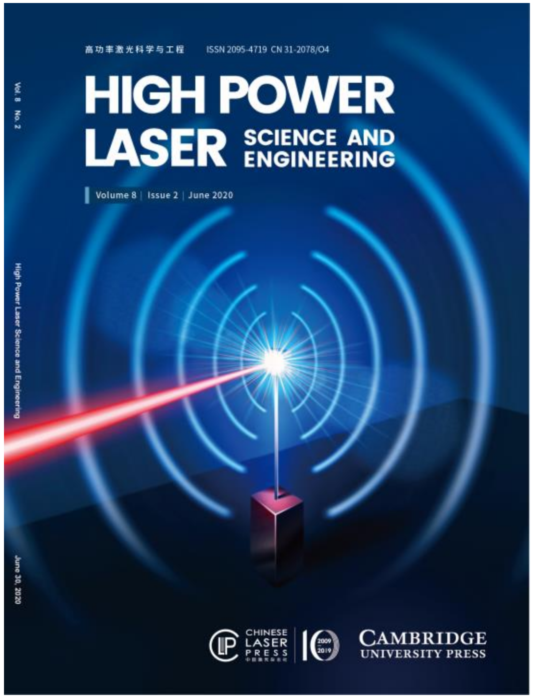
- **Numerical, theoretical and experimental studies**

- **Experiments with lasers at regimes of**
  - ✓ **Nanosecond: ABC (ENEA, Italy), Asterix (PALS, Czechia),…**
  - ✓ **Picosecond: Vulcan PW (RAL, UK), Phelix (GSI, Germany)**
  - ✓ **Femtosecond: FLAME (INFN, Italy), LLC laser (Lund University, Sweden), Apollon (France),…**



EMP growing community

- **A growing international community has been set up on the topic of radiofrequency-microwave field generation**
- **Laserlab-Europe AISBL, an Interest/Expert group has been created on «Laser-generated electromagnetic pulses», coordinated by ENEA (F. Consoli). It includes 26 research institutions from all over the world**
- **Review paper with contributions of the main laboratories on High Power Laser Science and Engineering, selected for the volume cover and got the Editor-in-Chief Choice Award 2020**



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doi:10.1017/hpl.2020.13

HIGH POWER LASER SCIENCE AND ENGINEERING

REVIEW

Laser produced electromagnetic pulses: generation, detection and mitigation

Fabrizio Consoli[1], Vladimir T. Tikhonchuk[2,3], Matthieu Bardon[4], Philip Bradford[5], David C. Carroll[6], Jakub Cikhardt[7,8], Mattia Cipriani[1], Robert J. Clarke[6], Thomas E. Cowan[9], Colin N. Danson[10,11,12], Riccardo De Angelis[1], Massimo De Marco[13], Jean-Luc Dubois[2], Bertrand Etchessahar[4], Alejandro Laso Garcia[9], David I. Hillier[10,12], Ales Honsa[3], Weiman Jiang[14], Viliam Kmetik[3], Josef Krása[15], Yutong Li[14,16], Frédéric Lubrano[4], Paul McKenna[17], Josefine Metzkes-Ng[9], Alexandre Poyé[18], Irene Prencipe[9], Piotr Rączka[19], Roland A. Smith[20], Roman Vrana[3], Nigel C. Woolsey[5], Egle Zemaityte[17], Yihang Zhang[14,16], Zhe Zhang[14], Bernhard Zielbauer[21], and David Neely[6,10,17]

F. Consoli et al, High Power Laser Science & Engin. 2020

International activities on Laser-generated Electromagnetic Pulses

International activities

- **Coordination (F. Consoli) of the Work Package on EMPs of the EUROfusion Enabling Research project on IFE "Routes to High Gain for Inertial Fusion Energy" PI: P. Norreys, ENR-IFE19.CCFE-01 - 2019-2020**

- **Coordination (F. Consoli) of the Laserlab-Europe AISBL Expert Group on "Laser-generated electromagnetic pulses". The Group collects more than 26 European and non-European institutions**

- **Participation to the Coordinated Research Projects of IAEA (International Atomic Energy Association): "Advanced Research Activity on Materials, Technologies and Devices for Inertial Confinement Fusion", under the IAEA Research Agreement No: 24232/R0 (2020-2023)**

EUROfusion

Laserlab Europe

IAEA International Atomic Energy Agency

ENEA

Main collaborations

Repubblica Ceca

- PALS laser facility, Praga
- Extreme Light Infrastructure (ELI) – Beamline, Dolní Břežany
- Institute of Physics of the Czech Academy of Sciences (Praga)

Francia

- Centre lasers intenses et applications (CELIA), University of Bordeaux, Bordeaux
- CEA-CESTA, Bordaux
- École Polytechnique, Palaiseau (Parigi)
- Kapteos SAS, Sainte-Hélène-du-Lac

Regno Unito

- Imperial College (Londra)
- Rutherforth Appleton Laboratories, Central Laser Facility (Didcot)
- University of York (York)

Polonia

- Institute of Plasma Physics and Laser Microfusion (Varsavia)

Cina

- University of Electronic Science and Technology of China (Chengdu)

Main research activities: Laser-generated Electromagnetic Pulses (EMPs)

- **Related publications:**

1) M. Salvadori et al, to appear on ***Journal of Instrumentation***
2) M. Salvadori et al, to appear on ***High Power Laser Science and Engineering***
3) M. Scisciò et al, ***Journal of Instrumentation*** 17, C01055 (2022)
4) M. Scisciò et al, ***High Power Laser Science and Engineering*** 9, e64 (2021)
5) M. Salvadori, et al, ***Scientific Reports*** 11, 3071 (2021).
6) F. Consoli, et al, ***Phil. Trans. Royal Society A -*** 379: 20200022 (2020). **Review**
7) F. Consoli, et al, ***High Power Laser Science and Engineering*** 8, e22 (2020). **Review. Editor in chief Award 2020**
8) J. Krása, F. Consoli, et al, ***Plasma Physics and Controlled Fusion*** 62, 025021 (2020)
9) F. Consoli, et al, ***Scientific Reports*** 9, 8551 (2019).
10) F. Consoli, et al, ***Journal of Instrumentation*** 14, C03001 (2019).
11) S. Vallières , M. Salvadori, et al, ***Review of Scientific Instruments*** 91, 103303 (2020)
12) G. Di Giorgio, et al ***Journal of Instrumentation*** 15, C10013 (2020)
13) M. Salvadori, et al, ***Journal of Instrumentation*** 15, C10002 (2020)
14) C. Verona, M. Salvadori, et al, ***Journal of Instrumentation*** 15, C09066 (2020)
15) F. Consoli, et al, ***Journal of Instrumentation*** 14, C03001 (2019).
16) F. Consoli , et al ***Plasma Physics and Controlled Fusion*** 60, 105006 (2018)
17) P. Bradford,.., F. Consoli, et al, ***High Power Laser Science and Engineering***, Vol. 6, e21 (2018).). **Editor in chief Award 2018**
18) T. Robinson, .., F. Consoli, et al, ***EPJ Web of Conferences*** 167, 03007 (2018).
19) M. De Marco, .., F. Consoli, et al ***EPJ Web of Conferences*** 167, 03009 (2018).
20) T.S. Robinson, F. Consoli, et al, ***Scientific Reports*** **7**, 983, (2017), DOI:10.1038/s41598-017-01063-1
21) R. De Angelis, et al ***Journal of Instrumentation*** **11**, C12048, 2016.
22) F. Consoli, et al ***Scientific Reports*** **6**, 27889, 2016, DOI:10.1038/srep27889.
23) F. Consoli, et al, ***Journal of Instrumentation*** **11**, C05010, 2016.
24) F. Consoli, et al, ***Proc. IEEE 15th Intern. Conf. Env. Electr. Engin. (EEEIC)***, 2015, 10-13 June 2015, Rome, 182
25) F. Consoli, et al,, ***Physics Procedia*** 62, 11-17, 2015.

Recognitions

- F. Consoli et al, “Laser produced electromagnetic pulses: generation, detection and mitigation”, ***High Power Laser Science and Engineering*** 8, e22, 2020, **Editor-in-Chief Choice Award 2020**, and also chosen to be **on the cover of the September 2020 edition** of the journal.
- P. Bradford et al, “EMP control and characterization on high-power laser Systems”, ***High Power Laser Science and Engineering*** 6, e21, 2018, **Editor-in-Chief Choice Award 2018**, and also chosen to be on the **cover of the June 2018 edition** of the journal.
- M. Sciscìò et al, "Numerical analysis of EMPs driven by laser plasma interactions on the nano and picosecond scale”, "***Leos Laska Prize***" for the **for Remarkable communication to the 9th PPLA, Frascati, October 2019**
- M. Salvadori et al, "Determination of accurate spectra for laser-accelerated MeV ions by CVD diamond-detector setups optimized of experiments subject to intense EMPs“ **Best poster award ECPD (EPS) – Lisbon, May 2019**
- F. Consoli, et al “Measurements by dielectric and conductive probes of electromagnetic pulses from laser-target interaction in the nanosecond ABC laser facility - "***Leos Laska Prize***" for the **Best contribution to the 7th PPLA, Frascati, October 2015**
- F. Consoli, et al “Measurement of the radiofrequency-microwave pulse produced in experiments of laser-plasma interaction in the ABC laser facility”, **Best Poster Presentation award 3rd ICFDT – Frascati, November 2013**

Funding

- **EUROfusion Enabling Research** project on IFE “Advancing shock ignition for direct-drive inertial fusion” PI: D. Batani, ENR-IFE.21.CEA - 2021-2023
- **Proof Of Concept 2020.02** by the Italian Ministry of Economical Development (2021-2022) – PI. F. Consoli
- **EUROfusion Enabling Research** project on IFE “Routes to High Gain for Inertial Fusion Energy” PI: P. Norreys, ENR-IFE19.CCFE-01 (2019-2020)
- **EUROfusion Enabling Research** project on IFE “Towards demonstration of Inertial Fusion for Energy”. PI. S. Jacquemot, AWP15-ENR-IFE/CEA-02 – 2015-2018

Next funded experiment

- Vulcan Petawatt. UK

Main collaborations for research activity

- Laser-generated Electromagnetic Pulses (EMPs)
- **Foam materials**
- Low-rate nuclear fusion reactions (p+^{11}B,…)
- Laser-produced radiation for applications
- Diagnostics (RF-Microwave, ions, electrons, UV, X)
- Others on Inertial Confinement Fusion
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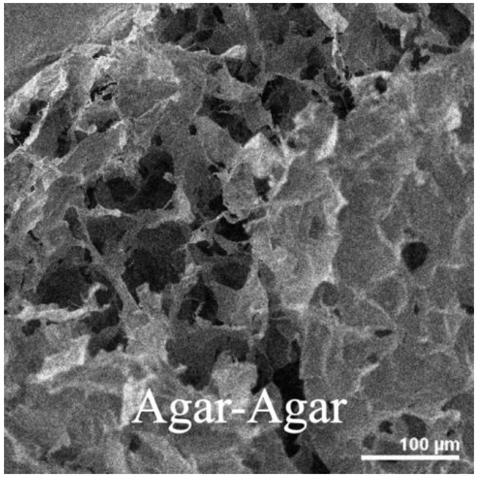
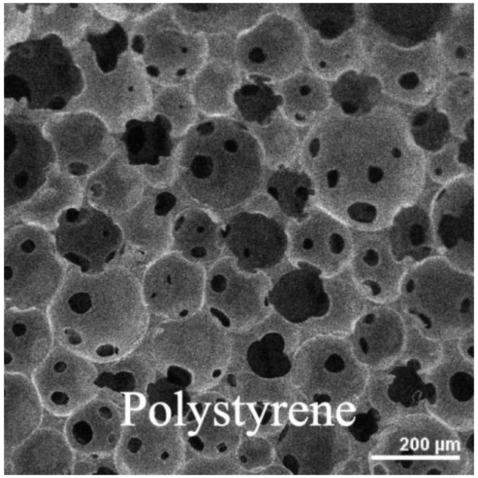
Main research activities: porous materials, or FOAMS

The internal structure of porous materials, or foams, is characterized by a random arrangement of filaments or membranes separated by large empty spaces

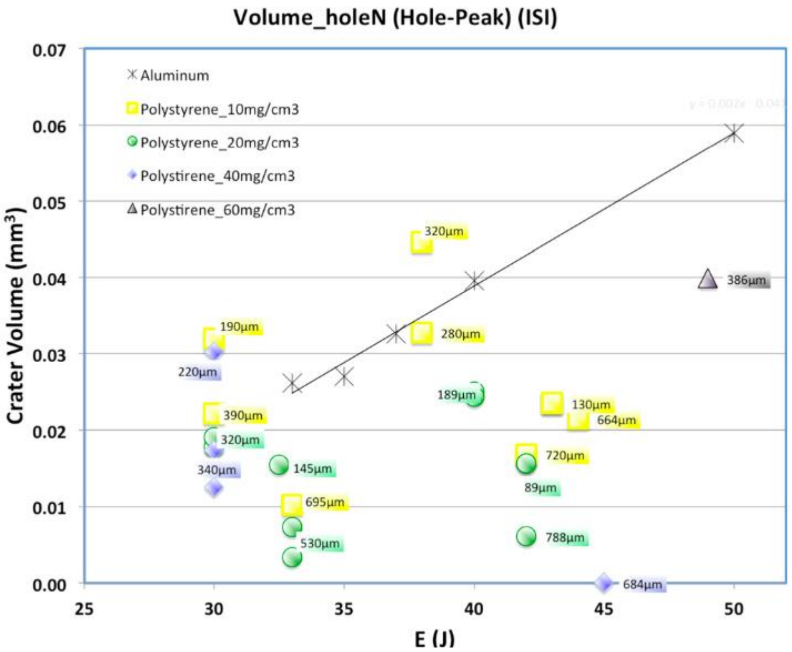
They have many applications in ICF

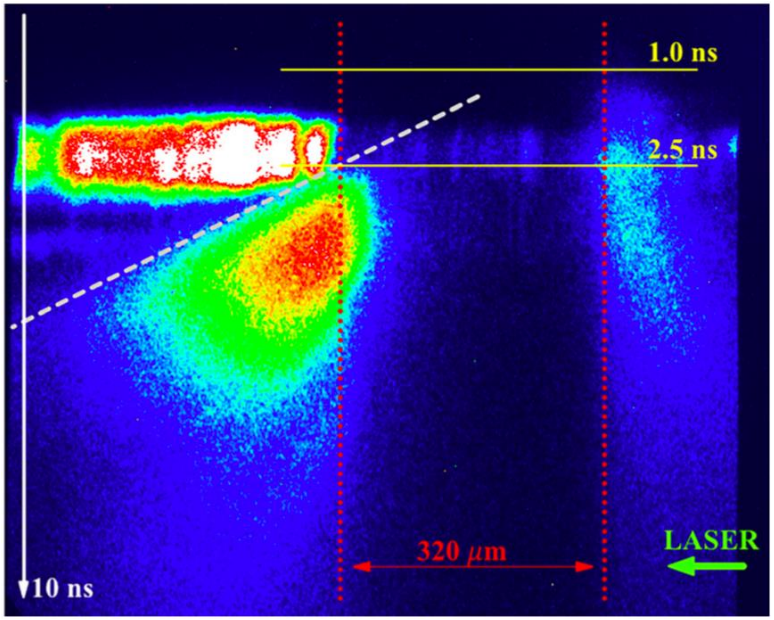
- **Increase of laser energy absorption on target (up to ~90%)**
- **Smooth the spatial laser energy profile**
- **Increase ablation loading on target**
- **Enhance electron acceleration with short laser pulses**
- **Measurements for equation of state or shockwaves**
- **Laser energy to X-ray conversion**
- **Reproduce long plasmas as expected in a fusion capsule corona**
- **…**





Main research activities: porous materials, or FOAMS





Experiments

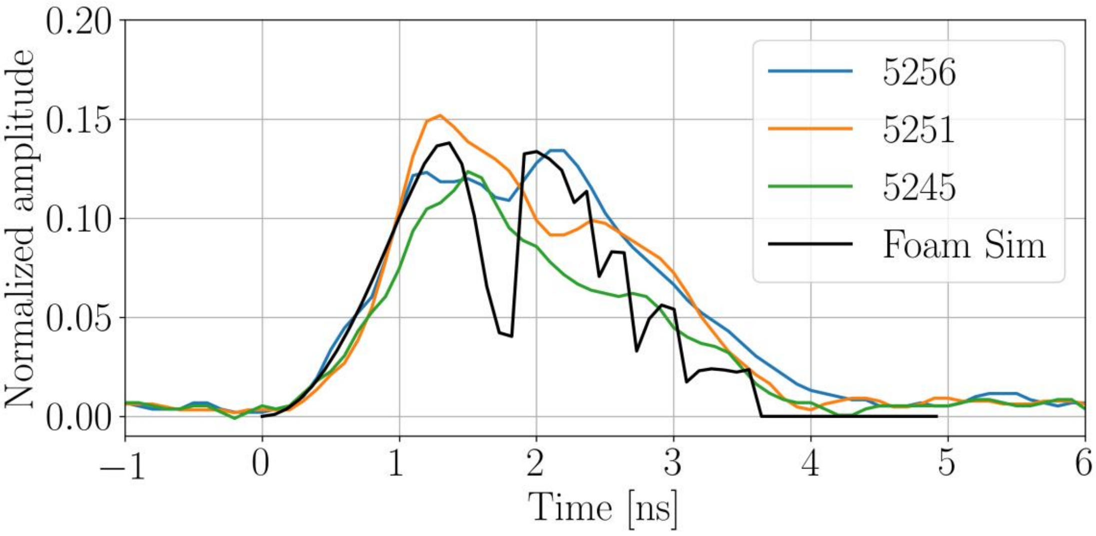
- **Measurement of the ablation loading on a solid substrate with a foam buffer**
- **Measurement of the speed of the propagation of the laser-driven hydrothermal wave in an overcritical foam**
- **Time-resolved measurement of the laser light reflected by an overcritical foam with large pores, the first to our knowledge: this measure could give an estimate of the homogenization time of the foam by combining simulations and experimental results**

M. Cipriani, et al., Physics of Plasmas **25**, 092704 (2018) | R. De Angelis et al., Physics of Plasmas **22**, 072701 (2015)

Main research activities: porous materials, or FOAMS

Theory and simulations

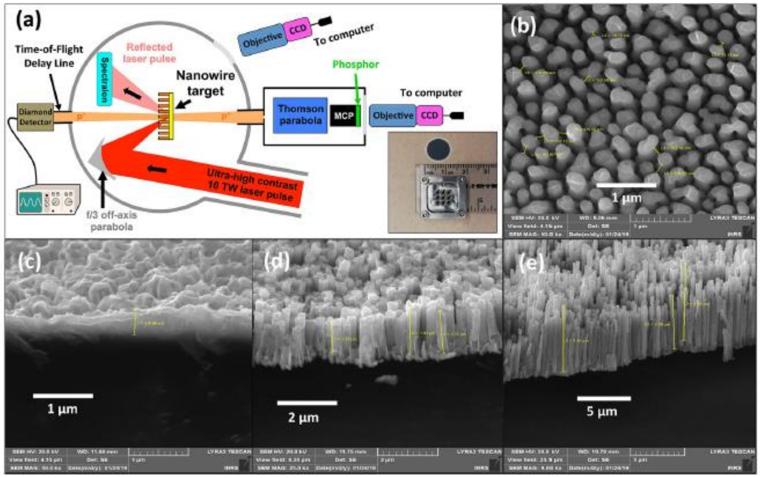
- **Development of the MULTI-FM hydrocode**
  - **An effective model for absorption, thermal conduction and mechanical behavior of a foam has been developed and implemented in the MULTI code**
  - **Good agreement with the measurement of the speed of the wave in overcritical foams**
- **Development and implementation in the MULTI-FM code of a model for the reflection of laser light in a foam**

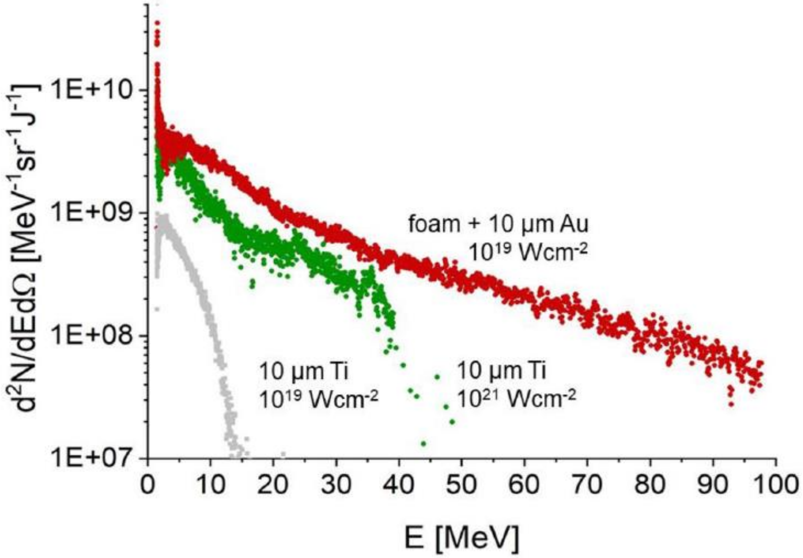


M. Cipriani, et al., Physics of Plasmas **25**, 092704 (2018) | M. Cipriani, et al, HPLSE **9**, e40 (2021)

Main research activities: micro- and nano-structured materials

- Use of foams to create near critical plasmas by nanosecond laser pulses
- On these plasmas high intensity pulses interact → enhanced electron and gamma generation
- Experiments on energetic picosecond facilities – Phelix Laser (GSI)
- Of primary importance the study of the generated nanosecond near critical plasma: experiments on ABC planned in May 2022
- The use of nano-structured materials has been observed to produce increase on ion generation when interacting with femtosecond pulses of high intensity (experiments with LUND laser, and Hebrew University, Jerusalem)





International activities on micro- and nano-structured materials

International activities

- **Coordination (M. Cipriani) of the Work Package 2 of the EUROfusion Enabling Research project on IFE "Advancing shock ignition for direct-drive inertial fusion" PI: D. Batani, ENR-IFE.21.CEA - 2021-2023**

- **Coordination (M. Cipriani) of the Laserlab-Europe AISBL Expert Group on "Micro- and nano-structured materials for experiments with high-power lasers". The Group collects more than 20 European and non-European institutions**

- **Participation to the Coordinated Research Projects of IAEA (International Atomic Energy Association): "Advanced Research Activity on Materials, Technologies and Devices for Inertial Confinement Fusion", under the IAEA Research Agreement No: 24232/R0 (2020-2023)**

EUROfusion

Laserlab Europe

IAEA International Atomic Energy Agency

ENEA

Main collaborations

Russia

- **Lebedev Physical Institute (Moscow) – A mutual Research Agreement – ENEA- LEBEDEV has been set on this purpose**

Lituania

- **Laser Research Center, Vilnius University, Vilnius**

Germania

- **GSI Helmholtz Centre for Heavy Ion Research, Darmstadt**
- **Technische University of Darmstadt, Darmstadt, Germany**
- **Freie Universität Berlin, Berlino**
- **Helmholtz Institute, Jena**

Francia

- **Ecóle Polytechnique, Palaiseau**
- **CNRS**

Regno Unito

- **University of Oxford, Oxford**

Polonia

- **IPPLM, Warsaw**

USA

- **University of California (Irvine)**

Israele

- **Hebrew University of Jerusalem, Gerusalemme**

Last publications: FOAMS

1) M. Cipriani, S. Y. Gus'kov, F. Consoli, R. De Angelis, A. A. Rupasov, P. Andreoli, G. Cristofari, and G. Di Giorgio, Time-Dependent Measurement of High-Power Laser Light Reflection by Low-Z Foam Plasma, **High Power Laser Science and Engineering** 9, e40 (2021). **Selected by the Editor**
2) S. Vallières, M. Salvadori, A. Permogorov, G. Cantono, K. Svendsen, Z. Chen, S. Sun, F. Consoli, E. d'Humières, C.-G. Wahlström, P. Antici, "Enhanced laser-driven proton acceleration using nanowire targets" ***Scientific Reports*** 11, 2226 (2021).
3) O.N. Rosmej, M. Gyrdymov, M. M. Günther, N. E. Andreev, P.Tavana, P. Neumayer, S.Zahter, N. Zahn, V. S. Popov, N. G. Borisenko, A. Kantsyrev, A Skobliakov, V.Panyushkin, A Bogdanov., F Consoli, X. F. Shen, A. Pukhov, "High-current laser-driven beams of relativistic electrons for high energy density research", **Plasma Phys. Control. Fusion** 62, 115024 (2020)
4) M. Cipriani, S. Yu. Gus'kov, F. Consoli, R. D. Angelis, A. A. Rupasov, P. Andreoli, G. Cristofari, and G. D. Giorgio, Hydrodynamics and Transport Processes in Porous Materials under Terawatt Laser Irradiation, ***J. Instrumentation*** 15, C10003 (2020)
5) M. Cipriani, S. Yu. Gus'kov, R. De Angelis, F. Consoli, A. A. Rupasov, P. Andreoli, G. Cristofari, and G. Di Giorgio, *Laser-Driven Hydrothermal Wave Speed in Low-Z Foam of Overcritical Density*, **Physics of Plasmas 25**, 092704 (2018), **Editor's Pick**
6) M. Cipriani, S. Yu. Gus'kov, R. De Angelis, F. Consoli, A. A. Rupasov, P. Andreoli, G. Cristofari, G. Di Giorgio, and F. Ingenito, *Laser-Supported Hydrothermal Wave in Low-Dense Porous Substance*, **Laser Part. Beams 36**, 121 (2018)
7) M. Salvadori, P. Luigi Andreoli, M. Cipriani, F. Consoli, G. Cristofari, R. De Angelis, G. di Giorgio, D. Giulietti, F. Ingenito, S. Yu. Gus'kov, and A. A. Rupasov, *Laser Irradiated Foam Targets: Absorption and Radiative Properties*, **EPJ Web Conf.** 167, 05003 (2018)
8) M. Cipriani, S.Yu. Gus'kov, R. De Angelis, P. Andreoli, F. Consoli, G. Cristofari, G. Di Giorgio, F. Ingenito, A.A. Rupasov, "Powerful laser pulse absorption in partly homogenized foam plasma" , ***Journal of Instrumentation*** **11**, C03062 (2016).
9) R. De Angelis, F. Consoli, S. Yu. Gus'kov, A. A. Rupasov, P. Andreoli, G. Cristofari, and G. Di Giorgio, *Laser-Ablated Loading of Solid Target through Foams of Overcritical Density*, **Physics of Plasmas 22**, 072701 (2015)
10) S. Y. Gus'kov, M. Cipriani, R. De Angelis, F. Consoli, A. A. Rupasov, P. Andreoli, G. Cristofari, and G. Di Giorgio, *Absorption Coefficient for Nanosecond Laser Pulse in Porous Material*, **Plasma Phys. Control. Fusion 57**, 125004 (2015)
11) R. De Angelis , F. Consoli, S.Yu. Gus'kov, A.A. Rupasov, P. Andreoli, G, Cristofari, G. Di Giorgio, D. Giulietti, G. Cantono, M. Kalal, "Ablation loading of solid target through foam absorber on ABC laser at ENEA-Frascati", ***Journal of Physics: Conference Series*** **688** (2016) 012013
12) F. Consoli, R. De Angelis, S.Yu. Gus'kov, A.A. Rupasov, P. Andreoli, G. Cristofari, G. Di Giorgio, D. Giulietti, G. Cantono, M. Kalal, "Experiments on laser-driven energy transfer to solid target through a foam on the ABC laser", ***Proceedings of the 40th EPS Conference on Plasma Physics***, 1-5 July 2013, Espoo, Finland. ECA, Vol 37D, **ISBN 2-914771-84-3.**

Recognitions

- M. Cipriani, S. Y. Gus'kov, F. Consoli, R. De Angelis, A. A. Rupasov, P. Andreoli, G. Cristofari, and G. Di Giorgio, Time-Dependent Measurement of High-Power Laser Light Reflection by Low-Z Foam Plasma, **High Power Laser Science and Engineering** 9, e40 (2021). **Selected by the Editor**

- M. Cipriani et al, "Numerical strategies for simulating the interaction of high-power laser pulses and porous media", "***Angelo Caruso Prize***" for the **for Remarkable communication to the 9th PPLA, Frascati, October 2019**

- M. Cipriani, S. Yu. Gus'kov, R. De Angelis, F. Consoli, A. A. Rupasov, P. Andreoli, G. Cristofari, and G. Di Giorgio, *Laser-Driven Hydrothermal Wave Speed in Low-Z Foam of Overcritical Density*, **Physics of Plasmas 25**, 092704 (2018), **Editor's Pick**

Funding

- **EUROfusion Enabling Research** project on IFE "Advancing shock ignition for direct-drive inertial fusion" PI: D. Batani, ENR-IFE.21.CEA - 2021-2023
- **EUROfusion Enabling Research** project on IFE "Study of Direct Drive and Shock Ignition for IFE: Theory, Simulations, Experiments, Diagnostics development" PI: D. Batani, ENR-IFE19.CEA-01 (2019-2020)
- **EUROfusion Enabling Research** project on IFE "Towards demonstration of Inertial Fusion for Energy". PI. S. Jacquemot, AWP15-ENR-IFE/CEA-02 – 2015-2018

Next funded experiment

- Vulcan TAE. UK – Now in execution

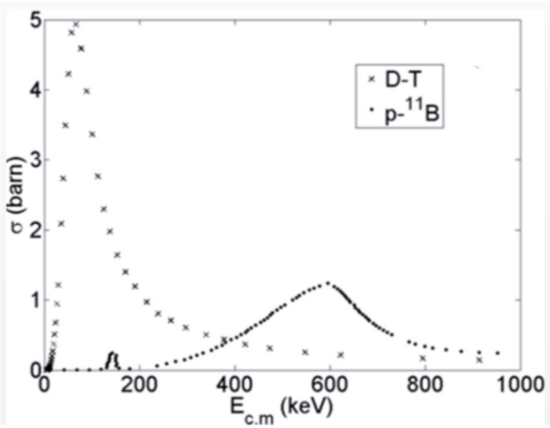
Main collaborations for research activity

- Laser-generated Electromagnetic Pulses (EMPs)
- Foam materials
- **Low-rate nuclear fusion reactions ($p+^{11}B$,…)**
- Laser-produced radiation for applications
- Diagnostics (RF-Microwave, ions, electrons, UV, X)
- Others on Inertial Confinement Fusion
- DTT

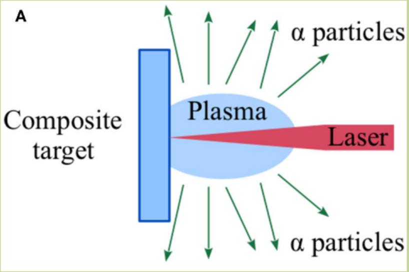
ENEA

Main research activities: laser-initiated p+^{11}B fusions

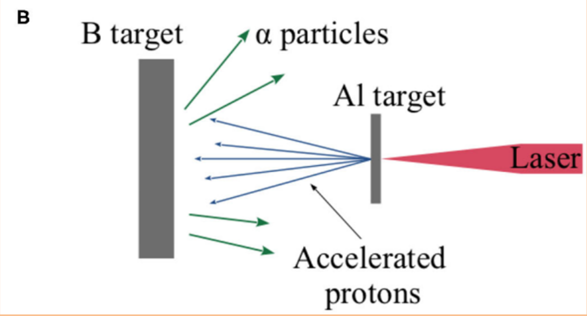
- ^{11}B(p,α)2α fusions by means of laser-plasma interaction demonstrated [1-2].
- A significant yield achieved → potential future employment in non-thermal conditions
- Study of low-rate nuclear reactions in plasmas also important for astrophysical researches
- Two main approaches to obtain p+^{11}B reactions from laser-matter experiments (Scheme A and B)



Scheme A. H and B plasma by laser pulses on composite targets: i.e. B-doped plastic or Si enriched with H and B.
ns and/or ps laser pulses.



Scheme B. Laser accelerated protons sent to a boron target or to a boron plasma.
ps or fs laser pulses



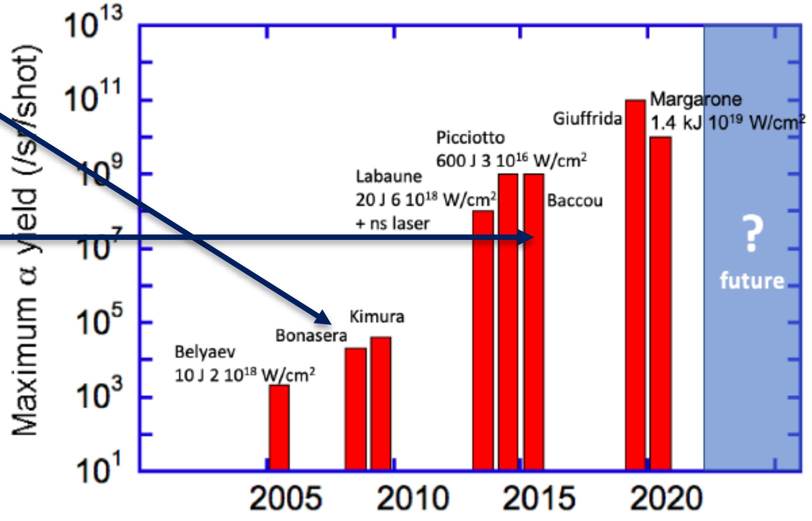
[1] VS Belyaev et al, Phys Rev E. (2005) 72, 026406; [2] A. Picciotto et al, Phys Rev X. (2014) 4, 031030; [3] DC Clayton. Principles of Stellar Evolution and Nucleosyntesis. Chicago Press (1983); [4] F. Consoli, et al, Front. Phys. (2020) 8, 561492

Main research activities: laser-initiated p+^{11}B fusions

- **First experiments of generation of alphas by p+^{11}B nuclear reactions with nanosecond lasers, currently the most promising technique [1].**

- **Participation to the first set of experiments in pitcher-catcher configuration at Ecóle Polytechnique (LULI) [2], in collaboration with Labaune group.**

- **Second set of experiments with pitcher catcher scheme in high repetition rate laser: Eclipse experiment, in collaboration with Batani group**



- **Further experiments performed at PALS in collaboration with Margarone (QUB), Picciotto (FBK), Cirrone (INFN) groups in 2020.**

- **Long-term development of diagnostic methodologies for the accurate determination of alpha yield, and in general for low-rate nuclear reactions → advanced use of SSNTD (CR39); high sensitivity Thomson and Time-Of-Flight diagnostics for ions [4].**

[1] A. Bonasera, et al. in "Fission and Properties of Neutron-Rich Nuclei" (Sanibel Island, USA: World Scientific), 503–507 (2008)
[2] C. Baccou, Laser and Particle Beams (2015), 33, 117–122.
[3] D. Giulietti, et al, Nucl Instrum Methods Phys Res B. (2017) 402:373– 5.
[4] F. Consoli, et al, Frontiers in Physics 8, 561492, (2020). Review Paper

Main collaborations

Italia

- **Istituto Nazionale di Fisica Nucleare**
  - **Laboratori Nazionali del Sud (Catania)**
  - **Sezione di Perugia**
- **Fondazione Bruno Kessler (Trento)**
- **University of Tor Vergata**

Repubblica Ceca

- **PALS laser facility, Praga**
- **Extreme Light Infrastructure (ELI) – Beamline, Dolní Břežany**
- **Institute of Physics of the Czech Academy of Sciences (Praga)**

Francia

- **Centre lasers intenses et applications (CELIA), University of Bordeaux (Bordeaux)**
- **École Polytechnique, Palaiseau (Parigi)**

Regno Unito

- **Queen’s University of Belfast (Belfast)**

USA

- **Cyclotron Institute, Texas A&M University, College Station, TX, USA**

Germania

- **Marvel Fusion GmbH (Non disclosure agreement signed)**

Australia

- **HB11**

Main research activities: laser-initiated p+^{11}B fusions

- **Related publications:**

1) M. Scisciò et al, ***Journal of Instrumentation*** 17, C01055 (2022)
2) M. Scisciò et al, ***High Power Laser Science and Engineering*** 9, e64 (2021)
3) F. Consoli et al, **Frontiers in Physics** 8, 561492, (2020). **Review Paper**
4) Di Giorgio G, et al. **J Inst.** 15, C10013 (2020).
5) Cipriani M, et al. **J Inst.** (2019) 14:C01027.
6) Consoli F, et al. Research activity in the laboratory for inertial confinement fusion in ENEA – Centro Ricerche Frascati. In: **LIMS 2018, Luce, Imaging,Microscopia, Spettri di applicazione**. Frascati (2018).
7) Ingenito F, et al **EPJ Web Conf**. (2018) 167:05006
8) De Angelis R, et al **EPJ Web Conf**. (2018) 167:05005.
9) Giulietti D, et al **Nucl Instrum Methods Phys Res B.** (2017) 402:373– 5.
10) Lattuada D, et al **Phys Rev C.** (2016) 93:045808.
11) Consoli F, et al **J Inst**. (2016) 11:C05010.
12) Baccou C, et al **Laser Part Beams**. (2015) 33:117–22.
13) Baccou C, et al **Rev Sci Instrum**. (2015) 86:083307
14) Barbui M, **AIP Conference Proceedings**. Sicily (2014). p. 168–172.
15) Consoli F, et al **NIMA**. (2013) 720:149–52.
16) Bonasera A, et al Measuring the astrophysical S-factor in plasmas. In: Hamilton JH, editor**. Fission and Properties of Neutron-Rich Nuclei.** Sanibel Island, FL: World Scientific (2008). p. 503–7.

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Recognitions

Funding

- **EUROfusion Enabling Research** project on IFE “Advancing shock ignition for direct-drive inertial fusion” PI: D. Batani, ENR-IFE.21.CEA - 2021-2023
- **EUROfusion Enabling Research** project on IFE “Towards demonstration of Inertial Fusion for Energy”. PI. S. Jacquemot, AWP15-ENR-IFE/CEA-02 – 2015-2018
- Proposal for collaborative **COST action** to be submitted
- Discussions with **private companies** (Marvel Fusion – Non disclosure agreement signed)

Next funded experiment

- VEGA III Petawatt, Salamanca, Spain – November 2022

Main collaborations for research activity

- Laser-generated Electromagnetic Pulses (EMPs)
- Foam materials
- Low-rate nuclear fusion reactions ($p+^{11}B$,…)
- **Laser-produced radiation for applications**
- Diagnostics (RF-Microwave, ions, electrons, UV, X)
- Others on Inertial Confinement Fusion
- DTT

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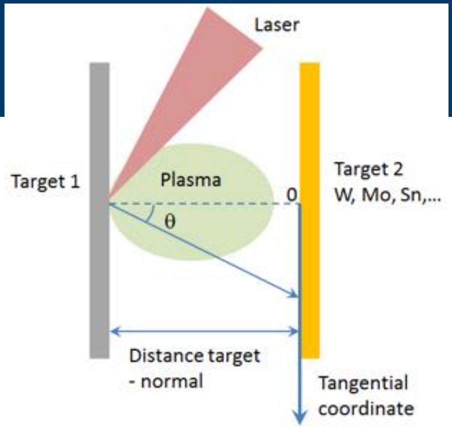
Main research activities: Laser-produced radiation for applications

Laser-generated plasmas for studies of first-wall Tokamak materials (collaboration ENEA-FSN)

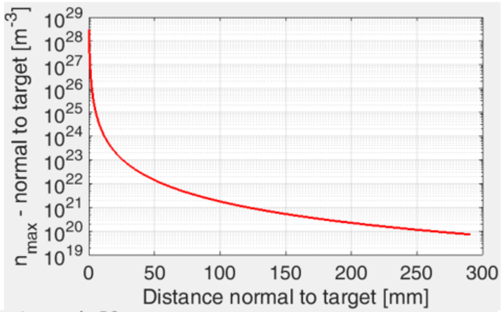
- Laser-generated plasmas to deal with the characterization of materials suitable for plasma-facing components in magnetic fusion reactors
- Plasmas produced, in suitable conditions, by devices normally devoted to laser-plasma and Inertial Confinement Fusion research experiments.
- This type of plasmas may offer specific conditions of interaction with the plasma-facing candidates and can supply important information on their possible use in Tokamaks.
- We propose to build a test-bench, by using the energetic ABC laser facility, for laser-matter interactions capable of generating plasmas with detailed characterization of their space-time evolution, density, temperature, electromagnetic and particle emission, to be used for testing plasma-facing eligible materials.
- Important applications:
    - emission spectroscopy of low-ionization states of elements – like W and Sn – still not thoroughly characterized in these conditions, particularly useful for the analysis of radiation emitted from the divertor region in Tokamaks
    - study of vapour shielding phenomena, still a very open problem for Tokamak plasma-facing components.

Main research activities: Laser-produced radiation for applications

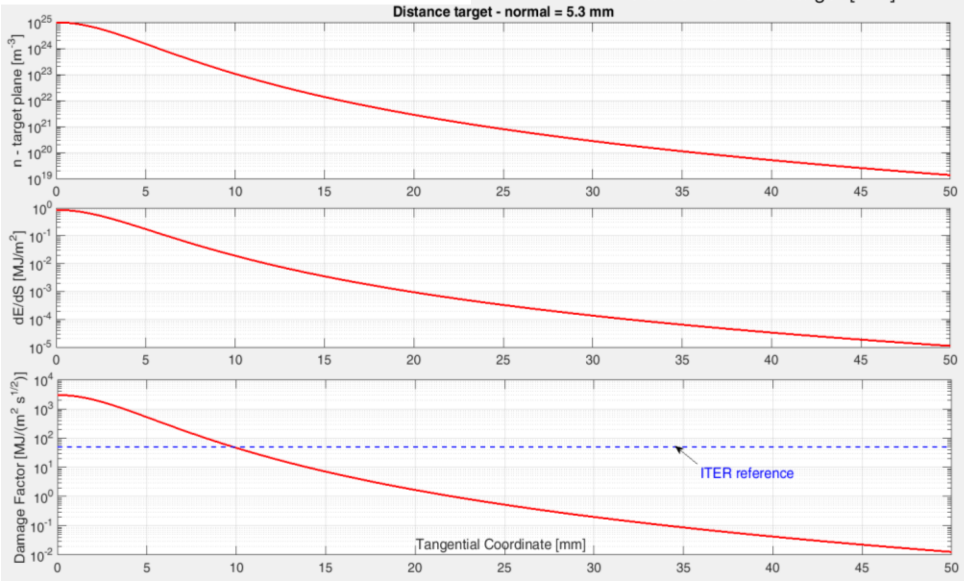


- **Damage Factors from laser-generated plasmas may exceed those obtained with classical QSPA (Quasi-Stationary Plasma Accelerators) devices of high performances, with extremely broad dynamic ranges and deposited energy density, in just one interaction.**

- **Important points**
  - **<u>versatility</u> of the setup to the different studies that can be performed**
  - **<u>broad range of loads</u> that can stress the material**
  - **<u>accuracy on diagnosing</u> the space-time evolution of the load-test plasmas to be directed on the plasma-facing candidate materials and the phenomena occurring in the target because of this interaction.**



- **Post-mortem analysis of the exposed targets → <u>definition of cross-correlation between damages caused on candidate plasma-facing materials by Tokamak plasmas and laser-generated plasmas</u>**

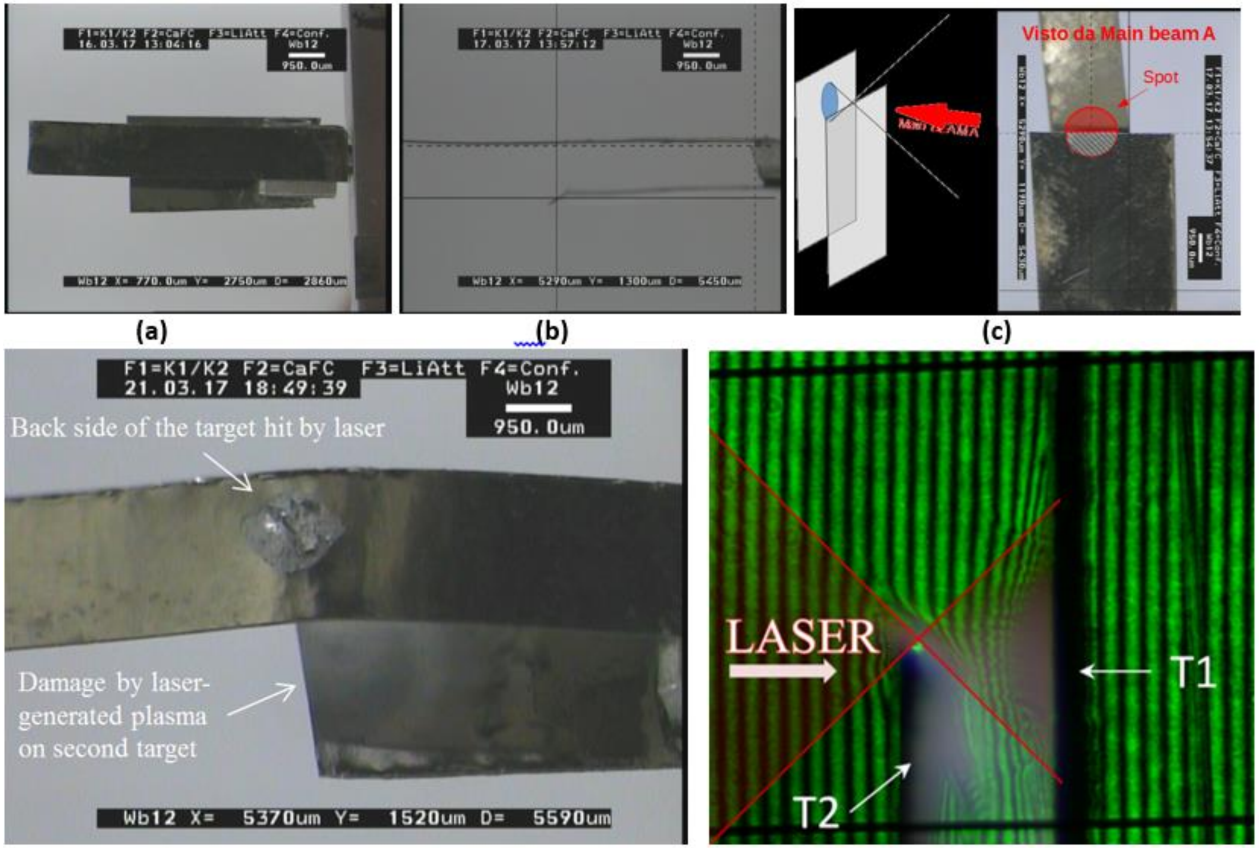


- **Purpose: enabling laser-generated plasmas to become a powerful way of testing plasma-facing materials with versatility and, in some cases, at regimes not accessible with conventional facilities (electron beams, QSPA,…).**

ENEA

Main research activities: Laser-produced radiation for applications

- **First tests already performed with the ABC laser**
- **Clear damage observed on W produced by ABC-generated plasma**



(a) (b) (c)

(d) (e)

- **Proposal for Enabling Research call for Materials submitted. Good marks but not funded**
- **Report in preparation**

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Main research activities: Laser-produced radiation for applications

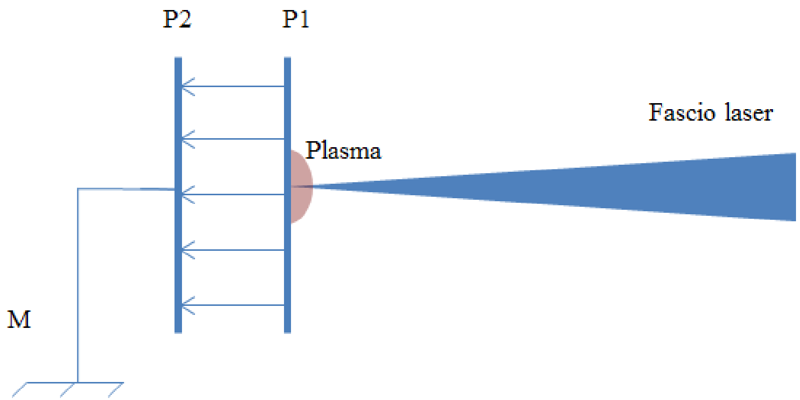
Laser-generated electromagnetic pulses for applications

- **Understanding of EMP physics opens to a wide number of significant applications for these high-intensity fields. A patent was issued by ENEA on this topic:"Method of generation of electromagnetic fields of high intensity", (PCT/IB2020/057464).**

- **The main purpose of the patent is to extend the use of laser-matter interactions also as sources of RF-microwave fields of high intensity and specific properties. Applications: Inertial Confinement Fusion (Fast Ignition and Shock Ignition), material science, avionics, aerospace, medicine, biology, electromagnetic hardness of devices and materials.**

- **These fields can be quasi-stationary or pulsed fields in radiofrequency-microwave regime, can be distributed over large volumes (up to several decimeter cubes and beyond), have: high intensities (MV/m order and beyond), fast rise/fall times (ps down to fs), tailored spatial profile ('uniform', not 'uniform' and if necessary with specific profile)**

- **Recent funding (Proof Of Concept 2020.02) by the Italian Ministry of Economical Development, specifically for the development of this patent.**



ENEA

Main research activities: Laser-produced radiation for applications

<u>Laser-generated ionizing radiation for biological applications (collaboration with Eccimeri Group)</u>

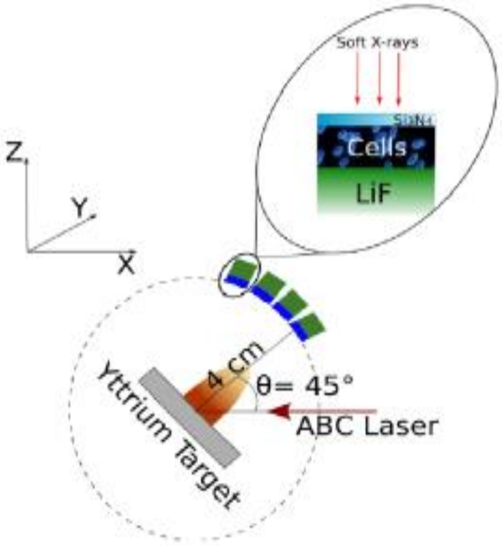
- Plasma generated by energetic laser-matter interaction can be used as an X-ray source for contact microscopy of biological samples

- In order to obtain high resolution images, the X-ray source has to satisfy some requirements
  - high-flux exposure
  - short duration of the irradiation.
  - radiation should interest the water window region: spectral region between Oxygen and Carbon K-absorption edges. There, the X-ray absorption of Carbon, the main constituent of proteins, is about ten times higher than that of Oxygen, providing a natural high contrast to the collected images.

- High care for the preparation of the samples to be irradiated is needed in order to keep them hydrated and at atmospheric pressure, allowing the in-vivo study of biological specimen.

- LiF detectors suitable diagnostics, also of high importance for Inertial Fusion, still with several issues for the optimal use

- Experiments require suitable characterization of the source my several diagnostics



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Main research activities: Laser-produced radiation for applications

Laser-generated ionizing radiation for Aerospace

- **With ABC laser it is possible to produce**
  - **Accelerated electrons**
    - **'thermal' up to a few kev**
    - **'hot', up to a few hundreds keV**
  - **Accelerated ions**
    - **Up to hundreds keV**
  - **Transient electromagnetic radiation at high intensity**
    - **RF-microwaves (100 ns)**
    - **Near infrared-visible (3-10 ns)**
    - **UV and soft X (3-10 ns)**
    - **hard X and γ (3-10 ns)**

- **Power for each of these components > 100 MW**

- **These can be used to test materials and devices to be used in aerospace applications → collaboration setting with other ENEA groups (Calliope, Eccimeri,…) and Italian Institutions (INAF,…) and companies (IMT)**

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Main collaborations: Laser-produced radiation for applications

Italia

- ENEA
  - FSN
  - Calliope
- Università La Sapienza
- Politecnico Torino
- INFN – Sezione di Roma
- Università di Tor Vergata

Francia

- Centre lasers intenses et applications (CELIA), University of Bordeaux (Bordeaux)
- Kapteos company (Saint-Helene Du Lac)

Regno Unito

- Queen’s University of Belfast (Belfast)

Germania

- Marvel Fusion GmbH (Non disclosure agreement signed)

Russia

- Joint Institute for High Temperatures Russian Academy of Sciences, Moscow, Russia

Giappone

- Open and Transdisciplinary Research Initiatives, Osaka University, Osaka
- Institute of Laser Engineering, Osaka University, Osaka

Main research activities: Laser-produced radiation for applications

- **Related publications:**

1. M. Salvadori, P.L. Andreoli, S. Bollanti, F. Bombarda, M. Cipriani, F. Consoli, G. Cristofari, R. De Angelis, G. Di Giorgio, F. Flora, D. Giulietti, L. Mezi, M. Migliorati, M.A. Alkhimova, S. Pikuz, T. Pikuz, R. Kodama, "A laser-produced plasma X-ray source for contact microscopy", **Journal of Instrumentation** 14, C03007 (2019).

International activities

- **Participation to the Coordinated Research Projects of IAEA (International Atomic Energy Association): "Advanced Research Activity on Materials, Technologies and Devices for Inertial Confinement Fusion", under the IAEA Research Agreement No: 24232/R0 (2020-2023)**

IAEA
International Atomic Energy Agency

ENEA

Recognitions

- M. Salvadori et al, "Characterization of X-Ray source for contact-microscopy applications obtained from laser-produced plasma“ **Best student Poster awards ICFDT – Frascati, Oct 2018**

Funding

- **Horizon Europe project Re-Made at Infrastructure call,** recently approved for **2022-2024,** for tests on materials for circular economy. Grant agreement in preparation. Involves **ABC** & **CETRA** facilities
- **Proof Of Concept 2020.02** by the Italian Ministry of Economical Development (2021-2022) – PI. F. Consoli
- Further proposals are in preparation

Main present research activities

- Laser-generated Electromagnetic Pulses (EMPs)
- Foam materials
- Low-rate nuclear fusion reactions (p+^{11}B,…)
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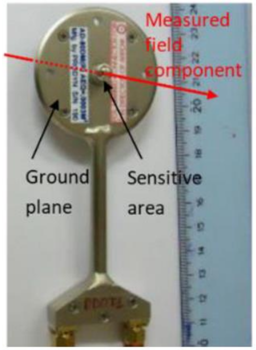
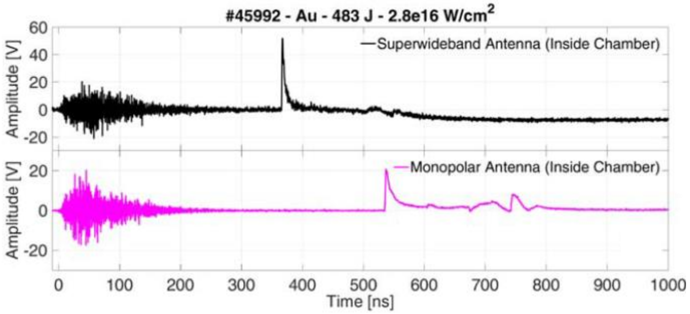
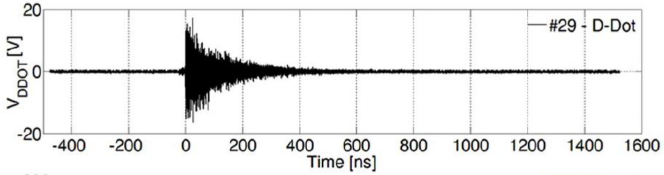
- Others on Inertial Confinement Fusion
- DTT

EMP diagnostics

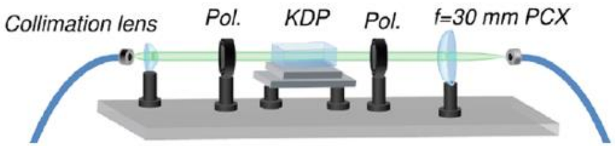
- **Conductive probes: antennas, D-Dot**

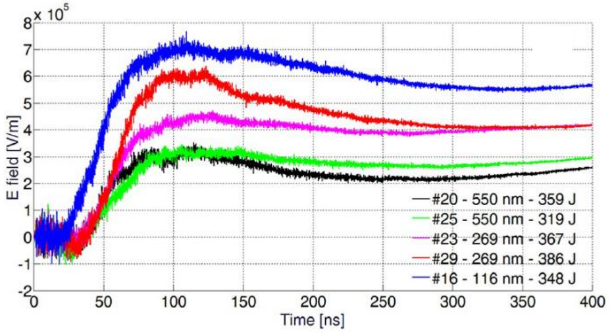


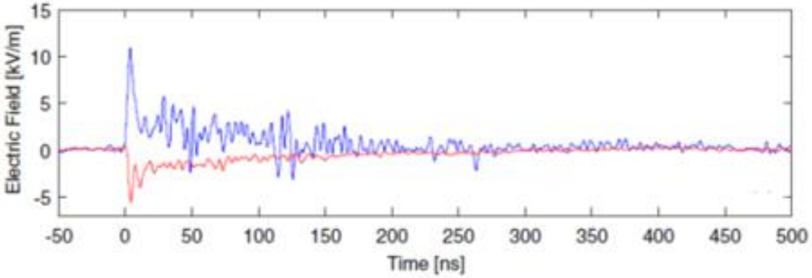




- **Advanced electro-optical medologies**
  - **Open structures**
  - **Pigtailed**







Main present research activities

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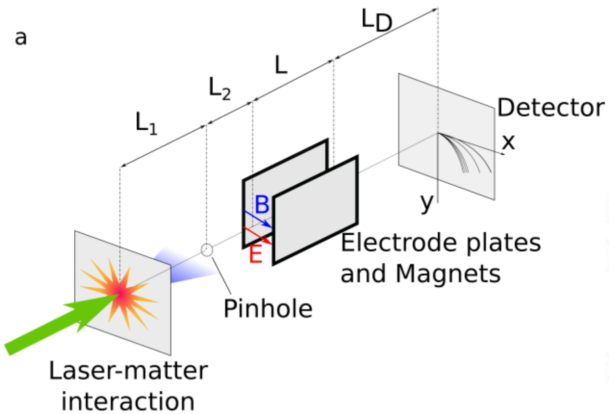
- **Laser-produced radiation for applications**
- **Diagnostics** (RF-Microwave**, ions, electrons**, UV, X)
- **Others on Inertial Confinement Fusion**
- **DTT**

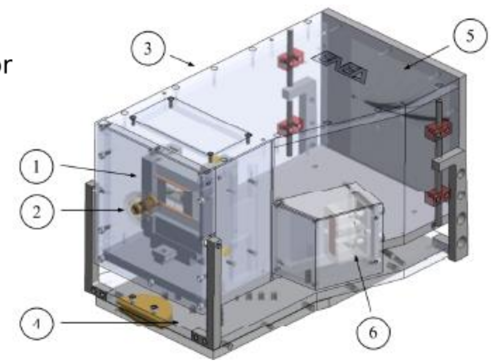
Diagnostics: ions, electrons. High sensitivity, low EMP coupling

- **Ions**
  - **Thomson Spectrometers: electtrostatic and magnetostatic parallel fields**
    - **High sensitivity, high rejection to EMPs, even at close proximity of target**

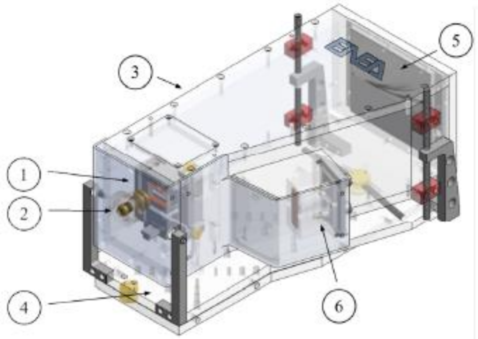
Scheme



Two prototypes

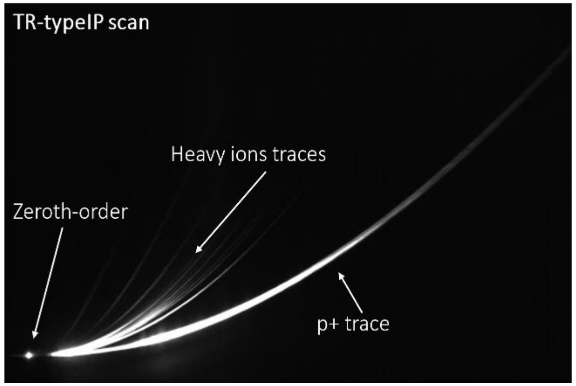


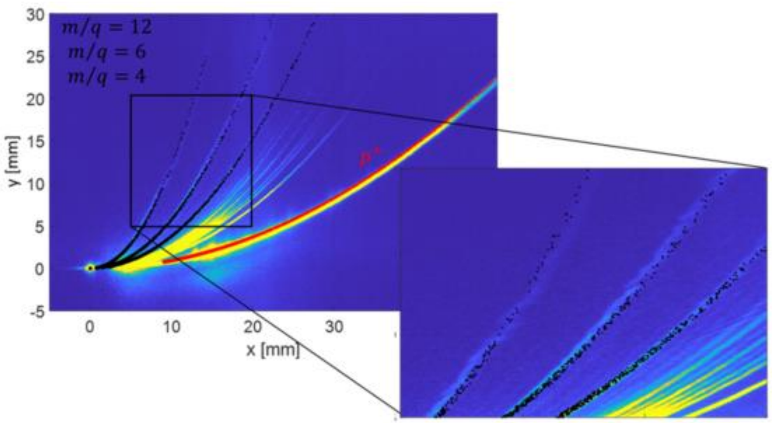
Protons: 100 keV- 10 MeV



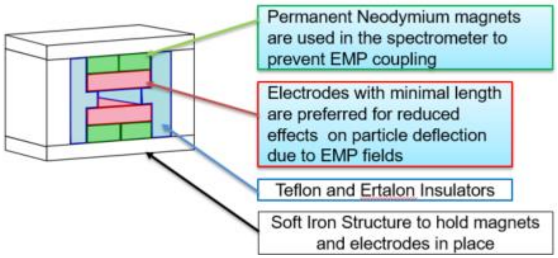
Protons: 5 keV- 1 MeV

Experiment Phelix (GSI)





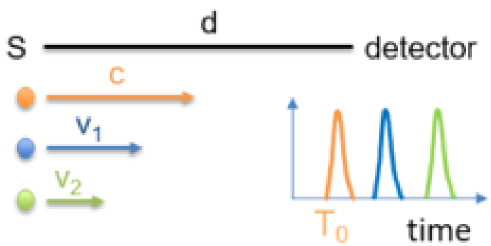
Electrodes and magnets



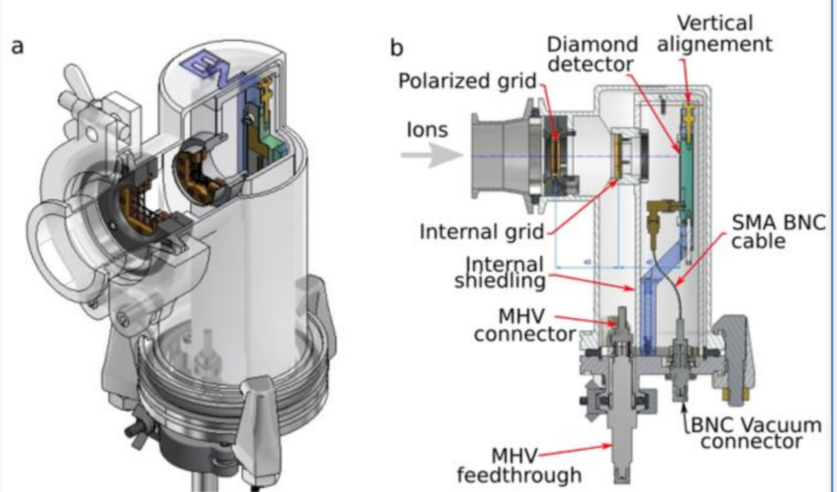
Diagnostics: ions, electrons. High sensitivity, low EMP coupling

- **Ions**
    - **Time-Of-Flight. High rejection to EMPs. Calibrated spectrum. High Repetition Rates**

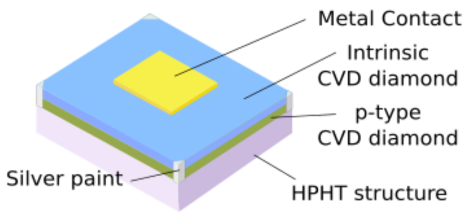
TOF technique relies on the measurement of the time needed by a particle to travel for a known distance

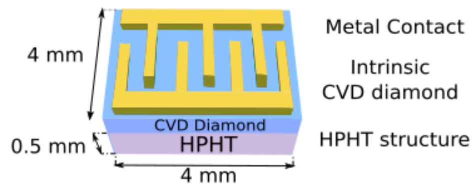


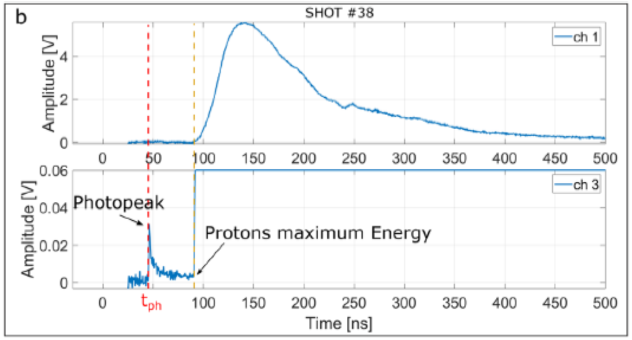
Monoscristalline detector

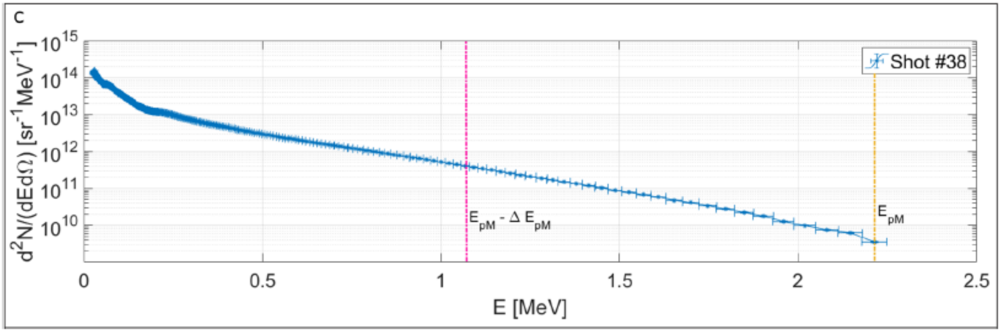


Policristalline, large area (15mmx15mm)



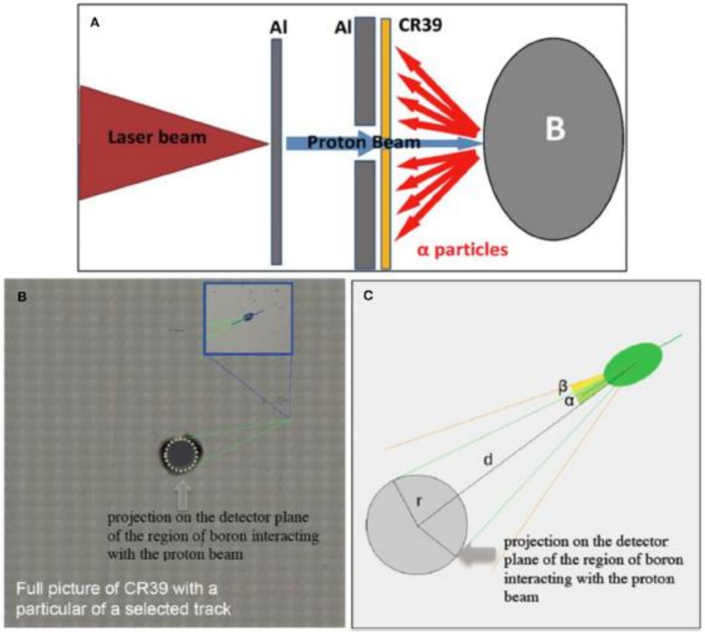






Diagnostics: ions, electrons. High sensitivity, low EMP coupling

- **Ions**
  - **Large area scintillator detectors (50mm x 50mm) under development**
  - **Solid State Nuclear Track Detectors: CR39**
    - **Determination of the type of particles by studying the track shape and numerical identification**



- **Electrons:**
  - **Low energy magnetic electron spectrometers (1-100 keV and 100 keV-10 MeV) under development**

Main present research activities

- Laser-generated Electromagnetic Pulses (EMPs)
- Foam materials
- Low-rate nuclear fusion reactions ($p+^{11}B$,…)
- Laser-produced radiation for applications
- **Diagnostics** (RF-Microwave, ions, electrons, **UV, X**)
- Others on Inertial Confinement Fusion
- DTT

Diagnostics: UV- X

- **Lithium fluoride: an imaging high resolution wide range detector for any ionizing radiation having E>14 eV (collaboration with Eccimeri group: Bollanti, Flora, Mezi)**

Main research activities: Diagnostics

International activities

- **Participation to the Coordinated Research Projects of IAEA (International Atomic Energy Association): “Advanced Research Activity on Materials, Technologies and Devices for Inertial Confinement Fusion”, under the IAEA Research Agreement No: 24232/R0 (2020-2023)**

Diagnostics: collaborations

Italia

- **INFN**
    - **Laboratori Nazionali del Sud**
    - **Laboratori Nazionali di Frascati**
- **Università di Tor Vergata**
- **Università della Sapienza**

Francia

- **École Polytechnique, Palaiseau (Parigi)**

Germania

- **GSI, Darmstadt**

Regno Unito

- **Imperial College, Londra**

Spagna

- **Centro de Láseres Pulsados (CLPU), Salamanca**

Israele

- **Hebrew University Jerusalem**

Canada

- **INRS Montreal**

USA

- **Texas A&M University, College Station**

Main research activities: diagnostics

1) M. Salvadori et al, to appear on ***Journal of Instrumentation***
2) M. Salvadori et al, to appear on ***High Power Laser Sci. Engin.***
3) M. Sciscìò et al, ***Journal of Instrumentation*** 17, C01055 (2022)
4) M. Sciscìò et al, ***High Power Laser Sci. Engin.*** 9, e64 (2021)
5) M. Salvadori, et al, ***Scientific Reports*** 11, 3071 (2021).
6) F. Consoli, et al, **Frontiers in Physics** 8, 561492, (2020). **Review Paper**
7) S. Vallières , M. Salvadori, et al, ***Review of Scientific Instruments*** 91, 103303 (2020)
8) G. Di Giorgio, et al ***Journal of Instrumentation*** 15, C10013 (2020)
9) M. Salvadori, et al, ***Journal of Instrumentation*** 15, C10002 (2020)
10) C. Verona, M. Salvadori, et al, ***Journal of Instrumentation*** 15, C09066 (2020)
11) F. Consoli, et al, ***Scientific Reports*** 9, 8551 (2019).
12) F. Consoli, et al, ***Journal of Instrumentation*** 14, C03001 (2019).
13) M. Salvadori et al, ***J. Instrumentation*** 14, C03007 (2019)
14) M. Cipriani et al ***J Inst.*** (2019) 14:C01027.
15) F. Ingenito et al, ***EPJ Web Conf.*** (2018) 167:05006
16) F. Consoli , et al ***Plasma Physics and Controlled Fusion*** 60, 105006 (2018)
17) T. Robinson, .., F. Consoli, et al, ***EPJ Web of Conferences*** 167, 03007 (2018).
18. M. De Marco, .., F. Consoli, et al ***EPJ Web of Conferences*** 167, 03009 (2018).
19. T.S. Robinson, F. Consoli, et al, ***Scientific Reports*** **7**, 983, (2017),
20. R. De Angelis, et al ***Journal of Instrumentation*** **11**, C12048, 2016.
21. F. Consoli, et al, ***Journal of Instrumentation*** **11**, C05010, 2016.
22. F. Consoli, et al ***Scientific Reports*** **6**, 27889, 2016, DOI:10.1038/srep27889.
23. C. Baccou et al, ***Rev Sci Instrum***. (2015) 86:083307
24. F. Consoli et al, ***NIMA.*** (2013) 720:149–52.
25. F. Consoli, et al, ***Proc. IEEE 15th Intern. Conf. Env. Electr. Engin. (EEEIC)***, 2015, 10-13 June 2015, Rome, 182
26. F. Consoli, et al,, ***Physics Procedia*** 62, 11-17, 2015.

Main present research activities

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Others on Inertial Confinement Fusion

- **Other research activities:**
  - **Shock Ignition & hybrid approach**
  - **Nuclear fusion by laser interaction with clusters**
- **Participation to the HiPER (European High Power laser Energy Research) project funded by ESFRI on the years 2008-2013, dedicated to explore the science and technology at the base of laser-driven schemes for ICF. After the recent NIF results, the HiPER-PLUS initiative is under discussion, to set the foundations of a new project related to laser fusion physics in EU.**

Main present research activities

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Participation to DTT Calls

- DIP_Diagnostics_INTERFEROMETER_POLARIMETER
- DCI_ Diagnostics_CAMERAS IR
- DCV_Diagnostics_CAMERAS_VIS
- DPV_Diagnostics_PASSIVE_SPECTROSCOPY_VIS/IR

- DTT-2021 Physics Task - DIAGNOSTICS - ADVANCED DIAGNOSTICS PHYSICS DESIGN
  - 11.1 Assessment of diagnostics needs and qualification
    - SUB-TASK 11.1.3 - Assessment of diagnostic needs for detachment control

Conclusions

- **Research activities of the ABC group regard**
  - **theoretical and numerical studies**
  - **intense experimental activity - ABC laser and other foreign laser plants worldwide**
  - **development of advanced diagnostic methodologies**

- **Practically all the activities of the ABC Group are carried out in collaboration with Italian and foreign Research Institutions and private companies**

- **This collaboration naturally leads to**
  - **Preparation of proposals for laser time in the main laser facilities in and out Europe**
  - **Preparation of proposals for funding**

- **Collaboration defined**
  - **by formal documents (agreements, such as with Lebedev Physical Institute, agreements with private companies)**
  - **by joint collaborative proposals for funding (EUROFusion Enabling Research)**
  - **by joint collaborative proposals for laser time (Vulcan, LULI, Apollon, VEGA III, …)**
  - **by participation to formalized international groups (Laselab-Europe AISBL Expert/Interest Groups, HIPER)**

Acknowledgments

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