



Laser and Particle Guiding in Plasmas at I-LUCE (INFN Laser indUCEd radiation production)

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Outline

High power lasers and radiation production

Protons and electrons acceleration: status and perspectives

The upcoming INFN I-LUCE high-power laser facility

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The laser: femtosecond and power explained INFN

100

pulse

pulse



POWER =
$$\frac{\text{ENERGY}}{\text{TIME}}$$
 [W = J/s] Surface= 4 μ m²

Power pressure = $10^{15}/10^{-8}$ cm² = 10^{23} W/cm²



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Laser plasma ion-acceleration *current facilities*





VULCAN, RAL (UK) Phelix, GSI (De) Texas PW (US)

Emax~ 100 MeV

ATON-L4 (ELI Beamlines) 10 PW (1.5kJ/150fs)

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Imax~ 10²¹ W/cm²



GEMINI, RAL (UK) Draco, HZDR (De) Pulser I, APRI (Kr) J-Karen, JAEA (J)

HAPLS-L3, (ELI Beamlines) **1 PW** (30J/30fs/**10Hz**)

E_{max}~ 70-110 MeV

2020 world lasers facilities



HZDR MBILLC ELI-CZ PALS 2020 Ultrahigh Intensity Laser Facilities 102 facilities (approx > 1TW) IOE FSU Not looking to the specific NII-OEP HU IPPLM HHU application LC LLANS SCAPA WILL QUB ICL UNeb UMich CSU UCD OSU UAIb JIHT JAP XCELS INCE OXED CoReLS UNev τυ KAERI BAL Dok RIKEN AWE LBNL PNLI VNIEF VNIITF UEC GSI KOALS LULI UTok LLNL-NIF APOLL CREIPI LFRC SLIC LLNL-JLF τAU UDel CLUPS GPI CAEP LOA WIS SLAC KvoU USC NRI SWJTU HUJ UCLA COLA KPS CREOL UCI L2I BARC ILE AFRL SIOM SNL UTex CLPU TIFR TIFR-H Osakall SJTU CESTA RRCAT SACLA NCU SULF SEL GAP-Bio ELI-NP UMed INFLPR PMil USze MPQ LNF LMU ELI-HU nal Committee on Ultrahigh Intensity Lase Beijing Edmonton Dublin Irvine Lovine Nework Bikyo Colligo Park Marsolilos Ann Antor Lincoln Reno Santiago Sant Pok PME PUU PU GUB INL RIKEN RIKEN SCAPA SEL SCAPA SEL SCAPA SLUF SWUT THER Paking Maan Moscow Princeton Beitast Didoot To kyo Indore Sayo Glasgow Shanghai Shanghai Shanghai Shanghai Shanghai Shanghai Shanghai Diacot Shanghai Shangh Cerosge Hamanatas Demotait Jena Denote Jena Deni Efeban Jenaalen Desiden Nichny Novg London D mak D ma Liabon Barkolay Warsaw Maryang Amsterdan Land Rochaster Uvermore Uvermore Uvermore Uvermore Dirochan Prazati Palaiseau Palaiseau Berlin Garching Taroyan CP Cocrossail GPI GRI HHJ HLASE HLU HCR HCL HCE LLL INFLRR KOE INFLRR KOE INFLRR KOE INFLRR KOE INFLRR KOE Dayton Vareenos Saclay Adeemaator Marebai Upton Maryang Bordeax Le Barp Balarmena Pata Gasngju Yokoska Orlande Pert Collina Basgad Doini Bredany Magurele

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From ICUIL (International Committee on Ultra-High Intensity Lasers) https://www.icuil.org/

Targets: for ions, electrons, gamma, ...







So far LPAs have demonstrated the production of high-quality electron beams with HEPrelevant parameters, such as relative energy spreads as low as ~ 1% [31, 32], normalized emittances of ~ 0.1 μ m [33, 34], and high charge (100s of pC) [35, 36],



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

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Featured in Physics



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Editors' Suggestion

Electrons acceleration





Courtesy of Massimo Ferrario, INFN-LNF



Let's concentrate on ion acceleration

Laser plasma ion-acceleration principal motivation







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Laser plasma ion-acceleration *physical picture*

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Target Normal Sheath Acceleration



REVIEW PAPERS:

- Macchi, Borghesi, Passoni, Rev. Mod. Phys. 85 (2013) 751
- Borghesi et al, Springer Proc. Phys. 231 (2019) 143



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Direct Laser interaction:

- + E ~ $I_L{}^{1/2}\lambda = 10^{14}~V/m$
- B = E/c = 3x10⁵ T
- •P_{rad} = I_L/c = 3x10¹⁰ J/cm³ = 300 Gbar

Laser-Plasma interaction:

- Debye Length $\lambda_D = 2.4 \mu m \cdot \sqrt{\frac{T_{hot}}{1MeV}} \cdot \sqrt{\frac{10^{19} cm^{-3}}{N_{hot}}} \implies ~ \mu m!$
- · Acceleration time

$$\tau = \sqrt{\frac{\lambda_D^2 m_{ion}}{T_{hot}}} = 0.24 \, ps \sqrt{\frac{\lambda_D^2 n_{hot}}{10^{19}}} \qquad \Longrightarrow \qquad \mathbf{\sim ps}$$

· Electric Field

$$\mathsf{E} = \frac{\tau_{hot}}{e\lambda_D} \approx \frac{MV}{\mu m} \qquad \longrightarrow \qquad \mathbf{\sim TV/m!}$$

Energy Gain: 100 MeV/um (in a plasma medium)!!!

Characteristics of the laser-driven protons

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Energy spectra

Boltzman-like (from zero to a given cut-off) 100% energy spread for a pure-TNSA Selection procedures are adopted

Angular divergency

30°/40° degree (FWHM)

Temporal features

10⁸ - 10⁹ selected 20 ns - 200 ns bunches 1 Hz - 10 Hz -





250 TW laser





Maximum proton energy experimental scaling laws (TNSA)



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The scaling of proton energies in ultrashort pulse laser plasma acceleration K Zeil et al 2010 New J. Phys. 12 045015

Laser-driven ion acceleration mechanisms

Mun LUCE stituto Nazionale di Fisica Nuclea

laser intensity vs target density

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Energy world record

nature physics

https://doi.org/10.1038/s41567-024-02505-0

Article

Laser-driven high-energy proton beams from cascaded acceleration regimes



TPS15

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2024



DRACO-PW laser systemem (Dresden, D)

Intensity = $\sim 6.5E21Wcm^{-2}$ Pulses of p-polarised, 1.053 µm-wavelength Pulse duration $\tau = 30$ fs Energy after the plasma mirror: 22.4 J

Target: thin planar plastic foil with thickness 250 nm



Hybrid TNSA and RPA mechanisms

- Hole-boring RPA
- Relativistic transparency front RPA
- Collisionless shock acceleration



I-LUCE at INFN-LNS

INFN Laser indUCEd radiation production





I-LUCE first phase

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Two interaction chambers

- 1) Interaction Chamber n.1: Radiation production (protons/ions, electrons, neutrons, gamma, etc.)
 - One in-air irradiation station for multidisciplinary studies

2) Interaction Chamber n.2: Warm Dense Matter studies (WDM)

- Nuclear physics in plasma
- Interaction of conventional ion beams with laser-generated plasma
- Nuclear physics fusion studies in plasma
-

Two working modalities

- 1) Low power: 50 TW/23fs/10Hz
- 2) High power: 350 TW/23fs/1Hz



Low power modality: 45 TW



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	Laser Power		≥ 50 TW
	Energy per pulse		≥1J
	Pulse duration		≤ 23 fs
	Focusing surface		36 μm²
	Max power density (at the target)		1.21·10 ²⁰
	Ι*λ2		7.72·10 ¹⁹
	Contrast ratio @100 ps (ASE)		> 10 ¹⁰
	Repetition rate		≥ 10 Hz
		Max energy	4 MeV
	Protons lons	Particle per pulse (at 2 MeV)	10 ¹¹ MeV ⁻¹ Sr ⁻¹
		Enormy enroad	100%
			100%
		Beam divergency (max)	±20°
		Max energy	0.1 GeV
	Eletrons	Particles per pulse	10 ⁹
		Beam divergency (max)	± 20 mad
		Max energy	TBD
	Noutrons	Particles per pulse	
	neutrons	Energy spread	
		Beam divergency	
		Synchrotron radiation of the electrons inside the plasma or breemsstrahlung	
	Gamma X-beams	Energy	up to 20 MeV
Deble Cirrer 5		Beam divergency	Directionality in the beam propabgation direction
rapio Cirrone, F	no - paolo.cinoneen	15.111111.10	

Fusion studies, nuclear studies, radioisotopes production,

.

Acting on the compression procedure, the pulse duration can be increased up to 1/10 ps: ==> 2.78 10^{18} W/cm² 2.78 10^{17} W/cm² ==> $i\mathcal{A}^2 = 1.77 \cdot 10^{18}$ $i\mathcal{A}^2 = 1.77 \cdot 10^{17}$

Longer plasma expansion times:

- Decay studies
- Stopping powers studies
- WDM characterisation

Power densities can be improved reducing the focusing spot: — shorter focusing parabola — but issues related to the: target dearee. back reflection. ...

High-power modality: 320 TW



Laser Power		350 TW
Energy per puls	e	>7 J
Pulse duration		≤ 25 fs
Focusing surfac	e	$36\mu m^2$ or better
Max power den	sity (at the target)	8.82·10 ²⁰
I* λ ²		5.64·10 ²⁰
Contrast ratio @	> 10 ¹⁰	
Repetition rate		1 Hz
	Max energy	50 MeV
Protons lons	Particle per pulse (at 30 MeV)	10 ¹¹ MeV ⁻¹ Sr ⁻¹
	Energy spread	100%
	Beam divergency (max)	±20°
	Max energy	3 GeV
Eletrons	Particles per pulse	10 ⁹
	Beam divergency (max)	± 20 mad
	Max energy	20 MeV
Neutrons	Particles per pulse	10 ¹⁰
Neutrons	Energy spread	100
Beam divergency		Isotropic
	Synchrotron radiation of the electrons inside the plasma or breemsstrahlung	
Gamma X- beams	Energy	up to 80 MeV
	Beam divergency	Directionality in th beam ropabgation direction

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



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)



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



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



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Protons acceleration up to 15 MeV with solid target (up to 50 MeV)

Electrons acceleration up to 300 MeV with capillary and gas-jet system

Neutron beam

Irradiations stations for both protons and electrons for medical and multidisciplinary applications

Radiobiology

FLASH radiotherapy applications

Material science

Interaction of conventional ion beams with laser-generated plasmas

Physics cases





Posítrons generation



Nuclear reaction schemes



Protons and electrons generation

Chapter 6.2 Laser applications

Regular Article	
	Check
Nuclear physics midterm plan at LNS	spon
C. Agodi ¹ , F. Cappuzzello ^{1,2} , G. Cardella ³ , G. A. P. Cirrone ¹ , E. De	e Filippo ³ , A. Di Pietro ¹ , A. Gargano ⁴ ,
G. G. Rapisarda ^{1,2,b} , M. L. Sergi ^{1,2} , S. Tudisco ¹ , J. J. Valiente-Dob	ón ⁷ . F. Vardaci ^{4,8} . H. Abramczyk ⁹ . L. Acosta ¹⁰ .
P. Adsley ¹¹ , S. Amaducci ¹ , T. Banerjee ⁴ , D. Batani ¹² , J. Bellone ^{1,2} ,	C. Bertulani ^{11,13} , S. Biri ¹⁴ , A. Bogachev ¹⁵ ,
A. Bonanno ^{1,16} , A. Bonasera ^{1,11} , C. Borcea ¹⁷ , M. Borghesi ¹⁸ , S. Bo	rtolussi ^{19,20} , D. Boscolo ¹⁴ , G. A. Brischetto ^{1,2} ,
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P. Russotto ¹ , V. Saiko ¹⁵ , D. Santonocito ¹ , E. Santopinto ⁶⁴ , G. Sarri	46, D. Sartirana ²⁵ , C. Schuy ¹⁴ , O. Sgouros ¹ ,
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Thanks for listening



The basic ingredients: an high-power, short-pulse laser



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ARTICLE

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Near-100 MeV protons via a laser-driven transparency-enhanced hybrid acceleration scheme

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C. Armstrong^{1,2}, J.S. Green², S.J. Hawkes^{1,2}, P. Martin³, W.Q. Wei⁴, S.R. Mirfayzi¹, X.H. Yuan⁴, S. Kar^{2,3},
M. Borghesi³, R.J. Clarke², D. Neely^{1,2} & P. McKenna¹

2018



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Vulcan laser at the Rutherford Appleton Laboratory (UK)

Intensity = $\sim 10^{20}$ Wcm⁻²

Pulses of p-polarised, 1.053 µm-wavelength

Pulse duration $\tau = (0.9 \pm 0.1)$ ps (FWHM) **Energy** after the plasma mirror: (210 ± 40) J

Target: thin planar plastic foil with thickness in the range 10 nm-1.5 um

Laser room implementation proposal and timeline

Control room and optical laboratory, December 2024

Laser and interaction areas July 2026

Laser system, November 2026

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THALES





I-LUCE current status



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Physics cases at I-LUCE

What we will have at disposal?



33

An high power laser: 8J/23fs/1Hz A plasma generated by the laser:

Temperature: 2 eV - 200 eV

Density: 10^{25} m⁻³ $n \approx \frac{I}{e^2 T}$ lon beams in a wide Z range $n \approx \frac{\varepsilon_0 m_e \omega_p^2}{e^2}$ n^{10^4} up to 70 AMeV



Medical and interdisciplinary applications



MDPI

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Use of ions/electrons beams for radiobiology studiesfor radioisotope production for hydrogen productionfor cultural heritage applications

... for inertial confinement studies



ELIMED/LIMAIA beamline th ELI-Beamlies facility (CZ)



uantum beam

Multidisciplinary Applications

ELIMAIA: A Laser-Driven Ion Accelerator for

Daniele Margarone^{1,*}, G. A. Pablo Cirrone^{1,2}, Giacomo Cuttone², Antonio Amico², Lucio Ando³, Marco Borghesi³, Stepan S. Bulanov⁴, Sergei V. Bulanov¹, Denis Chatain⁵, Antonin Fajstav¹, Lorenzo Giuffrida¹, Filip Grepl¹, Satyabrata Kar³, Josef Krasa¹, Daniel Krame¹, Giuseppina Larosa², Renata Lenza², Tadzio Levato¹, Mario Maggiore⁶,

cience

Nuclear astrophysics



THE COULOMB EXPLOSION PARADIGMA

The interaction of ultra-short laser pulses with an expanding gas mixture at controlled temperature and pressure inside a vacuum chamber causes the formation of **plasmas with multi-keV temperature**. These energies overlap with the typical temperatures of stellar environments **where thermonuclear reactions occur**, thus making this paradigm a <u>perfect scenario for</u> <u>nuclear astrophysics research</u>.



Example: deuterium-deuterium fusion $d + d \rightarrow {}^{3}\text{He}(0.82MeV) + n(2.45MeV)$

 $d + d \rightarrow p(3.02MeV) + t(1.01MeV)$

 $d + {}^{3}\text{H}e \rightarrow p(14.7MeV) + {}^{4}\text{H}e(3.6MeV)$



Step 1 Clusters are irradiated by high intensity laser pulse (~10¹⁶~10¹⁸ W/cm²).

Step 2

Laser pulse energy is first absorbed by electrons via heating mechanisms such as rapid collisional heating.

Step 3

Electrons escape from the cluster and leave positive charge build-up on the cluster.

Step 4

The cluster "explodes" and deuterons acquire multi-keV kinetic energy.



Pablo Cirrone, PhD - pablo.c.....

Nuclear astrophysics: dd fusion

Krauss et al. 1987

Greife et al. 1995

 10^{2}

Brown & Jarmie 1990

10



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S. Tarilles Pit Philip

 10^{2}

E_{c.m.} [keV]

 $d + d \rightarrow {}^{3}He + n$

 10^{3}

This method will open the way for a new approach to study nuclear astrophysics reactions such as: -deuterium- deuterium -deuterium-³He -proton-lithium -proton-boron $-^{12}C-^{12}C$ _16O_16O -and much more....
Stopping powers in plasma



Stopping power of ions in plasma is a process of fundamental importance in many applications:

- Inertial Confinement Fusion
- Astrophysics and Nuclear Astrophysics
- High-energy Density Physics
- Plasma strippers
- Solid State Physics

Characterization of ions stopping power in plasma at I-LUCE facility

Collaboration: C. Altana, G. Castro, S. Cavallaro, C. Ciampi, G.A.P. Cirrone, R. De Angelis, S. De Luca, G. Lanzalone, L. Malferrari, F. Odorici, L. Palladino, G. Pasquali, A. Russo, A. Trifirò and S. Tudisco

Partecipating INFN sections: Catania, LNS, LNGS, Bologna, Firenze

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Stopping powers in plasma





Nuclear physics mid-term plan



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Protons and electrons generation

Chapter 6.2 Laser applications

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Regular Article	
Nuclear physics midterm plan at LNS	updates
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Take-to-home message



New radiation beams, complementary to the existing ones

New basic physics and multidisciplinary studies (also complementary to other apparata in realisation, i.e PANDORA)

A new European facility with unique features

Pablo Cirrone, PhD - pablo.cirrone@lns.infn.it



Thanks for Listening



Laser-plama Ion acceleration: some physical quantities



I_L (Laser intensity) = 10^{21} W/cm²

Direct laser interaction

- E \sim IL^{1/2} λ = 10¹⁴ V/m
- B = E/c = 3*10⁵ T
- $P_{rad} = I_L/c = 3*10^{10} \text{ J/cm}^3 = 300 \text{ Gbar}$

Laser-plasma interaction

Debye Length:
$$\lambda_D = 2.4 \mu m \cdot \sqrt{\frac{T_{hot}}{1MeV}} \cdot \sqrt{\frac{10^{19} cm^{-3}}{N_{hot}}} \longrightarrow ~ \mu m!$$

Acceleration time: $\tau = \sqrt{\frac{\lambda_D^2 m_{ion}}{T_{hot}}} = 0.24 ps \sqrt{\frac{\lambda_D^2 n_{hot}}{10^{19}}} \longrightarrow ~ ps!$
Electric Field: $\tau = \frac{T_{hot}}{e\lambda_D} \approx \frac{MV}{\mu m} \longrightarrow ~ TV/m!$



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Concept of the "coherent acceleration"

The accelerating field on each particle is proportional to the number of particles being accelerated (Veksler, V., 1957, At. Energ. 2, 525.)

Use of intense laser pulses on a target

In this case the energy transferred to the target produce a **displacement of a large number of electrons**; this produce a strong **electric field able to accelerate ions** until the neutrality is again reached.



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Observation of fast ions in a laser plasma

Yu. A. Zakharenkov, O. N. Krokhin, G. V. Sklizkov, and A. S. Shikanov

P. N. Lebedev Physics Institute, USSR Academy of Sciences (Submitted March 18, 1977) Pis'ma Zh. Eksp. Teor. Fiz. 25, No. 9, 415–418 (5 May 1977)

Experiments on heating of spherical targets with the high-power "Kal'mar" laser installation revealed a group of fast ions with energy ≤ 0.5 MeV. The possible generation mechanisms are discussed.

PACS numbers: 52.50.Jm, 52.25.Lp

The appearance of a group of fast ions that carry away an appreciable fraction of the energy absorbed by the plasma has been reported repeatedly in recent years.^[1] These ions were registered with the aid of time-of-flight corpuscular methods having a small angular aperture and in which the plasma is investigated during the later stages of the dispersal.

In our experiment, using high-speed multiframe interferometry, ^[2] we observed generation of fast ions in a plasma produced with the 9-channel laser setup "Kal'mar" and by irradiating solid and hollow targets of glass (SiO₂) of ~100 μ diameter. At a light-beam diameter ~150 μ in the target region and at an energy $E_L \approx 150$ J, the flux density was $q \sim 10^{14}$ W/cm². ^[3]



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Before the year 2000

Many experiments observed MeV ion emission from laser with **thick solid**, gas-jet and sub micrometric cluster.

Common feature of these experiments:

- isotropic ion emission
- low brilliance

In 2000

Three different experiments independently observed high-intensity, **multi MeV** emission from the high-intensity laser interaction with micrometric-scale targets

- Particles on the back side of the target
- Much more collimated

Clark, E. L., et al., 2000a, Phys. Rev. Lett. 84, 670. Snavely, R. A., et al., 2000, Phys. Rev. Lett. 85, 2945.

Maksimchuk, A., S. Gu, K. Flippo, D. Umstadter, and V.Y. Bychenkov, 2000, Phys. Rev. Lett. 84, 4108.

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Proton Spectra Protons per MeV 10000 ntegral Joules Above E Proton spectrum from the rear side of a 100 (a) um solid target irradiated by a 423 J, 1000 0.5 ps pulse at normal incidence, 100 100 corresponding to an intensity 10 10 of 3*10²⁰ W/cm². The integrated energy of protons indicates a 1 (b) N* 10⁹ conversion efficiency of 10% for protons 0.1 0.1 above 10 MeV. 20 30 40 50 10 Proton Energy (MeV)

Snavely, R. A., et al., 2000, Phys. Rev. Lett. 85, 2945.

0			
	Laser intensity [W cm-2]	Number of protons	Max proton energy [MeV]
Maksimchuk et al., 2000	3*E18	> 1E9	1.5
Clark et al., 2000	5E+19	1E+12	18
Snavely et al., 2000	3E+20	2E+13	58



Emission of protons from metallic targets (not containing hydrogen) may sound surprising:

thin layer of water or hydrocarbons normally present on solids surface in standard conditions

With "long" nano-second laser protons/ions emissions were observed in the rear part of the target with a broad angular distribution)

This acceleration was interpreted in terms of acceleration during the expansion of the hot laserproduced plasma at the front laser irradiated side of the target



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Emission of protons from metallic targets (not containing hydrogen) may sound surprising:

thin layer of water or hydrocarbons normally present on solids surface in standard conditions

The characteristics of the forward proton emission in the new experiments, such as the **high degree of collimation** and laminarity of the beam, were much more impressive





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A debated started around 2000 related to the physics mechanisms of this observed acceleration

Some authors suggested that protons were accelerated on the front side of the target and then cross the target reaching the other surface

Other authors in contrast, provided evidence th Clark, E. L., et al., 2000a, Phys. Rev. Lett. 84, 670. accelerated at the rear side

These experiments were performed at the Lawrence Livermore Petawatt facility

The TNSA (Target Normal Sheet Acceleration) mechanism snavely, R. A., et al., 2000, Phys. Rev. Lett. 85, 2945.

Wilks, S. C. et al, 2001, Phys. Plasmas 8, 542.

TNSA



Briefly, TNSA is driven by the space-charge field generated at the rear surface of the target **by highly energetic electrons accelerated at the front surface**, <u>crossing the target bulk</u>, and attempting to escape in vacuum from the rear side.

Most of the experiments investigating proton acceleration by laser interaction with solid targets have been interpreted **in terms of the TNSA framework**

At present it is not guaranteed that the ion energy **scaling observed so far will be maintained** at such extreme intensities (E22 W/cm2, today) nor that TNSA will still be effective.



TNSA: a robust and experimentally wellestablished mechanism



Clark, PRL (2000); Maksimchuk, PRL (2000) Snavely, PRL (2000)



TNSA mechanism

- a) Typical Laser Intensity $(10^{18}-10^{20} \text{ W/cm}^2)$
- b) Accelerated Relativistic Electrons (multi MeV) traverse the thin target (0.1÷100 mm).
- c) H-ultrathin rear-side layer is ionized by the electron beam and protons are generated.
- d) Fast electron cloud builds up a quasielectrostatic field exceeding ~1 TV/m accelerating protons in the forward direction to multi-MeV energies.

TNSA features

- a) Protons/ions are accelerated along the target normal
- b) Ions with the highest charge-to-mass ratio (protons) dominate the acceleration, gaining the most energy (electric field screening effect)
- c) Exponential ion energy distribution (large energy spread)

TNSA scaling law





Behind TNSA

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Is not only the maximum proton energy an important parameter

It is also of crucial importance to establish the most relevant scaling parameters as well as to **improve or optimize beam emittance, brilliance, and monoenergeticity** for specific applications.

These issues motivate the search for other ion acceleration mechanisms

Radiation pressure acceleration

Collisionless shock acceleration

Break-out afterburner

Ion acceleration



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Ingredients

Solid target

High-power (TW/PW), short-pulse (20 fs - 500 fs) laser

- focused in a target $10^{19} 10^{22} \text{ W/cm}^2$
- The ponderomotive force and the relativistic transparency caused by the laser-matter interaction

What is a solid target?

A solid material where the electron density n_e greatly exceeds the so-called critical or cutoff density n_c

$$n_c = \frac{m_e \omega^2}{4\pi e^2} = 1.1 \cdot 10^{21} cm^{-3} (\frac{\lambda}{\mu m})^{-1}$$

Ion acceleration

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Plasma frequency

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_e}}$$

Laser frequency $\omega = \frac{2\pi c}{\lambda}$

Linear refractive index of the plasma

$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} = \sqrt{1 - \frac{n_e}{n_c}}$$



Ion acceleration



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Linear refractive index of the plasma

$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} = \sqrt{1 - \frac{n_e}{n_c}}$$

Bourdier, A., 2020, "Calculation of the refractive index for plane waves propagating in ionized gas" Results in Physics 18, 103250.

- when ne > nc we say that we are in an "overdense" condition. In this case n assumes an imaginary valued the laser cannot propagate in the medium (plasma mirroring)
- All the laser plasma interaction occurs in the case of "underdense" regions ne < nc or at the "near critical" region (ne ≃ nc)
- The condition $\mathbf{n}_{e} = \mathbf{n}_{c}$ is equivalent to $\boldsymbol{\omega}_{p} = \boldsymbol{\omega}$

The ponderomotive force



Before the accelerating phenomena become evident laserelectrons interactions where treated as plane waves interaction

• Plane waves: radiation whose magnitude is uniform in space and slowing varying in time

Short pulse lasers tend to violate these conditions:

- tight focusing create strong radial intensity gradients over a few wavelengths
- ==> non adiabatic treatment is required

This curious force is heuristically defined as **the gradient of the time averaged oscillation potential occurring** when laser interact with a single electron

The ponderomotive force



General definition

In physics, a **ponderomotive force** is a nonlinear force that a charged particle experiences in an inhomogeneous oscillating electromagnetic field.

It causes the particle to move towards the area of the weaker field strength, rather than oscillating around an initial point as happens in a homogeneous field.

$$F_p = \frac{e^2}{4m\omega^2} \nabla(E^2)$$

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The ponderomotive force and laser penetration



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In an oscillating, quasi-monochromatic electromagnetic field described by a vector potential $\mathbf{a}(\mathbf{r},t)$, the relativistic ponderomotive force is given by:

$$f_p = -m_e c^2 \nabla \sqrt{(1 + \langle a \rangle^2)}$$

Action of the ponderomotive force on a solid target

- For a plane-wave interacting with an **overdense target**, the fp acts more on the electrons (lightest particles) in the inward direction
- A laser pulse of finite width may produce a **density depression** around the propagation axis also because of the ponderomotive force pushing the electrons in the radial direction. Jointly with the relativistic effect and target expansion driven by electron heating, this mechanism may lead to a **transition to transparency as soon as the electron density drops below the cutoff value**

Role of the electron density

The hot electrons



We said that the laser pulse cannot penetrate into solid targets

But the energy is transported to the intern target mostly by the so called "hot" or "fast" electrons that are generated by the laser-matter interaction with different mechanisms

The energy of these electrons is of the order of the cycle-averaged oscillation energy in the laser electric field

$$\epsilon_p = m_e c^2 (\sqrt{1 + a_0^2/2 - 1})$$

Hot electrons are important because

Role in laser-driven photo nuclear physics

Fast ignition of fusion target

Protons/ions acceleration

$$f_p = \frac{dp^s}{dt} = -mc^2 \nabla \gamma$$
$$\gamma = \sqrt{1 + p_s^2/m^2 c^2 + a_0^2}$$

This is called the Ponderomotive energy

Hot electrons transport in solid matter



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It is of extreme importance especially in the field of Inertial Confinement Fusion processes Fusion Sci. Technol. 49, 297. [http://www.new.ans.org/pubs/ journals/fst/a 1150]

Most important aspects characterising this regime:

- Very high currents
- Self-generated fields

Density currents in front of the target associated to the hot electrons:

$$J_h = -en_h v_h \sim en_c c \approx 4.8 \cdot 10^{12} A cm^{-2}$$

Corresponding to a current of **around 15 MA over a spot of 10 um radius**

Summarising the TNSA





Fig. 1: Target normal sheath acceleration. A thin target foil with thickness $d = 5-50 \ \mu\text{m}$ is irradiated by an intense laser pulse. The laser prepulse creates a preplasma on the target's front side. The main pulse interacts with the plasma and accelerates megaelectronvolt electrons, mainly in the forward direction. The electrons propagate through the target, where collisions with the background material can increase the divergence of the electron current. The electrons leave the rear side, resulting in a dense sheath. An electric field due to charge separation is created. The field is of the order of the laser electric field (~ TV/m), and ionizes atoms at the surface. The ions are then accelerated in this sheath field, pointing in the target normal direction.

Conversion efficiency from laser energy to hot electrons is not perfect but can reach 69% in some configuration

$$n_0 = rac{\eta E_{
m L}}{c au_{
m L} \pi r_0^2 k_{
m B} T_{
m hot}} \; ,$$

 $\eta = 1.2 \times 10^{-15} I^{0.74}$



Published by CERN in the Proceedings of the CAS-CERN Accelerator School: Plasma Wake Acceleration, Geneva, Switzerland, 23–29 November 2014, edited by B. Holzer, CERN-2016-001 (CERN, Geneva, 2016)

Ion Acceleration—Target Normal Sheath Acceleration*

M. Roth and M. Schollmeier Institute for Nuclear Physics, Technische Universität Darmstadt, Darmstadt, Germany **Fig. 2:** Schematic of laser-generated fast-electron transport. The laser (shown in red) impinges on a preplasma with exponential density profile from the left side. The light pressure leads to profile steepening, depicted in the graph at the top of the figure. An ablation plasma creates an inward-travelling shockwave that heats, ionizes, and compresses the target. Fast electrons are created by the laser, propagating into the dense plasma towards the target's rear side. The high electron current $j_{\rm fast}$ can lead to filamentation and magnetic field generation (shown by the light red- and blue-coloured areas), as well as driving a return current $j_{\rm ret}$. The global magnetic field tends to pinch the fast-electron current. Electrons propagating in the dense solid matter interact with the background material by binary collisions. This leads to a spatial broadening of the electron dustribution, which becomes the major effect for longer distances. At the rear side, the electrons, heating the target even further.







Back to the 2000

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Snavely et al, "Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids" PRL, 85,2945 (2000)

Proton energy spectrum from the rear side of a 100 um solid target irradiated by a 423 J, **0.5 ps** pulse at normal incidence, corresponding to an intensity of 3E20 W/cm2.

The integrated energy of protons indicates a conversion efficiency of ' 10% for protons above 10 MeV.



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Characteristics of the laser-driven protons



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Energy spectra

Boltzman-like (from zero to a given cut-off) 100% energy spread for a pure-TNSA Selection procedures are adopted

Angular divergency

30°/40° degree (FWHM)

Temporal features

10⁸ - 10⁹ selected 20 ns - 200 ns bunches

1 Hz - 10 Hz -



Proton energy scaling with short-pulse drivers



Proton energy spectra from experiments using high contrast, **sub-100 fs, sub-10 J laser** pulses and thin solid targets, shown as simple exponential interpolations (dashed lines) Np(E) = Np0 exp(-E/Tp) (with E \leq Eco, the cut-off energy) of the high-energy tail of experimentally measured spectra.

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Interaction enhancement



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Margarone, PRL (2012) Margarone, PRAB (2015) Giuffrida, PRAB (2017)

Cryogenic hydrogen ribbon (ELISE)



Garcia LPB (2014) Margarone PRX (2016)





Curtesy of Prof Marco Borghesi





Rerspectives: Multidisciplinary applications of laser-driven ion sources

Word facilities

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2009: 19 facilites

https://www.icuil.org/index.php



The International Committee on Ultra-High Intensity Lasers



2020: 90 facilities
Applications

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- Diagnosis of intense interaction phenomena by Proton Radiography
- Nuclear Reactions initiated by Laser-Driven Ions (PET, fast and brilliant neutron source for radiography, ICF fast ignition with protons, protonboron fusion, ...)
- Studies of ion stopping power in plasmas
- Innovative approaches to ("FLASH") Radiobiology and Hadrontherapy
- Radiation chemistry (pulsed radiolysis of water, management of nuclear wastes, medical therapy)
- Mimicking space radiation for testing electronics/detectors
- Archeology (PIXE, DPAA)

Proton radiography/deflectometry



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Curtesy of Prof Marco Borghesi (QUB)

FIG. 13. Proton probing of the expanding sheath at the rear surface of a laser-irradiated target. (a) Setup for the experiment. A proton beam is used as a transverse probe of the sheath. (b)–(g) Temporal series of images produced by the deflection of probe protons in the fields, in a time-of-flight arrangement. The probing times are relative to the peak of the interaction. (h) A deflectometry image where a mesh is placed between the probe and the sheath plasma for a quantitative measure of proton deflections. From Romagnani *et al.*, 2005.

Pablo Cirrone, PhD - pablo

Laser-based radiotherapy applications



Reduced cost/shielding

- Laser transport rather than ion transport (vast reduction in radiation shielding)
- Reduced size of gantry

Flexibility/modularity

- Controlling output energy and spectrum
- Possibility of varying accelerated species

• Spectral shaping for direct "painting" of tumor region (*no degrader needed*) Novel therapeutic/diagnostic options

- Mixed fields: ions, X-rays, electrons, neutrons
- In-situ diagnosis (PET, X-rays) Radiobiological advantages
- Short pulse radiation might reduce damage to healthy tissues
- Increase in RBE (relative biological effectiveness)?





Radiobiology



Radiation physics Radiation chemistry		try	Radiation biolog		biology	
10 ⁻¹⁵ 10 ⁻¹²	10 ⁻⁹	10-6	10-3	1	10 ³	10 ⁶
sec sec	sec	sec	sec	sec	sec	sec
•lonization •Radical •Excitation formation •Dielectric relaxations		•DNA damage formation		•Repair •Replication •Cell death •Somatic mutations		

Possible effects proposed in literature:

- Spatio-temporal overlap of independent tracks causing collective effects and enhancing LET (hence RBE)
- Local depletion of oxygen causing a reduction in cell radiosensitivity (healthy tissues)

Remarks:

- ✓ Laser-driven ions are emitted at the source within a time ∆T< ps resulting in dose deposition in 100s ps - ns pulses
- Dose rates > 10⁹ Gy/s can be achieved (compared with Gy/min used in radiotherapy)

Motivations:

- Development of a methodology and demonstration of viability at ultra-high dose rate
- Validation of laser-driven sources in view of future therapeutic use
- Provision of an alternative, flexible source for radiobiological studies

Radiobiology



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Recent results with C-ions (courtesy of M. Borghesi)





Example of irradiation facilities

DRACO - Dresden (D) ILIL - Pisa (I) ELI-Beamlines, Dolni Brezani (CZ) I-LUCE facility, Catania (I)

What is done what is needed



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Done

A beam sufficient energy

A beam with sufficient intensity

A reliable dosimetric diagnostic, while still room for improvement

What is needed

Increase the monochromaticity

Increase the current for FLASH schemes (do you know what is FLASH radiotherapy?)

A better control of the beam characteristics ==> laser-target interaction level

Stability and repeatability of the emitted particles

More **open access** facilities

Status of the art

30 MeV - 60 MeV proton beams

- Focused and selected with electromagnets
- Coil targets + quadrupoles and/or solenoids

Facility I: DRACO, Dresden (D)

Helmholtz-Zentrum Dresden-Rossendorf D 18 J in 30 fs on the target. Protons are emitted from plastic foils of ~220 nm thickness, cut-off energy of up to ~70 MeV.

ESA: Energy selection aperture: protons of higher energies have larger beam diameters because of the rising focal length of the solenoid lens with increasing particle energy

ARTICLES tps://doi.org/10.1038/s41567-022-01520-3

OPEN

Tumour irradiation in mice with a laser-accelerated proton beam

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Nature Physics | VOL 18 | 316 March 2022 | 316-322 | www.nature.com/naturephysic

а Mouse bedding unit IC ESA Final beam LPA protons Laser target aperture TOF PTV LPA source Beam transport system Beam monitoring and dosimetry d h С RCF# 2 4 6 8 10 12 14 16 18 20 22 24 1×10^{9} $\begin{array}{c} (1 \times 10^{11} \\ \text{J} \times 10^{10} \\ 1 \times 10^{10} \\ 1 \times 10^{9} \\ 1 \times 10^{8} \end{array}$ 4.5 N_{P.No ESA} 2 × N_{P.ESA} • E_{Mer} RCF stac (MeV⁻¹) 4 dBCF 10. PTV BCF TOF Dose (Gy) 3 Dose (Gy) 4.0 number 1×10^{8} 2 Proton 107 3 5 C 20 40 60 80 0 0 10 20 30 40 0 1 2 3 4 5 6 7 8 5 mm E_{kin} (MeV) Ekin (MeV) Water depth (mm)







Facility II: ILIL Pisa (I)





Figure 1. Schematic view of the ILIL-PW facility at INO, including the main amplifier room, the shielded target area, and the laser-driven light ions acceleration (L3IA) dedicated line. OAP: Off-Axis Parabolic.

NEW HAP LASER DEV. LAB USER CONTROL TESTING AND ROOM PROTOTYPING LASER FRONT END HIGH DOSE 10 TW, 10 Hz POWER UNDERGROUND AMPLIFIER BUNKER SHIELDED TARGET Up to 240 TW AREA FOR NEW BEAMLINE for PARTICLE PRE-CLINICAL ACCELERATION STUDIES

LASER CAPABILITIES:

- •240 TW, Ti:Sa, up to 5 Hz, 27 fs;
- •1kHz, >20 mJ, Ti:Sa + OPA
- •100 Hz, >1J, TiSA (procurement in progress)



Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment Volume 909, 12 November 2018, Pages 160-163

Light Ion Accelerating Line (L3IA): Test experiment at ILIL-PW

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Facility II: ILIL Pisa (I)



Intense Laser Irradiation Laboratory, CNR (I) https://ilil.ino.cnr.it/ 400 mJ/30 fs/14 TW Ti:Sa Laser 7-8*10¹⁹ W/cm² cut-off energy of up to ~3.5 MeV.





Article A Few MeV Laser-Plasma Accelerated Proton Beam in Air Collimated Using Compact Permanent Quadrupole Magnets

Fernando Brandi ^{1,+},⁽⁰⁾, Luca Labate ^{1,2,*}, Daniele Palla ^{1,†}, Sanjeev Kumar ^{1,+,‡}, Lorenzo Fulgentini ¹, Petra Koester ¹, Federica Baffigi ¹, Massimo Chiari ³, Daniele Panetta ⁴, and Leonida Antonio Gizzi ^{1,2}



Six permanent magnets quadrupoles



Figure 2. Proton beam characteristics at 1 cm after Kapton windows. (a) Proton particles distribution and final energy at various initial energy ranges calculated over an area of 40 mm \times 40 mm centred on the MBL axis at position (20 mm, 20 mm); the highlighted numbers represents the values on the MBL axis; (b) graph of the ToF as function of the initial proton energy, with final energy also indicated.

Facility III: ELIMED at ELI-Beamlines, Dolni Brezani (CZ)





D Margarone, GAP Cirrone, "ELIMAIA: A Laser-Driven Ion Accelerator for Multidisciplinary Applications", Quantum Beam Sci. 2 (2018) 8

ELIMAIA experimental area 30J / 30fs Protons are emitted from metallic/plastic foils um thickness cut-off energy of up to ~40 MeV.







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Curtesy of Dr Daniele Margarone and Lorenzo Giuffrida (ELI-Beamlines (CZ)

Facility III: ELIMED at ELI-Beamlines, Dolnì Brezanì (CZ)



Curtesy of Dr Daniele Margarone and Lorenzo Giuffrida (ELI-Beamlines (CZ)

Pointing stability beamlines Intensity within FWHM: 3.5e+21 W/cm²±3.2% Energy within FWHM: 34.3±0.94% FWHM: 2.16±0.06 x 1.4±0.05 µm -3 Intensity [W/cm²] (@10 J) 2.5 [m] > ³ RMSx: 1.3, RMSy: 1.5, RMSr: 0.9 μrad 0.5 Energy above 1/e²: 62.4±1.1% Intensity above 1/e²: 2e+21 W/cm²±3.7% 2 0 2 .1 4 X [μm]

Basic commissioning	Fluctuation of the main experimental parameters			
Fluctuations	Single shot series			
Laser energy	0.3%	9.95 <u>+</u> 0.025 J		
Laser intensity @FWHM	0.8%	(1.39 <u>+</u> 0.01)*10 ²¹ W/cm ²		
Thot	3.96%	3.057 <u>+</u> 0.121 MeV		
Photon flux	1%			
Ермах	1.2%	14.48 <u>+</u> 0.17 MeV		
Proton flux >3 MeV	5.3%	6.0710 ¹⁰ +0.3210 ⁹ sr-1		
Pointing Stability	<<2,7 μrad	(RMS		

ELIMAIA commissioning started!

1

L3-HAPLS laser system @ ELIMAIA			
Energy	10 J		
Laser spot	~2*2 μm		
Pulse duration	<30 fs		
Laser intensity	>>2e21 W/cm ²		





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	-		Protor	1 spect	ra	
-	1E11-	@	@different contrast levels			
	1E10 1E9	1e-9		1e-11 .e-10		
		10	20	30	40	
			Energy [N	leV]		

Main proton beam features Max proton energy ~40 MeV Flux above 3 MeV: 8.5e11 /sr Flux at 15 MeV (+/- 5%): 2.7e10 /sr Flux at 25 MeV (+/- 5%): 9.3e9 /sr

Facility III: ELIMED at ELI-Beamlines, Dolnì Brezanì (CZ)





NOTE: the beam have to be transported in air for the majority of the applications !



Curtesy of Dr Daniele Margarone and Lorenzo Giuffrida (ELI-Beamlines (CZ)

Facility IV: I-LUCE, Catania (I)



SAMOTHRACE EICLANAGER AND AND FEMALE

Anthem

Interaction chamber II: Warm Dense Matter, nuclear physics.

Two laser lines

45 TW, >1J/<24fs/10Hz 7*10¹⁹ W/cm² 320 TW, >7J/<24fs/1Hz 1*10²¹ W/cm²

station

Utility



Pablo Cirrone, PhD - pablo.



Laserlab



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Welcome to Laserlab Europe

Laserlab-Europe, the Integrated Initiative of European Laser Research Infrastructures, understands itself as the central place in Europe where new developments in laser research take place in a flexible and coordinated fashion beyond the potential of a national scale. The Consortium currently brings together 35 leading organisations in laserbased inter-disciplinary research from 18 countries. Its main objectives are to maintain a sustainable inter-disciplinary network of European national laboratories; to strengthen the European leading role in laser research through Joint Research Activities; and to offer access to state-of-the-art laser research facilities to researchers from all fields of science and from any laboratory in order to perform world-class research.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 871124



Open access beam in different facilities around the world

Thanks for Listening



The role of the target thickness



The laser penetration depends also on the target thickness

when it becomes close or small then one wavelength

It exist a relation between the target thickness and the laser amplitude **for which we can reach the transparency** threshold:

$$a_0 = \pi \frac{n_e}{n_l} \frac{l}{\lambda} \equiv \xi$$

1 is the target thickness

The hot electrons: heating models



The most famous is the **capacitor model**

In this model, electrons are dragged out of the surface of a perfect conductor by an oscillating "capacitor field," **extending on the vacuum side**

Electrons are considered to be "absorbed" when after having performed about half of an oscillation on the vacuum side, they reenter the target, there delivering their energy, which is of the order of the oscillation energy in the external field.

$$\frac{d^2\xi}{dt^2} = \begin{cases} -\omega_p^2 \xi - eE_d/m_e & (x_0 + \xi > 0), \\ +\omega_p^2 x_0 - eE_d/m_e & (x_0 + \xi < 0). \end{cases}$$



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Hot electrons transport in solid matter



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Different effects occurs:

The large current generated is locally neutralised by a **return** current

This return current comes from both the free conduction electrons in the metals or produced by field and collisional ionization in insulators

Filamentation instabilities and dependence on the target material have also been extensively studied

Finally, it is noticeable that at least a fraction of hot electrons propagates coherently through the target **conserving the temporal periodicity of the driving force**

Ion acceleration mechanisms





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Ion acceleration mechanisms



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There are different acceleration mechanisms

They can occur in different target regions

Rear surface acceleration

Front surface acceleration

TNSA (Target Normal Sheet Acceleration) and RPA (Radiation Pressure Acceleration)



Rear surface acceleration



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Hot electrons generated on the front side reaches the rear side

These hot electrons attempt to escape in vacuum and the charge unbalance create a sheath field Es normal to the rear surface

 $eE_s \sim \frac{T_h}{L_s}$

Higher is the electron temperature higher is the electric field

Higher is the sheath distance lower is the electric field

Ls is may be roughy estimated as the Debye length of the hot electrons

Debye length and acceleration effects



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You already know what a Debye length is?

Electric fields cannot penetrate a magnetic one in a charged "solution" (a plasma) as ...

charges produce a screening ==> this screening length is the Debye distance

Typical values $I\cdot\lambda^2=10^{20}W/cm^{-2}\mu m^2$

 $T_h = 2.6 \text{ MeV}$

 $n_{\rm h} = 8 \ 10^{20} \ {\rm cm}^{-3}$ $\lambda_D = 4.2 \cdot 10^{-5} cm$ $E_{s} \sim 6 \cdot 10^{10} V cm^{-1}$

This large field will backhold most of the escaping electrons, ionize atoms at the rear surface, and start to accelerate ions.

Debye length and acceleration effects



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The energy acquired by a test-ion crossing the sheath is

 $\epsilon_i = ZeE_sL_s = ZT_h$

==> ions reach MeV scale energy

TNSA modelling

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Is described by a relatively simple system of equations that can be investigated analytically and numerically

We alway assume an **electrostatic approximation**, so that the electric field is $E = -\nabla \phi$;

 $\nabla^2 \phi = 4\pi e (n_e - \sum_j Z_j n_j)$

with the sum running over each species of ions, having density n and charge Z.

As a consequence of the laser-solid interaction, the electron density n_e may be described as composed of at least two qualitatively distinct populations, which will be labeled **cold and hot**

TNSA modelling



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The electron density in the interaction is then divided in:

 $n_e = n_c + n_h$

Thermal moments are neglected for the cold population

while density for the hot component is given by a one-temperature Boltzmann distribution

 $n_h = n_0 e^{e\phi/T_h}$

This formulation is good when we have only to take into account the presence of self-consistent sheath field

In more complex scenarios, the electron dynamics shall be included via either **fluid** or **kinetic** equations.

TNSA modelling



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Considering this two main categories of TNSA models are developed

The **static (or quasi-static) models** in which it is assumed that the light ions, or at least the most energetic ones, are accelerated in the early stage of the formation of the sheath, so that the latter may be assumed as stationary.

The **dynamic model** where the system is described as a neutral plasma in which the ions acquire kinetic energy in the course of the sheath evolution

The last case is connected to the classical problem of the plasma expansion in vacuum

Multi MeV ions acceleration from the "rear" of thin foils was studied from 2000

100



Intensities rising above E19 W/cm² – electron acceleration to MeV energies

Thin foils allow electrons to reach the rear of the target and **establish a field**.

Protons (from contaminants) **have beam features** contrary to lower energy, isotropic emission previously observed from the front.

Clark et al, "Measurements of Energetic Proton Transport through Magnetized Plasma from Intense Laser Interactions with Solids" PRL, 84,670 (2000)

Snavely et al, "Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids" PRL, 85,2945 (2000)

Maksimchuk et al, "Forward Ion Acceleration in Thin Films Driven by a High-Intensity Laser" PRL, 84, 4108 (2000)

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Complex acceleration scenario

E laser sheath



Laser pulse intense enough to ionise matter and couples with the fare electrons which **absorb energy** and **momentum**

- 1. Heating of electrons ==> "sheath" region where electrons and ions are accelerated
- 2. Momentum absorption due to the ponderomotive force (is the local flow of the electromagnetic momentum) ==> radiation pressure on plasma

Target transparency for the e.m. wave occurs when plasma density becomes lower the critical density

$$n_c = n_c(\omega_L) = \frac{m_e \omega_L^2}{4\pi e^2}$$

 $n_e > n_c ==>$ Plasma opacity (or overdense) $n_e < n_c ==>$ Plasma transparence

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Complex acceleration scenario

 $E(0) = \frac{KT_h}{e\lambda_D} = \sqrt{\frac{n_h KT_h}{\varepsilon_0}}$ F laser Typical values are: $\lambda D^{2} 1 \mu m$ Th ~ MeV sheath n At rear: n_e ~ (Ιλ²)^{0.5} $E(0) = \frac{10^6 V}{10^{-6}},$ n_{hot}ł $\rho = -en_{hot} = -en_0 \exp\left(-\frac{x}{\lambda_D}\right)$ $\sim TV/m$

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Complex acceleration scenario: role of the hot electrons

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The lines give scaling laws derived from different models

Gibbon, P., 2005b Short Pulse Laser Interaction with Matter (Imperial College Press, London)



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On the theoretical side



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The interpretation of experiments has revitalized classic and often controversial problems of plasma physics:

plasma expansion into vacuum

formation of collisionless sheaths

motion of relativistic moving mirrors, a concept already discussed in the original work on special relativity by Einstein (1905) (used for the RPA description)

Even if we try to develop simple models a rich al Einstein, A., 1905, Ann. Phys. (Berlin) 322, 891. dynamics of laser-plasma interaction and ion acceleration, involving **collective and self-organization effects**, is evident.

Unfolding such dynamics requires the use of self-consistent electromagnetic (EM), kinetic simulations. To this aim, the particle-in-cell (PIC) method.

Ion acceleration



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Relativistic effects produce an **increase of the cutoff density** ==> the critical density is closer to that of a solid:

Relativistic self-induced transparency reduces the plasma mirroring effects

However laser-plasma interaction mechanisms are complicated by many phenomena:

- nonlinearity in the wave equations

— modification of the plasma density profile due to the **radiation pressure** that are described via the **ponderometive force**

The basic ingredients



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Ingredients

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TW/PW class lasers

Usually Ti:sa

mJ - tens of J

20 fs to 30 fs

Good profile

Good contrast

Focused on a target

Usually solid/

The process occurs in vacuum

Brutal forces and less elegant then laser Wakefield

Based on "charge separation"

 $T_{\rm hot} \approx U_{\rm pond} \approx 1 \,\,{
m MeV} \times (I\lambda^2/10^{19}\,{
m W}\cdot\,\mu{
m m}^2/{
m cm}^2)^{1/2}$

Laser-plama lon acceleration: a compact solution



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Conventional ion acceleration

LHC @ CERN

- circular tunnel (27 km long!!!)
- superconductive electromagnets
- proton energy (per beam): 6.5 TeV



E-field $_{max} \approx$ few 10 M V /meter (Breakdown)

Laser-plasma acceleration No breakdown limit 10 - 100 GV/m

0.1-10 ບm



The energy gain for ions in a laser-plasma accelerator is of several tens of MeV/mm (just few tens of MeV/m in conventional accelerators due to breakdown effects)


I-LUCE layout



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The main ingredients for radiation productions



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A laser

. .

High power (TW - PW) Short pulse duration (ps - fs) Intensity $> 10^{16}$ W/cm²

A Target: Thin/thick solid/liquid/gassous

Other useful things High contrast laser High quality target fabrication High quality wave front-end

•••••

How Much Pressure Does a PW Laser Exert?

1 PW/1µm spot size corresponds to 10²³ w/cm²

That is the equivalent of the pressure of 10 million Eiffel Towers on the tip of your finger!!

Seriously extreme

Curtesy of Gerard Morou Ecole Polytechnique (F)

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The main ingredients for radiation productions



113

A laser

```
High power (TW - PW)
Short pulse duration (ps - fs)
Intensity > 10^{16} W/cm<sup>2</sup>
```

A Target: thin/thick solid/liquid/gassous ...

Other useful things

High contrast laser High quality target fabrication High quality wave front-end [many other laser and target parameters]

Laser-solid target interaction for protons, ions acceleration •Multi species production: g, e-, p, ions • Emax ~ 10 TV/m Rear (Vacuum) Front (Vacuum) Target •Short distance (~µm) Hot e Proton characteristics Forward Backward High energy: up to ~ 100 MeV Accelerated lons Pulse duration \approx 10s fs - 100s ps ppb ≈ 108-1011 Broad energy spectra (100%) Wide angular divergence ($\approx 10^{\circ}-20^{\circ}$) e sheath (RPA) current aser Pulse (TNSA)



Laser plasma ion-acceleration *physical picture*



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Target Normal Sheath Acceleration

REVIEW PAPERS:

- Macchi, Borghesi, Passoni, Rev. Mod. Phys. 85 (2013) 751
- Borghesi et al, Springer Proc. Phys. 231 (2019) 143

Laser-driven ion acceleration				
from plastic target				
The association of the matter of the measurements of the gas-meaning law association of the gas meaning law association of the distribution of the gas meaning law association of the distribution of the gas meaning law association of the distribution of the gas meaning law association of the distribution	r public garantetism are those flag participants (SSS) garantetism (SSS) and than the non-solid Such and than the non-solid Such and than the non-solid Such solid Such (SSS) (SSS)			
carbon energy (MeV) and cost 0.01 0.1 1 10	proton energy (3647/savboo) 0.1 1 10 100	ax 0.5 1 2 5	-100	

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Role of the ponderomotive force on electrons energy gain

In an oscillating, quasi-monochromatic electromagnetic field described by a vector potential $\mathbf{a}(\mathbf{r},t)$, the relativistic ponderomotive force is given by:

$$f_p = -m_e c^2 \nabla \sqrt{(1 + \langle a \rangle^2)}$$

$$f_p = \frac{dp^s}{dt} = -mc^2 \nabla \gamma$$

Energy Gain: 100 MeV/um (in a plasma medium)!!!