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Accelerazione di particelle tramite laser intensi ed applicazioni (biomediche, materiali, beni culturali, ambiente)

Patrizio Antici

The advent of High-Power lasers thanks to the CPA

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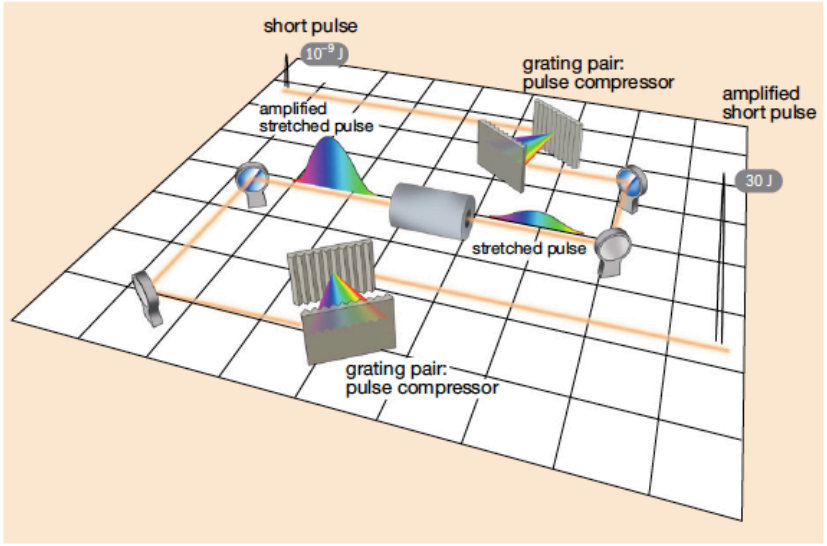
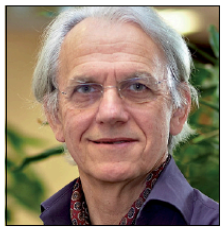
Focus on: CPA

CPA: 25 years of intense laser pulses



Basic working principle of CPA. An initially very short but low energy laser pulse (top left) is first stretched, then amplified and then recompressed (bottom right). Numbers are indicative only.

ELI gathers momentum



Gérard Mourou

At the European Conference on Research Infrastructures, in Barcelona, we were pleased to see ELI in the spotlight of many talks, showing the high interest of the scientific community – and its policymakers – in making ELI become reality.

ELI's future hosts – the Czech Republic, Hungary and Romania – recently set a new landmark on the way to its materialization (p9). In April they signed a Memorandum of Understanding. It is the first joint legal and political commitment of the three countries in which the intention to build a common infrastructure is stated. The ELI Delivery Consortium has also now been established: a new organization that all the funding agencies represented in the Steering Committee are invited to join. From this issue on, the three host countries have a dedicated column on the back page where they can summarize progress so far.

With the approach of a technical design report for ELI – "the white book" – scientists, technicians and engineers

eli Courier

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The field of high-power lasers is booming (investments of over >1 B€ in 10 years!) (including INFN !)

BELLA 30 M€

APPOLON 50 M€

CALA 65 M€

ALLS 30 M€

FLAME/INFN-PI 6 M€

2000-2005 Experimental Discovery of laser-accelerated particles

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2000

VOLUME 85, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 2000

Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids

R. A. Snavely,[1,2] M. H. Key,[1] S. P. Hatchett,[1] T. E. Cowan,[1] M. Roth,[3,*] T. W. Phillips,[1] M. A. Stoyer,[1] E. A. Henry,[1] T. C. Sangster,[1] M. S. Singh,[1] S. C. Wilks,[1] A. MacKinnon,[1] A. Offenberger,[4,*] D. M. Pennington,[1] K. Yasuike,[5,*] A. B. Langdon,[1] B. F. Lasinski,[1] J. Johnson,[6] M. D. Perry,[1] and E. M. Campbell[1]

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(Received 19 January 2000)

[illegible] energy is transferred to 2×10^{12} protons of energy >10 MeV. The energy spectrum exhibits a sharp high-energy cutoff as high as 58 MeV on the axis of the beam which decreases in energy with increasing off axis angle. Proton induced nuclear processes have been observed and used to characterize the beam.

PACS numbers: 41.75.Jv, 07.77.Ka, 52.50.Jm

The generation of fast protons from laser irradiated solid surfaces is well understood [1,2] and attributable to electrostatic fields produced by hot electrons acting on protons from adsorbed hydrocarbons. An empirical power law relationship between the mean proton energy and intensity x (wavelength) [2] ($I\lambda^2$) was identified and proton energies up to a few MeV were observed for $I\lambda^2$ up to 10^{18} W cm^{-2} μm^2 in nanosecond pulses [1]. Scaling laws for the maximum energy were similarly derived [3].

Chirped pulse amplification (CPA) laser technology [4] has since enabled widespread generation of terawatt power and the first petawatt laser [5]. CPA lasers generate pulses in the range 20 fs to 1 ps. 10 MeV protons were observed with a 1 ps CPA laser at $I\lambda^2 = 10^{19}$ W cm^2 μm^2 consistent with the previous scaling [6,7].

New mechanisms of ion acceleration have been studied with CPA lasers. Ponderomotive pressure of the laser radiation causes radial acceleration when laser beams are focused in gas jets and subcritical density plasmas [8] and also axial acceleration into solid targets [9]. Coulomb explosion of molecules [10] and clusters [11] has produced energetic ions. The ion energies from these newly studied processes have been <1 MeV/nucleon.

We report a laser induced proton beam with much higher particle energy (up to 58 MeV). The maximum energy is about 2× higher than is given by extrapolating the previous scaling law [7] to the 30× higher intensity of this work. A distinctive feature is emission with good beam collimation perpendicular to the rear-unirradiated surface(s) of the target. Similar rear surface beaming of protons of energy <1 MeV was reported in nanosecond pulse CO_2 laser experiments [12]. Our observed high proton energies open up access to nuclear processes.

The experiments used a CPA laser system generating 1 PW pulses of 500 fs duration [5]. With $f/3$ parabolic mirror focusing, the peak intensity was 3×10^{20} W cm^{-2} in a focal spot of 9 μm FWHM with 30% of the energy inside the first minimum. Amplified spontaneous emission in a 4 ns period before the main pulse had 10^{-4} of the main pulse energy and there was a 3×10^{-4} prepulse 2 ns before the main pulse. This precursor radiation generated a plasma [illegible] by [illegible] optical interferometry [illegible] 3×10^{19} cm^{-3} in a plume 70 μm from a flat CH polymer target with an approximately exponential fall to lower densities having a scale [illegible]

The proton beam [illegible] film which changes through polymerization of a diacetylene active layer, from transparent to dark blue in proportion to the dose [illegible] 100 ergs/g). A 90° cone [illegible] and sheets of RC film was used. The cone is 4 cm deep at its apex, which [illegible] the laser axis [illegible] sphere. The RC film response was calibrated absolutely and the image data were analyzed by digital densitometry and transformed geometrically to produce contour plots of dose as a function of angle illustrated in Fig. 1.

The data in Fig. 1 show a collimated intense proton beam emitted perpendicular to the rear target surface of a Au target at 45° to the laser axis. Its angular width narrows to 10° in the image through 600 μm of Ta. The beam is rather uniform in intensity with near circular sharp boundaries. There is a low intensity wide-angle background, which is discussed elsewhere and is due to escaping relativistic electrons [14]. Similar results were seen for normal incidence, S polarization, and target thickness down to 20 μm. The proton beam profiles from CH targets have nonuniform edges and exhibit internal fine structure as illustrated in Fig. 2 for a 100-μm thick CH target at normal incidence. There was typically a 5 times greater proton induced dose recorded from CH relative to Au targets. Data

0031-9007/00/85(14)/2945(4)$15.00 © 2000 The American Physical Society

High quality and high energy protons are accelerated by high intensity lasers…

Proton beams:
- High number
- High energy
- Very laminar

2004

1000 x more compact
+ other properties (short duration)

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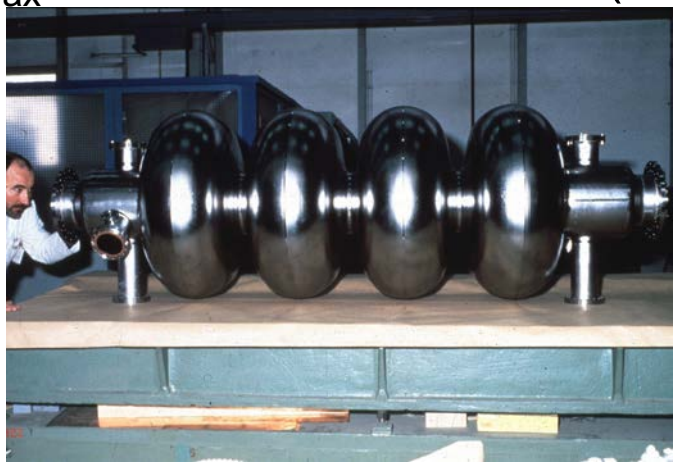
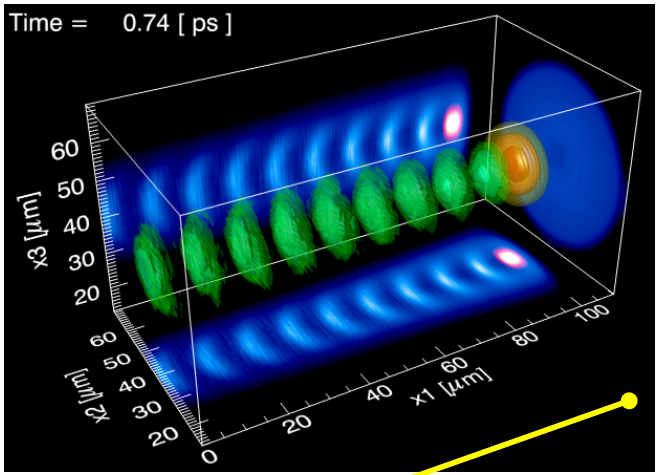
E-field $_{max}$ ≈ 50-100 MeV /meter (Breakdown)

1 m



RF cavity

Courtesy of W. Mori & L. da Silva



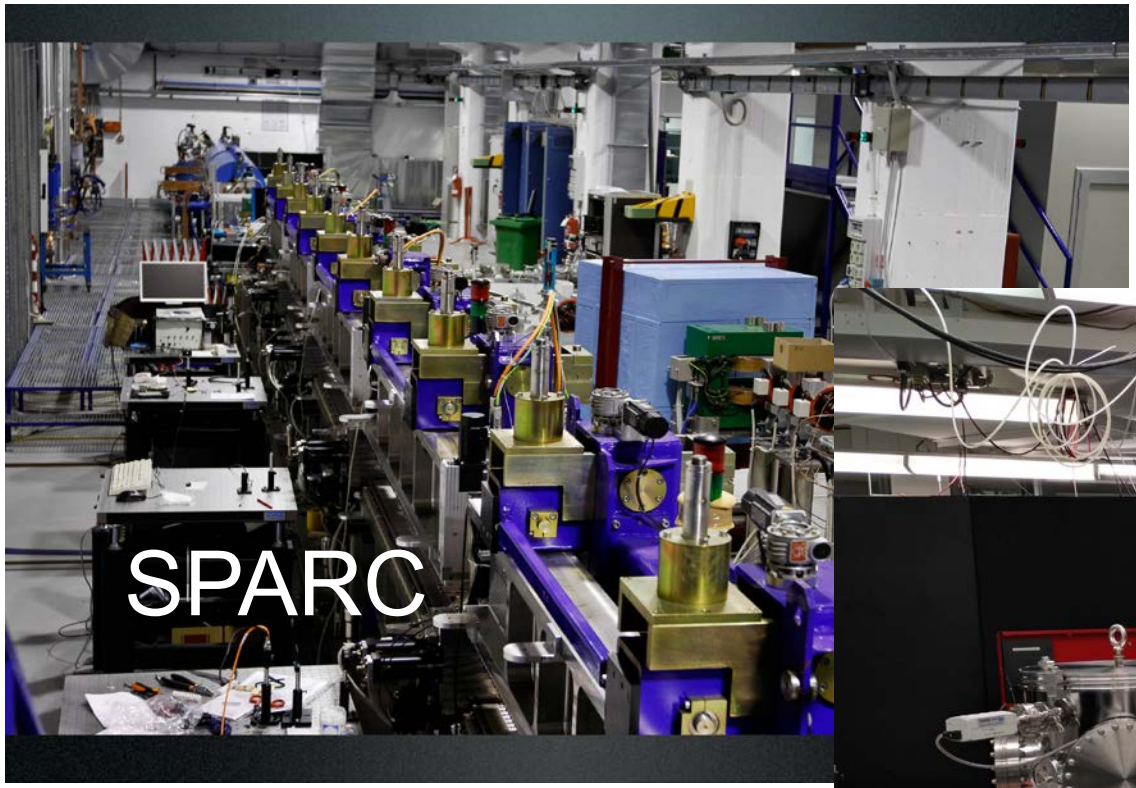
Plasma cavity

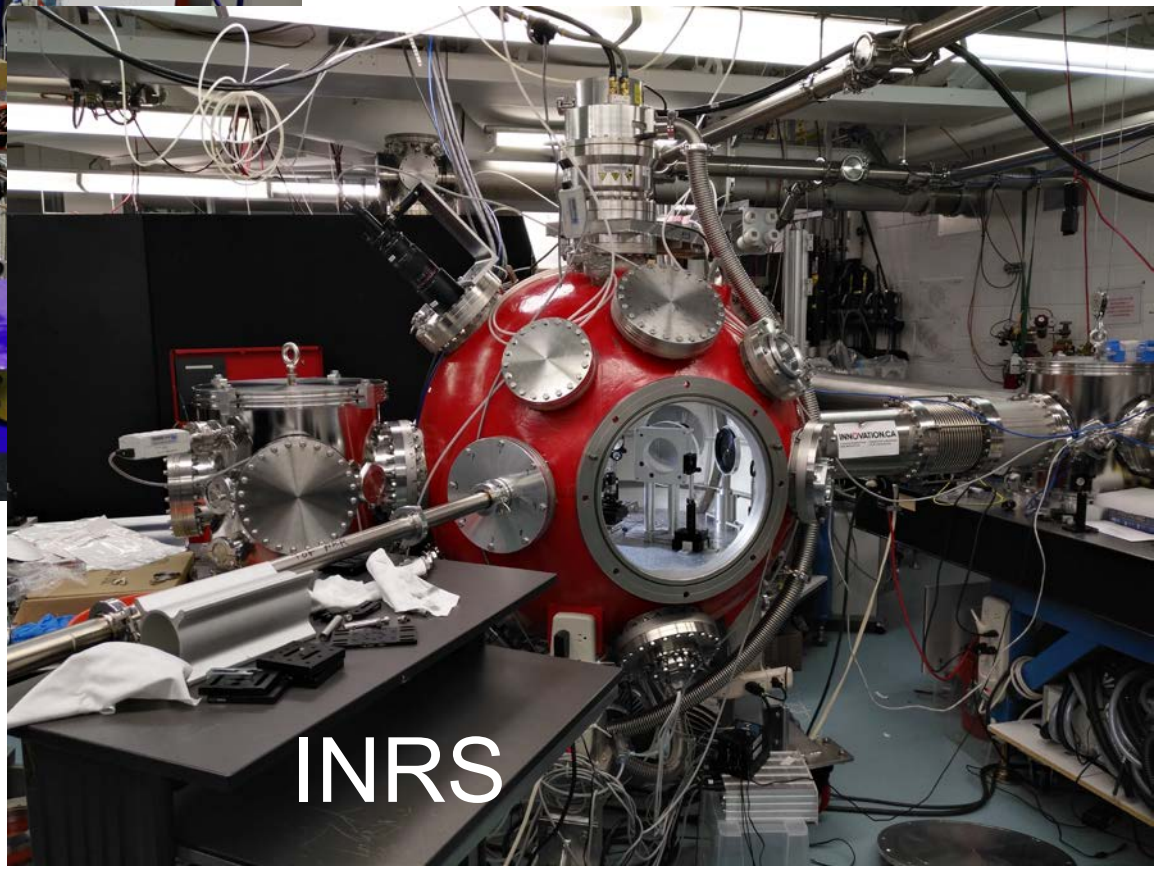
100 um

From particles to light

…

From light to particles





Opening of new lab for proton acceleration at INRS-EMT on the ALLS 200 TW laser facility

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2426 OPTICS LETTERS / Vol. 36, No. 13 / July 1, 2011

Single shot phase contrast imaging using laser-produced Betatron x-ray beams

S. Fourmaux,[1,*] S. Corde,[2] K. Ta Phuoc,[2] P. Lassonde,[1] G. Lebrun,[1] S. Payeur,[1] F. Martin,[1] S. Sebban,[2] V. Malka,[2] A. Rousse,[2] and J. C. Kieffer[1]
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*Corresponding author: fourmaux@emt.in

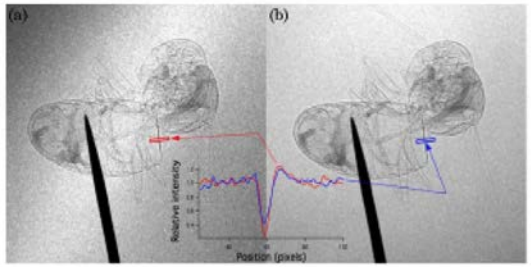

Fig. 3. (Color online) Bee imaged with the x-ray Betatron beam with an edge line out indicated by the rectangular area: (a) one laser shot; (b) 13 laser shots.

APPLIED PHYSICS LETTERS 101, 111106 (2012)

Quasi-monoenergetic electron beams production in a sharp density transition

S. Fourmaux,[1,a)] K. Ta Phuoc,[2] P. Lassonde,[1] S. Corde,[2] G. Lebrun,[1] V. Malka,[2] A. Rousse,[2] and J. C. Kieffer[1]
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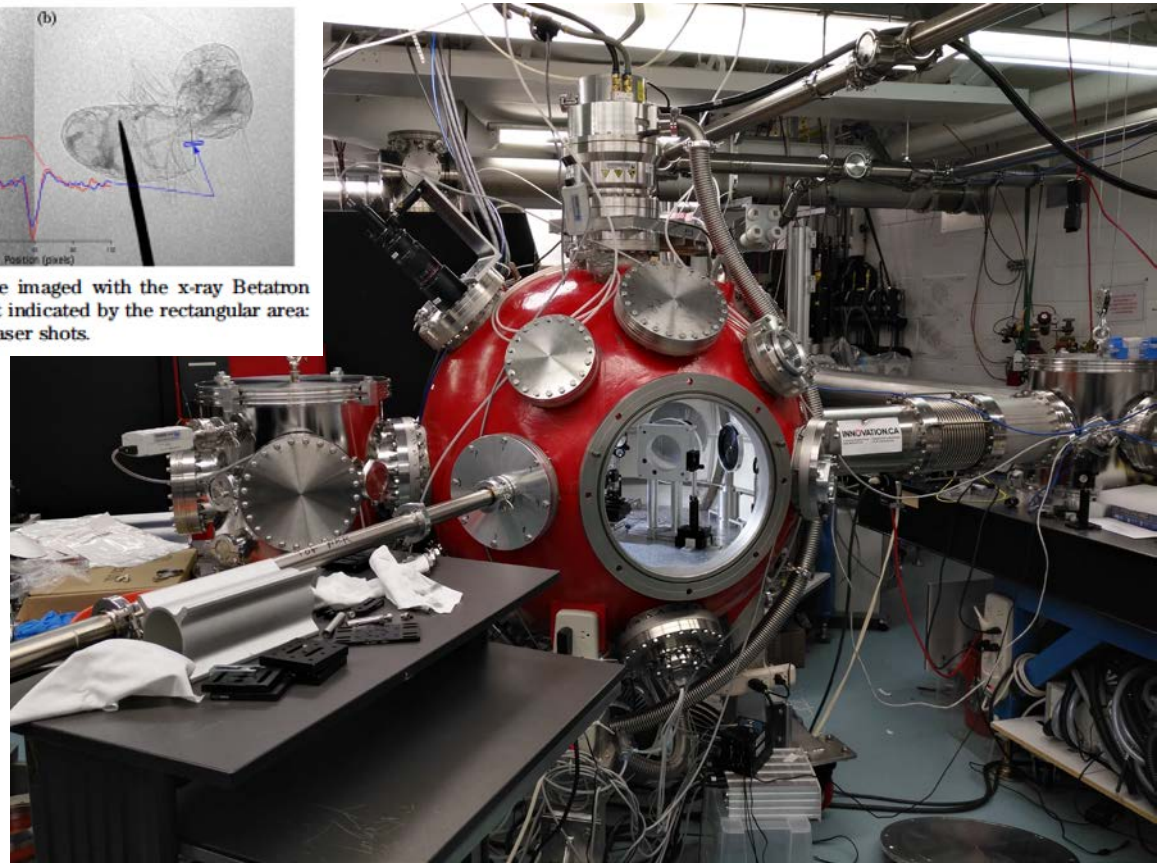
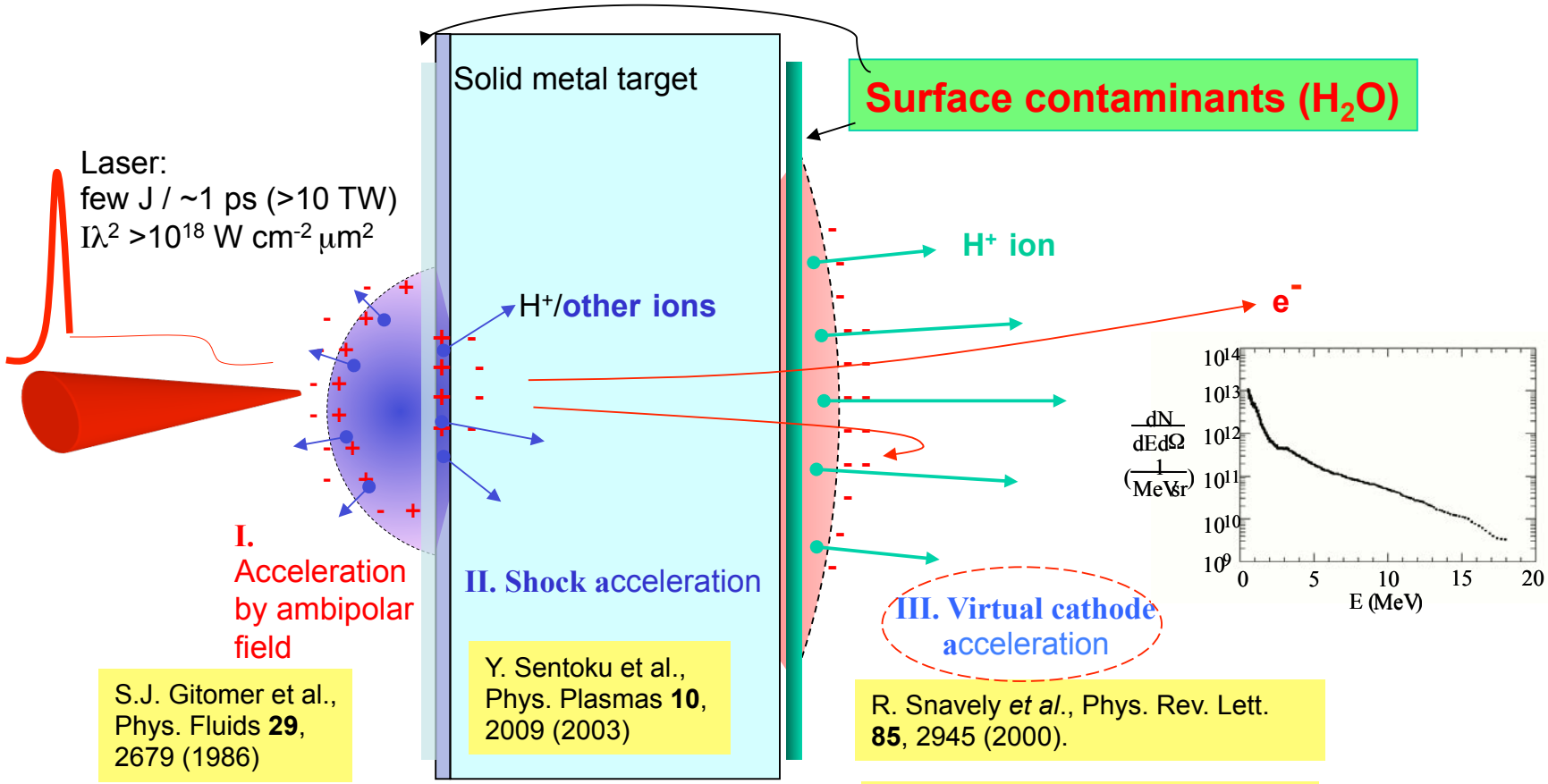
(Received 29 May 2012; accepted 28 August 2012; published online 12 September 2012)

Using a laser plasma accelerator, experiments with a 80 TW and 30 fs laser pulse demonstrated quasi-monoenergetic electron spectra with maximum energy over 0.4 GeV. This is achieved using a supersonic He gas jet and a sharp density ramp generated by a high intensity laser crossing pre-pulse focused 3 ns before the main laser pulse. By adjusting this crossing pre-pulse position inside the gas jet, among the laser shots with electron injection, more than 40% can produce quasi-monoenergetic spectra. This could become a relatively straight forward technique to control laser wakefield electron beams parameters. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4752114]



How works laser-driven proton acceleration ?



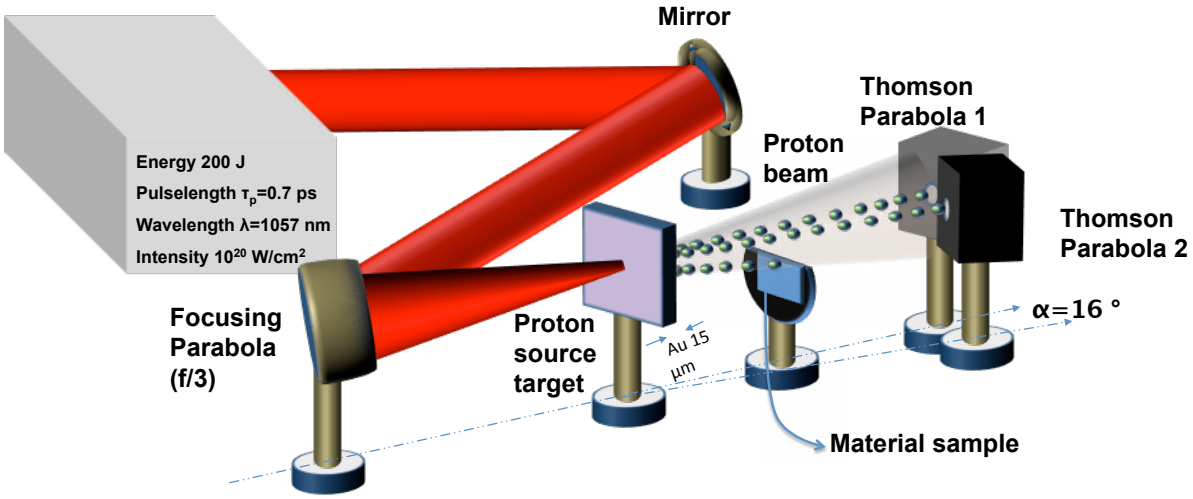
S.J. Gitomer et al., Phys. Fluids **29**, 2679 (1986)

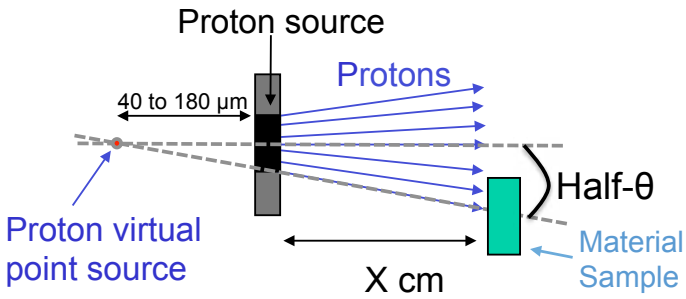
Y. Sentoku et al., Phys. Plasmas **10**, 2009 (2003)

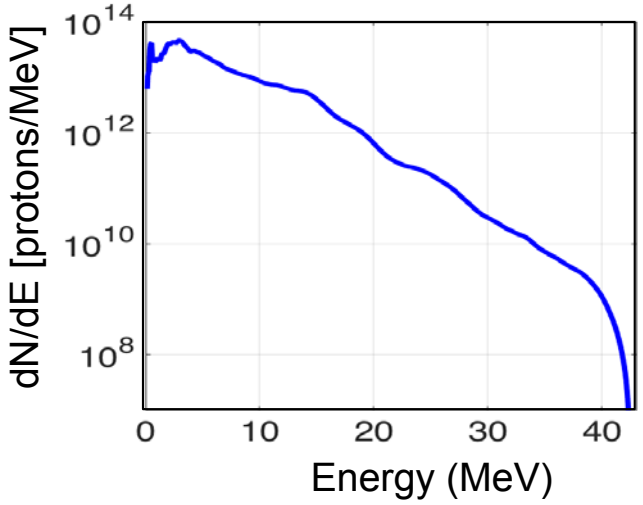
R. Snavely *et al.*, Phys. Rev. Lett. **85**, 2945 (2000).

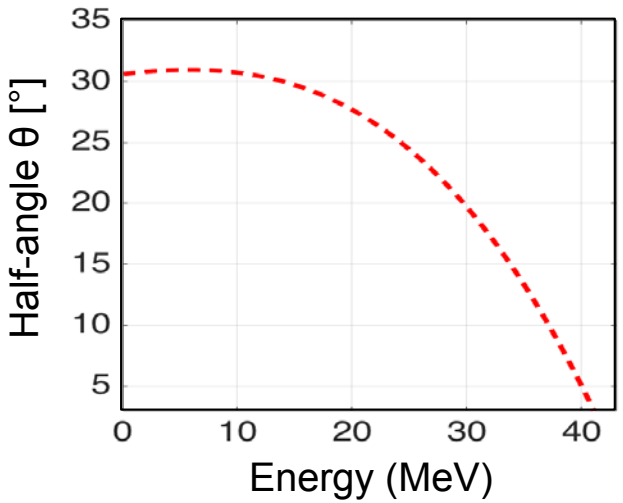
J. Fuchs *et al.*, Phys. Rev. Lett. **94**, 045004 (2005).

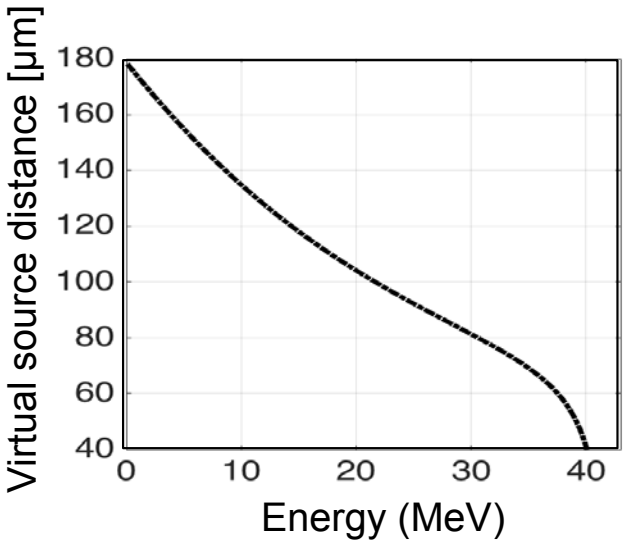
The TITAN laser and its proton parameters











1. Improvement of a laser-driven proton beamline (high-repetition rate targetry system – implementation of QP)

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SCIENTIFIC REPORTS

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Design and optimization of a compact laser-driven proton beamline

Received: 13 November 2017
Accepted: 19 March 2018
Published online: 19 April 2018

M. Scisciò[1,2], M. Migliorati[1], L. Palumbo[1] & P. Antici[2]

Laser-accelerated protons, generated by irradiating a solid target with a short, energetic laser pulse at high intensity ($I > 10^{18} W \cdot cm^{-2}$), represent a complementary if not outperforming source compared to conventional accelerators, due to their intrinsic features, such as high beam charge and short

Laser and Particle Beams

cambridge.org/lpb

Design and optimization of a laser-PIXE beamline for material science applications

A. Morabito[1,2], M. Scisciò[2,3], S. Veltri[4], M. Migliorati[2] and P. Antici[5]

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Research Article

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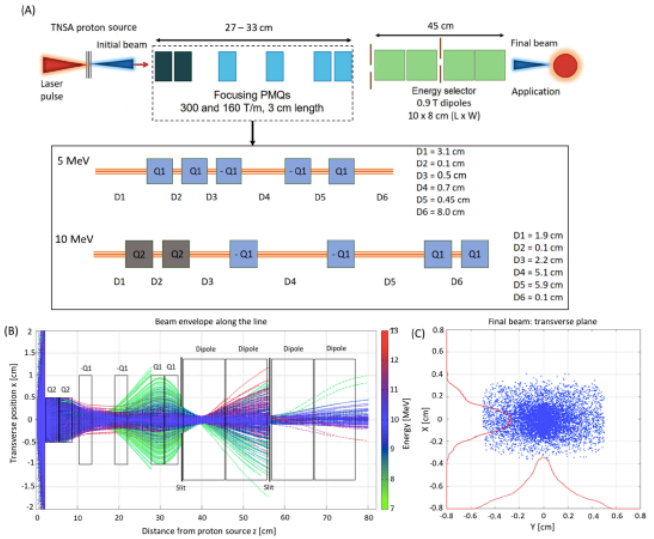
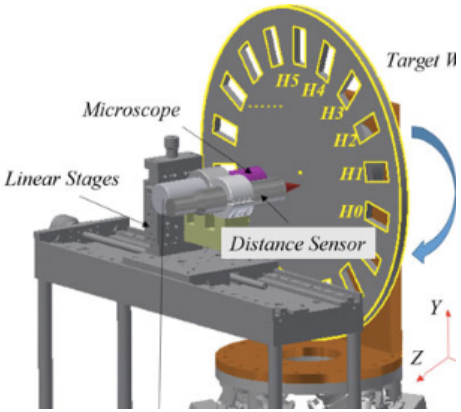
Received: 11 June 2019
Revised: 1 August 2019
Accepted: 6 August 2019

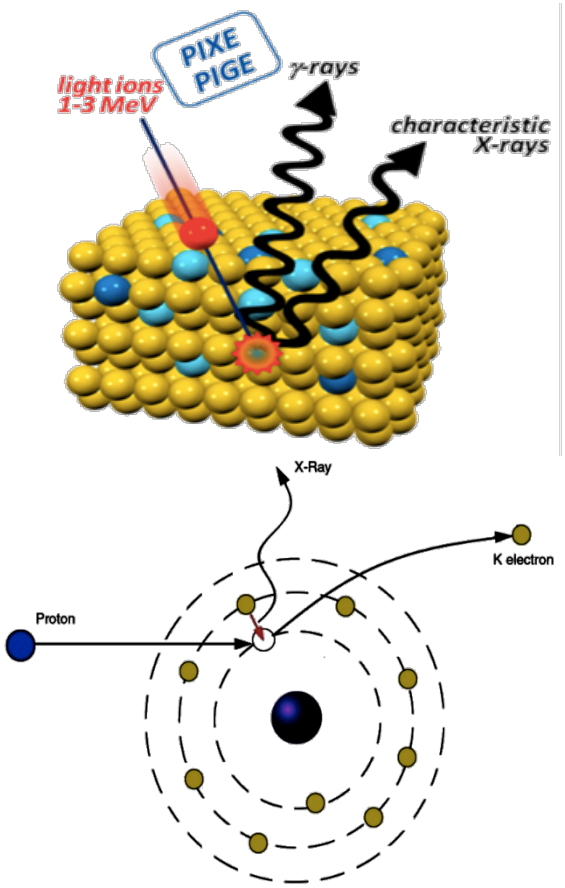
Abstract

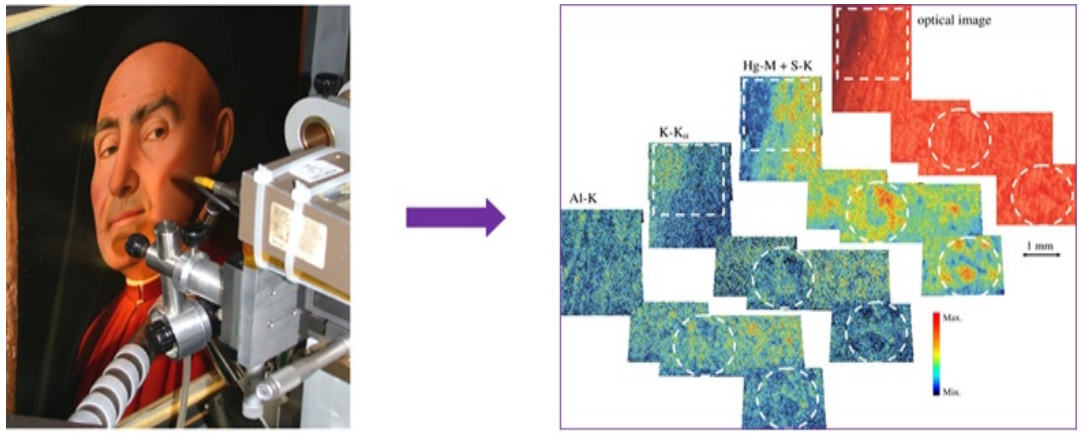
Multi-MeV proton beams can be generated by irradiating thin solid foils with ultra-intense (>10^{18} W/cm^2) short laser pulses. Several of their characteristics, such as high bunch charge and short pulse duration, make them a complementary alternative to conventional radio frequency-based accelerators. A potential material science application is the chemical analysis



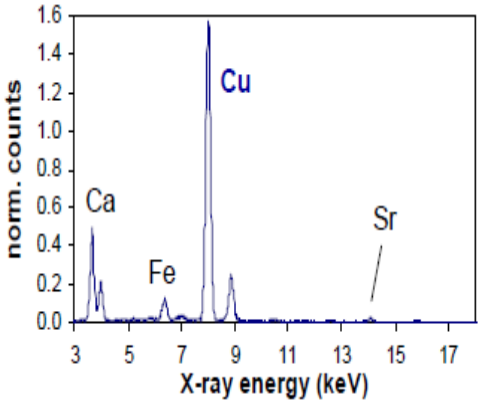


2. Laser-PIXE for Cultural Heritage





Example of PIXE to analyze the pigment's composition of The Trivulzio portrait by Antonello da Messina



2. Laser-PIXE for Cultural Heritage

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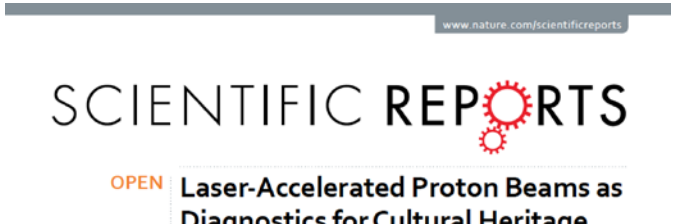
Une statuette en bronze du forum de Bavay analysée avec Aglaé.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SCIENTIFIC REPORTS
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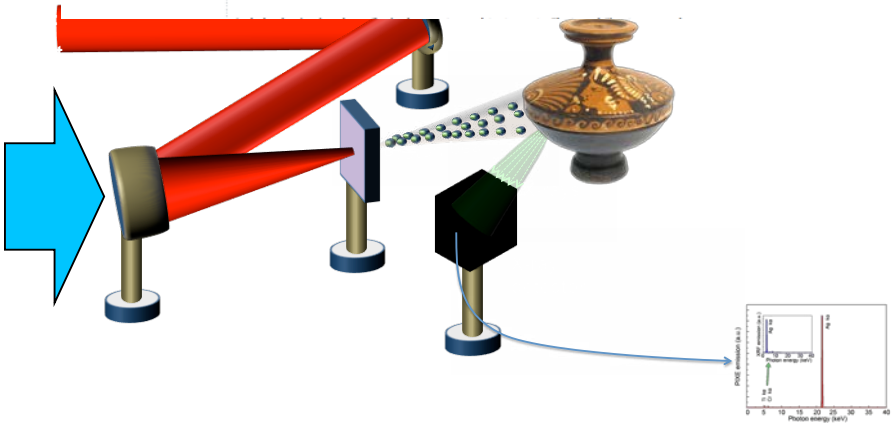
Laser-Accelerated Proton Beams as Diagnostics for Cultural Heritage

M. Barberio[1,2], S. Veltri[1], M. Scisció[1,3] & P. Antici[1,3]

Received: 21 October 2015
Accepted: 07 December 2016
Published: 01 March 2017

This paper introduces the first use of laser-generated proton beams as diagnostic for materials of interest in the domain of Cultural Heritage. Using laser-accelerated protons, as generated by interaction of a high-power short-pulse laser with a solid target, we can produce proton-induced X-ray emission spectroscopies (PIXE). By correctly tuning the proton flux on the sample, we are able to perform the PIXE in a single shot without provoking more damage to the sample than conventional methodologies. We verify this by experimentally irradiating materials of interest in the Cultural Heritage with laser-accelerated protons and measuring the PIXE emission. The morphological and chemical analysis of the sample before and after irradiation are compared in order to assess the damage provoked to the artifact. Montecarlo simulations confirm that the temperature in the sample stays safely below the melting point. Compared to conventional diagnostic methodologies, laser-driven PIXE has the advantage of being potentially quicker and more efficient.



Explore different materials / Limits of this tecnique / Damage ?

2. Laser-PIXE for Cultural Heritage
We are not alone !

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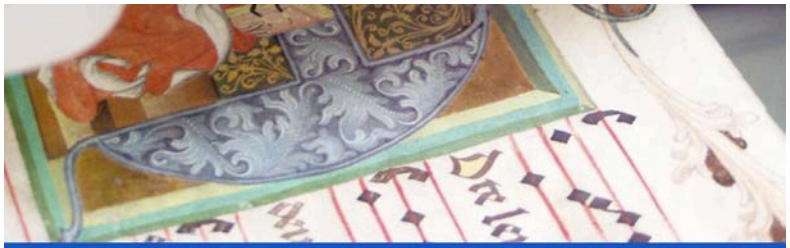

ELI Beamlines and its new project: Non-Destructive Laser-driven Heritage Testing

Institute of Physics of the Academy of Sciences of the Czech Republic / B
a new project called Non-Destructive Methods of Heritage Testing , fina
(Pól růstu ČR, the City of Prague). Researchers from ELI-Beamlines work
Acceleration by Laser, and currently commissioning the ELIMAIA user b
the project by the Institute of Nuclear Physics in Řež and Istituto Nazion
Nazionali del Sud (INFN LNS) in Catania. INFN ranks among the best in r
and restoration of monuments, but with a conventional particle acceler
protons will be worldwide unique for the combination of the planned a

Intense Laser Irradiation Laboratory

National Institute of Optics – National Council of Research

CNR INO
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Laser-PIXE

Laser driven Particle Induced X-ray Emission:
source development and X-ray spectral/spatial analysis

The PIXE (Particle Induced X-ray Emission) is a multi-elemental, quantitative, highly s
ments with concentrations in parts-per-million), rapid, non-invasive and non-destructive
to determine the composition of surface layers of a sample. The technique is based on s
characteristic X radiation emitted by each atom following irradiation with proton/ion bea
protons with MeV energies (2-3 MeV typically) that are currently produced with particle
dimensions (and costs) represent a limit for the application of the same technique outside o

ENSURE

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DIPARTIMENTO DI ENERGIA

Exploring the New Science and engineering unveiled by Ultraintense ultrashort Radiation interaction with mattEr

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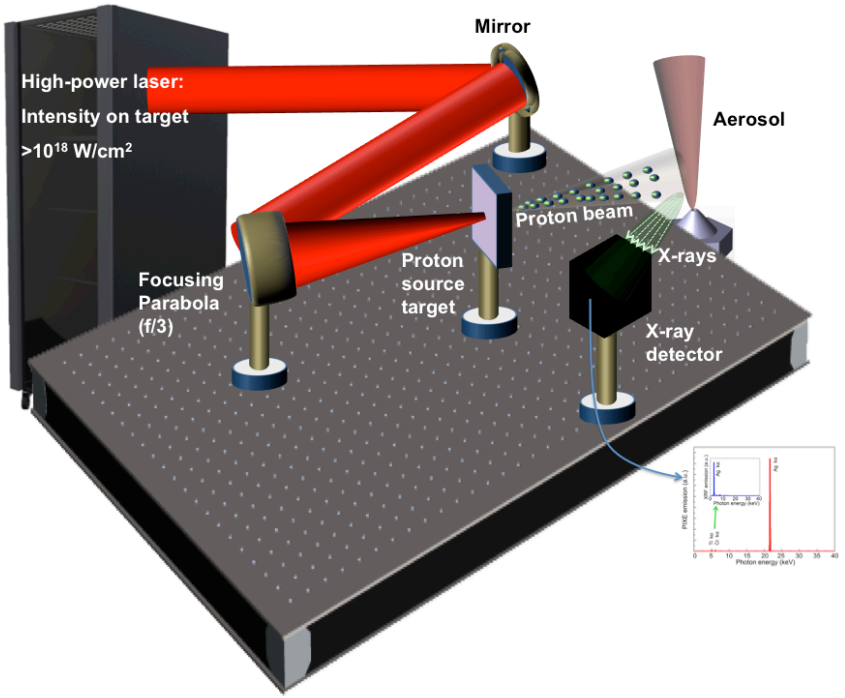
PEOPLE

CORE TEAM

PRINCIPAL INVESTIGATOR

Matteo Passoni

3. Laser-PIXE for Environment (Exhaust detection)



Nuclear Instruments and Methods in Physics Research B 363 (2015) 86–91

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

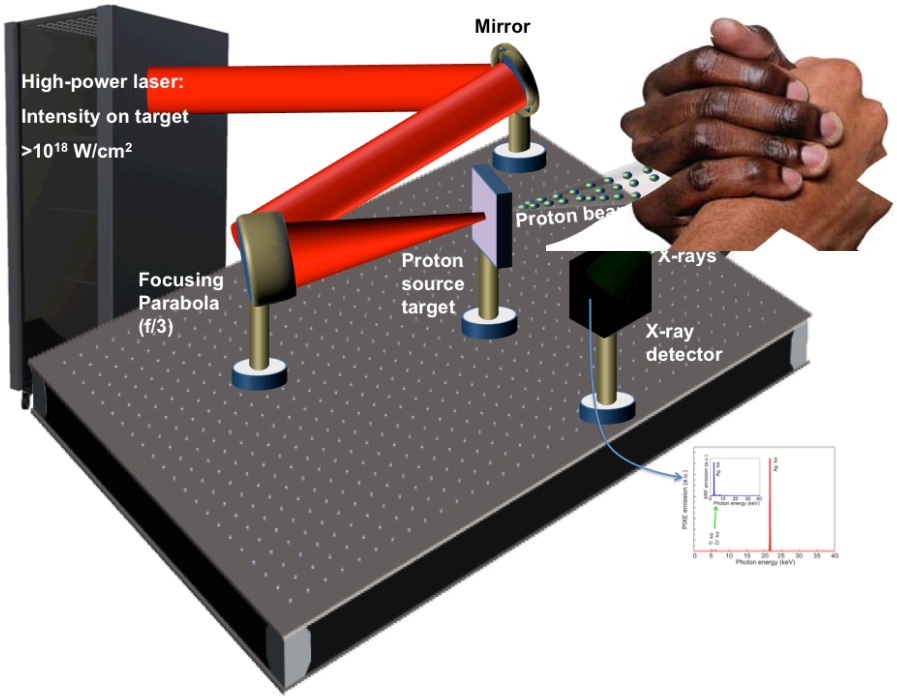
Present role of PIXE in atmospheric aerosol research

Willy Maenhaut *

Ghent University, Department of Analytical Chemistry, Krijgslaan 281, S12, BE-9000 Gent, Belgium
Department of Pharmaceutical Sciences, University of Antwerp (Campus Drie Eiken), Universiteitsplein 1, BE-2610 Antwerp, Belgium

Is laser-PIXE applicable for Exhaust-detection ?

4. Laser-PIXE for early cancer and Alzheimer detection



There is a correlation between the alteration of selected trace elements concentration in brain tissue and certain neurological diseases (Alzheimer's disease, Parkinson's disease, and brain tumors). Most attention has been given to Fe, Cu and Zn and their concentration in different parts of the brain.

5. Laser-accelerated proton for stress testing materials

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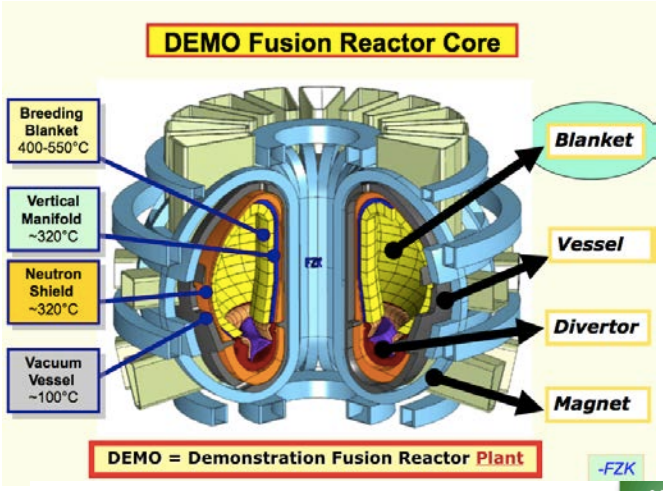
Materials that need to withstand highest energy flux are used in Nuclear Reactors, MCF, ICF: Plasma Facing Materials - Divertors



DEMO must integrate, demonstrate and validate all relevant technology (I)

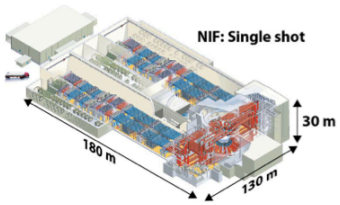
- DEMO construction Materials must be robust against 14 MeV neutron damage.
  - Mechanical, thermal and structural quantities must show minimum change with high radiation dose.
  - Plasma facing materials must additionally resist erosion and sputtering and be compatible with high plasma performance.
  - Divertor materials must further be capable to take high-heat-flux and be compatible with joining to substructures with high flow active coolant capabilities.

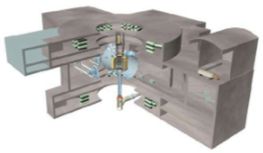
UKAEA Fusion

18
D Stork : 3rd Karlsruhe Intl School on Fusion Technology – Sept 2009

LIFE

Experience with NIF, and evidence from the ignition campaign, are being used to define a path for LIFE

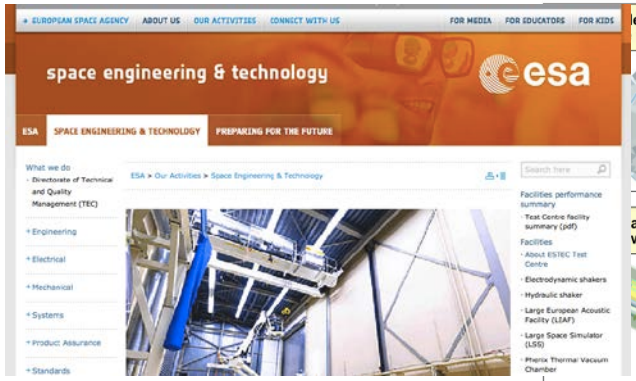


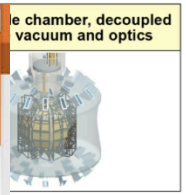


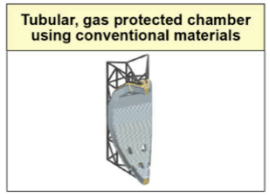
Similar:
- Physical size
- Laser energy
- Target performance
- Concept of operations (LRUs, ...)

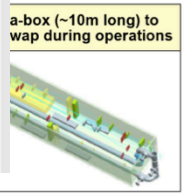
LIFE

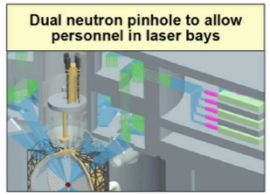
A new approach is required to meet the Primary Criteria set for robust power production











6. Laser-accelerated proton for stress testing materials

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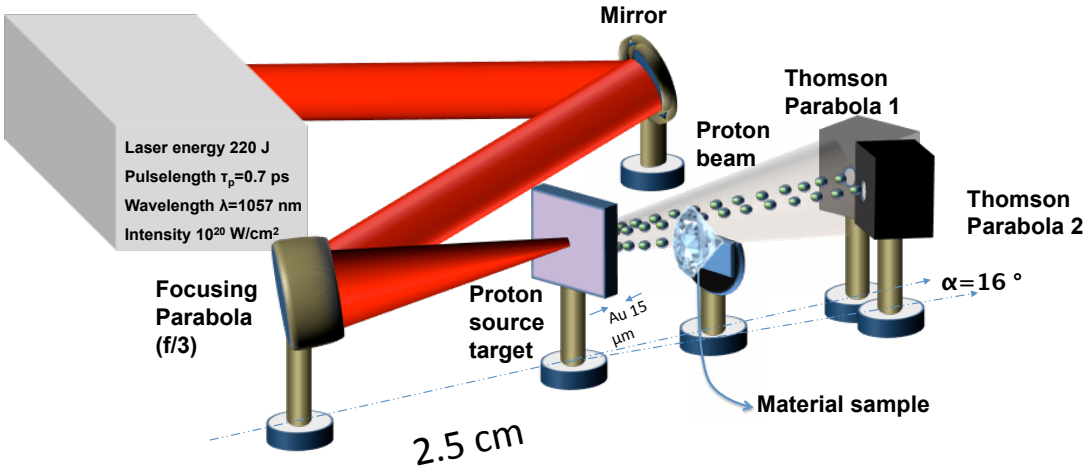
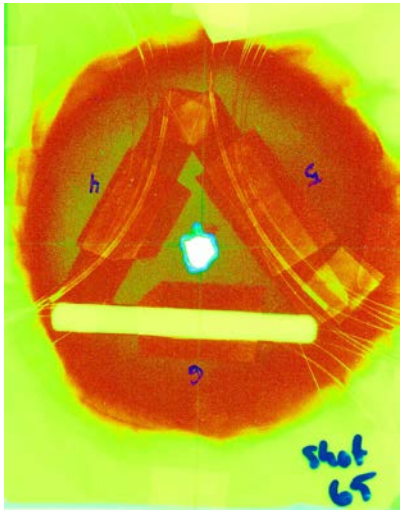


ARTICLE

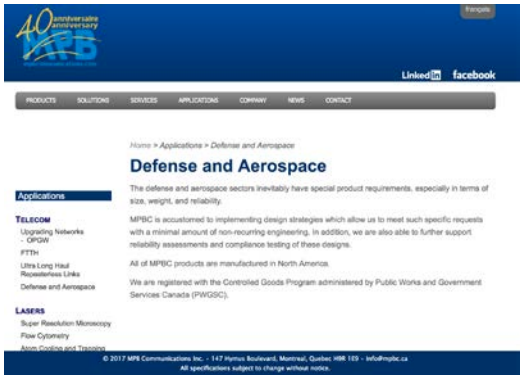
DOI: 10.1038/s41467-017-02675-z OPEN

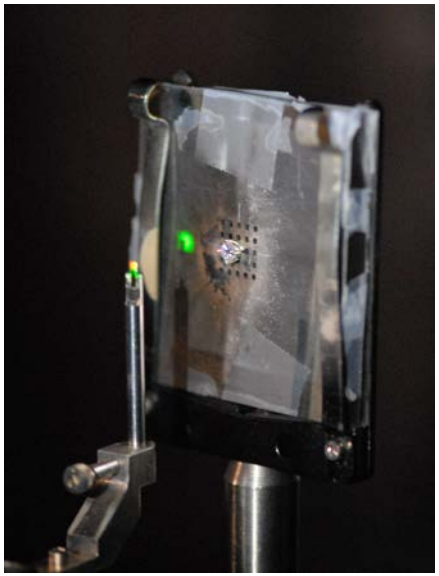
Laser-accelerated particle beams for stress testing of materials

M. Barberio[1], M. Scisciò[1,2], S. Vallières[1], F. Cardelli[1,2], S.N. Chen[3,4], G. Famulari[5], T. Gangolf[3], G. Revet[3,4], A. Schiavi[2], M. Senzacqua[2] & P. Antici[1]

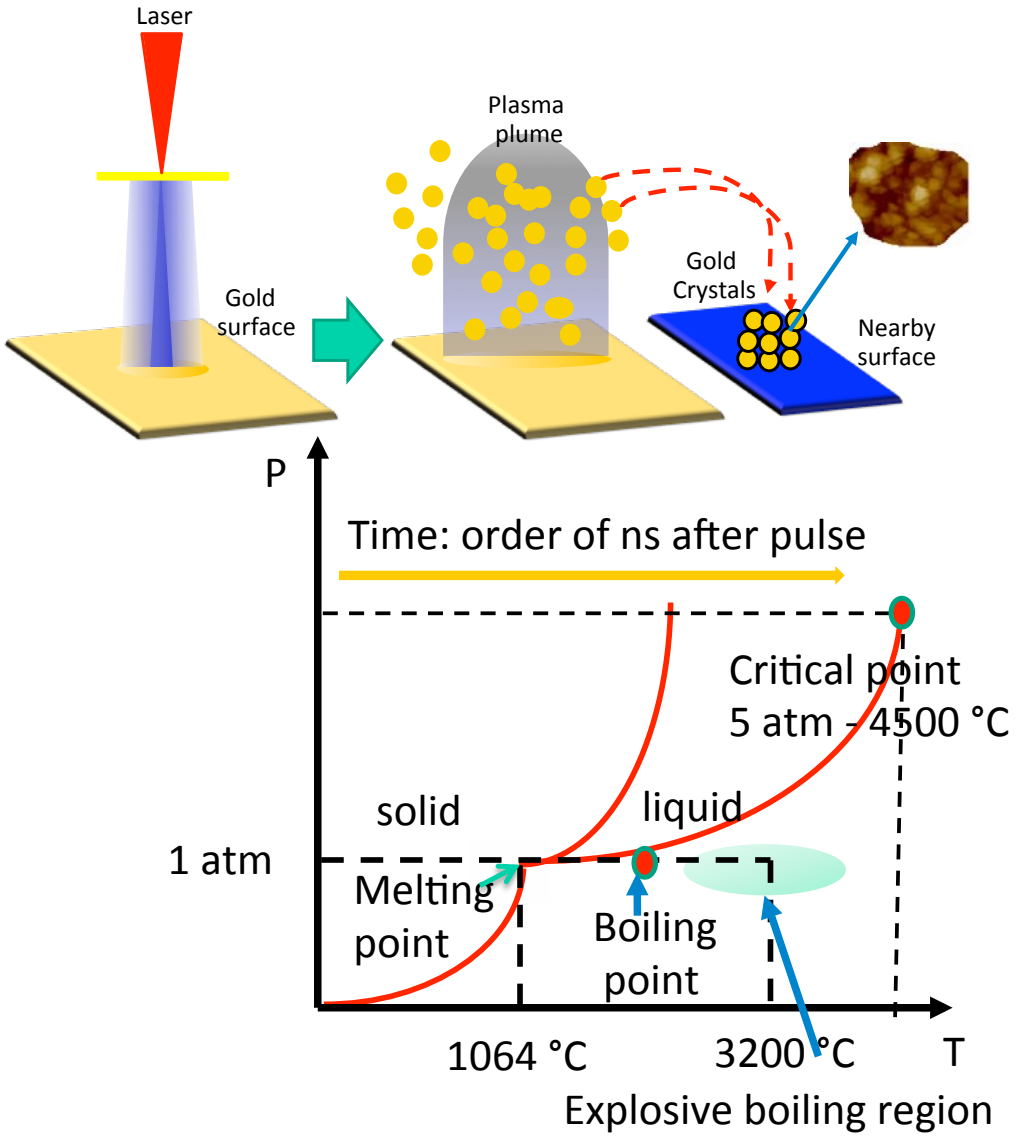


Test stress test on different materials and see linear stress testing effect.





7. High-precision Nanoparticle generation



Proton irradiation

Temperature increases above boiling point in sub-ns timescale

«Explosive boiling» with formation of plasma plume

Aggregation of microparticles in plasma plume and formation of supersonic jet

Deposition of particle on close surfaces

Tunable Nanoparticle source

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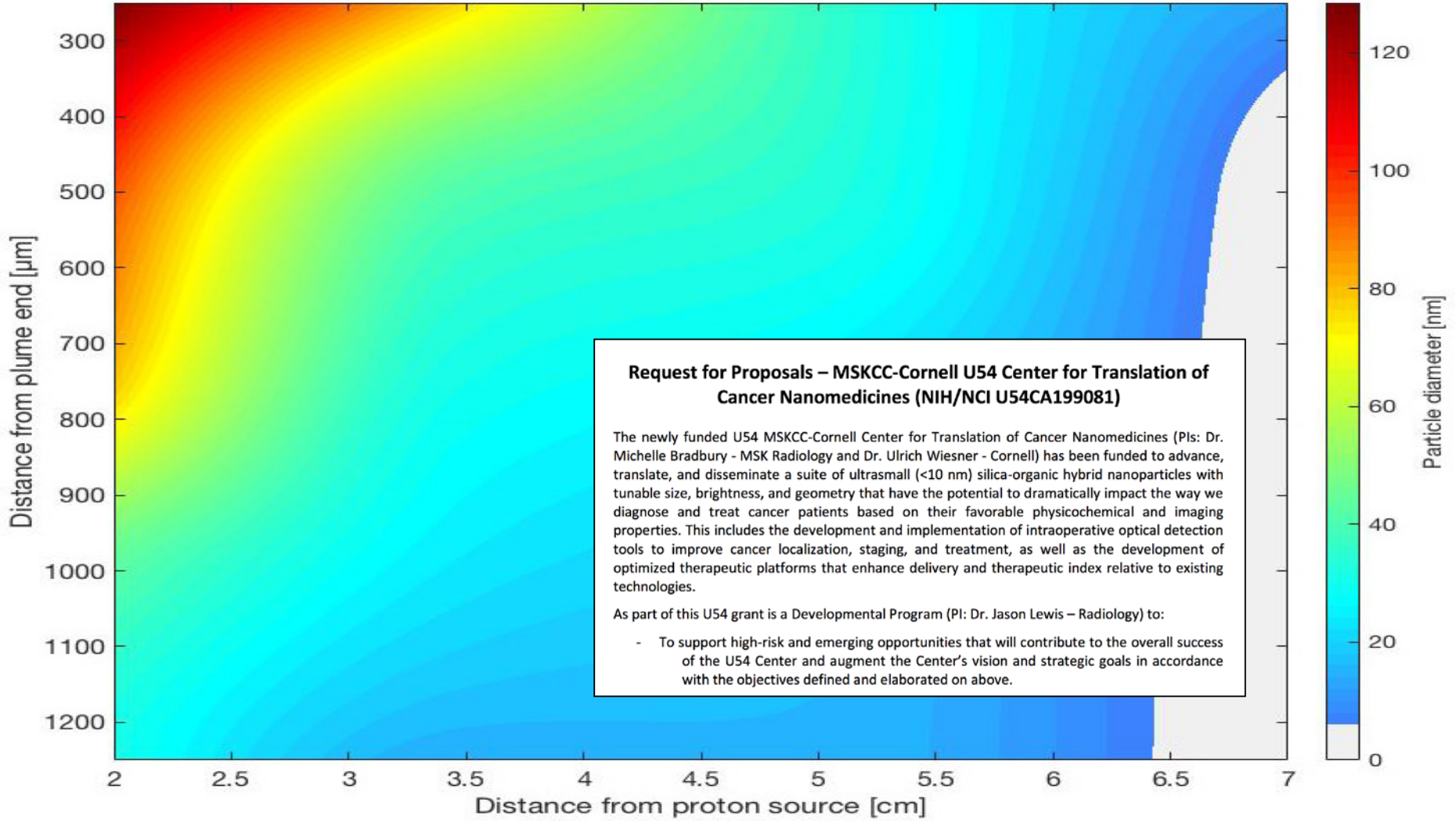

M. Barberio et al., in discussion with Nat. Comm.

These are some teams

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LLNL @ San Francisco

LULI @ Paris

ALLS @ Montréal

FORTH @ Crete

Advantages / Disadvantages of a joint PhD

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- International exposure (network)
- Multidisciplinary
- Multitasking (theory/ experiment)
- Salary is doubled (!)
- High productivity and flexibility
- Independent working

-> Good Job insertion

- Flexibility in travels and working time
- Good language skills
- Result oriented
- Able to work independently
- Fast decision making, fast acting

What is INRS ? We are located in (and near) Montréal, center EMT (Energy-Materials-Telecommunications)

INRS
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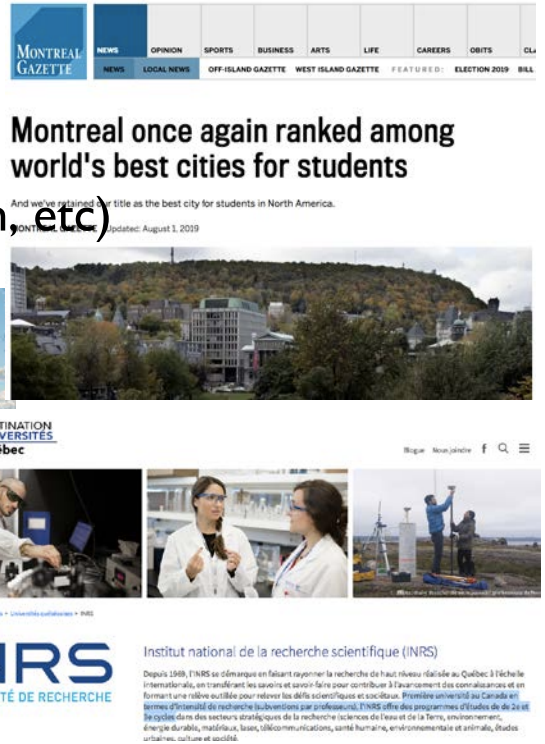
- Excellence center (only graduate) - among best centers in North America (2019)
- Multidisciplinary center (40 professors, each in different field)
- Internationally oriented (1/5 are Italians)
- High flexibility and productivity
- Montréal among word's best cities for students (2019)
- Strongest links with INFN and U.Sapienza
- Easy accessible (many low cost flights – near NY, Boston, etc)



We publish… have fun...
and they talk about us…

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M. Barberio, S. Giusepponi, *S. Vallières, M. Scisció,* M. Celino, *P. Antici*
Ultra-Fast Metallic Nanoparticle Synthesis using Laser-Accelerated Protons
Scientific Reports, in press

C. Bienvenue, S. Vallières, S. Payeur, and P. Antici
Fast Submicrometric Absolute Positioning of Flat Reflective Surface by Monochromatic Interferometry
Review of Scientific Instruments, in press

S. Vallières, M. Barberio, M. Scisció, E. d'Humieres, and P. Antici
Enhanced laser-driven proton acceleration using ultrasmall nanoparticles
Physical Review Accelerators and Beams 22, 091303 (2019)

A. Morabito, M. Scisció, S.Veltri, M. Migliorati, P. Antici
Design and optimization of a dedicated laser driven hybrid proton beam-line for cultural heritage applications
Laser and Particle Beams, https://doi.org/10.1017/S0263034619000600

S. Vallières, C. Bienvenue, P. Puyuelo-Valdes, M. Salvadori, E. d'Humières, F. Schiettekatte, and P. Antici
Low-energy proton calibration and energy-dependence linearization of E
Review of Scientific Instruments **90**, 083301 (2019)

M. Barberio, E. Skantzakis, P. Antici,
Material analysis using laser-plasma driven luminescence spectroscopy
Journal of Luminescence **214**, 116603 (2019)

M. Barberio, E. Skantzakis, S. Sorieul, P. Antici
Pigment darkening as case study of In-Air Plasma Induced Luminescenc
Science Advances **5**, 6, eaar6228 DOI: 10.1126/sciadv.aar6228 (2019)

M. Barberio, P. Antici
Laser-PIXE using laser-accelerated proton beams
Scientific Reports **9**, 6855 (2019)

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ULTIME NOTIZIE 27/10/2019 - 19:45 : DIFESA: DELEGAZIONE BRASILIANA VISITA I REPARTI DELLA BRIGATA INFORMAZIONI TATTICHE

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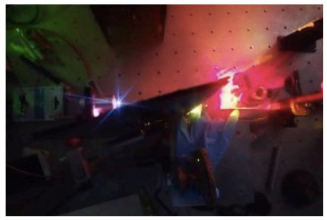
ITALIA-QUÉBEC: LA COOPERAZIONE VA SU SCIENCE



- Nell'ambito del **Programma esecutivo di cooperazione culturale, scientifica ra Italia e Québec** per il periodo 2017-2019, un'innovativa **ricerca** nel campo **applicate alla tutela del patrimonio culturale**, guidata dal professore **Patrizio** italiano in forza all'**Institut National de la Recherche Scientifique (INRS)** del nuto la pubblicazione sulla prestigiosa rivista **Science Advances**.
ai suoi collaboratori e a un gruppo di ricerca internazionale, che vede coinvolta tà della Calabria, l'acceleratore di particelle francese AIFIRA ed il laboratorio ha sviluppato un nuovo strumento diagnostico per esaminare lo stato di delle opere pittoriche: il metodo di ricerca impiega la tecnologia laser per spiegare i pigmenti di alcune opere pittoriche, tra cui i celebri Girasoli di Van Gogh, abbiano entezza originaria nel corso del tempo, diventando via via più scuri.
gneria presso la Sapienza Università di Roma, con dottorato in fisica presso nique in Francia e dottorato in ingegneria presso la Sapienza, Antici spiega che ogia, che prende il nome di In-Air PIL (dall'inglese In Air Plasma-Induced può essere usata non solo per analizzare lo stato di conservazione delle opere , ma anche per appurarne l'autenticità, la composizione e la provenienza. L'In-Air ratica ed economica del sistema diagnostico più efficace maggiormente in uso nel nservazione, il PIXE (Particle-Induced X-ray Emission), pertanto si configura come nativa presto commercializzabile, con potenzialità che non riguardano unicamente la preservazione del patrimonio artistico, ma coinvolgono anche altri nze dei materiali".

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Home / australia / Powerful lasers for fragile works of art

POWERFUL LASERS FOR FRAGILE WORKS OF ART

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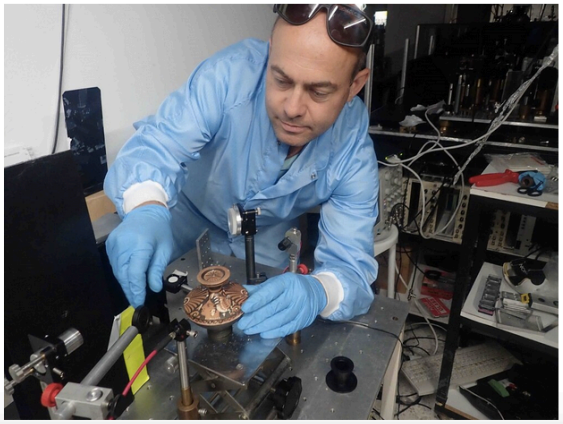

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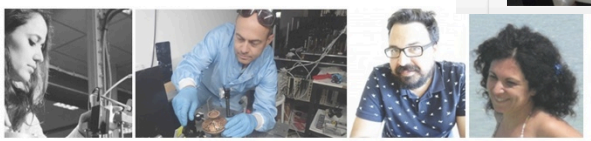
Teknik Laser Untuk Diagnosa & Analisa K Seni Rapuh

(STAGING-POINT.COM, 2019/06/14) In Jurnal IPTEK



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Italia-Québec, la cooperazione va su "Science Advances"

Data 11/10/2017

Nell'ambito del **Programma esecutivo di cooperazione culturale, scientifica e tecnologica tra Italia e Québec** per il periodo 2017-2019, un'innovativa ricerca nel campo delle tecnologie applicate alla tutela del patrimonio culturale, guidata dal professore **Patrizio Antici**, studioso italiano in forza all'**Institut National de la Recherche Scientifique (INRS) del Québec**, ha ottenuto la pubblicazione sulla prestigiosa rivista "*Science Advances*".

Antici, assieme ai suoi collaboratori e a un gruppo di ricerca internazionale, che vede coinvolta anche l'Università della Calabria, l'acceleratore di particelle francese AIFIRA ed il laboratorio Greco FORTH, ha sviluppato un nuovo strumento diagnostico per esaminare lo stato di conservazione delle opere pittoriche: il metodo di ricerca impiega la tecnologia laser per spiegare come mai alcuni pigmenti di alcune opere pittoriche, tra cui i celebri Girasoli di Van Gogh, abbiano perso la loro lucentezza originaria nel corso del tempo, diventando via via più scuri.

Antici - laureato in ingegneria presso la Sapienza Università di Roma, con dottorato in fisica presso l'Ecole Polytechnique (Francia) e dottorato in ingegneria presso la Sapienza spiega: "La nuova

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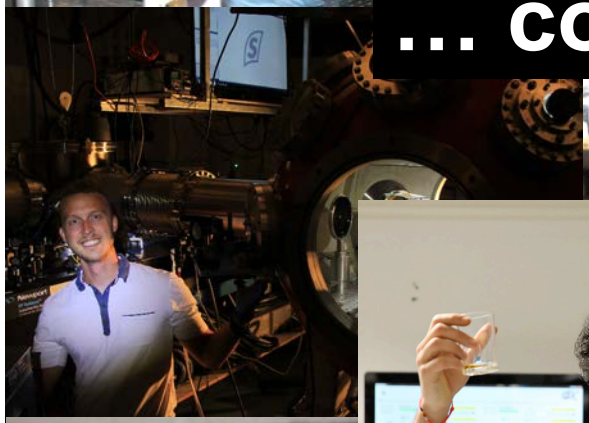
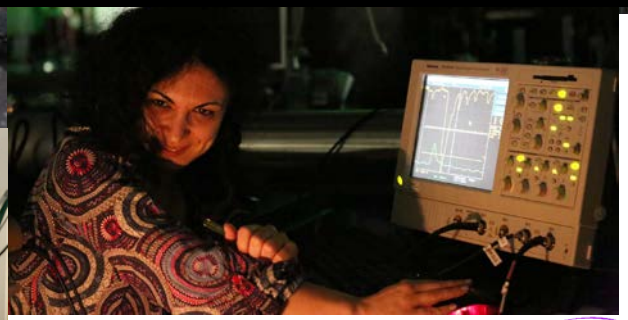
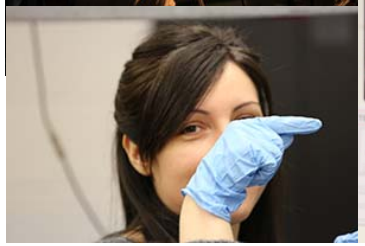
… collaborate or join us !



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