EUROPEAN UNION

Structural Instruments
2014-2020

Project co-financed by the European Regional Development Fund through the Competitiveness Operational Programme
“Investing in Sustainable Development”

eli nuclear physics

IFIN-HH

High Intensity Laser-Matter interaction and Nuclear Physics
(with a view of what’s happening at ELI Nuclear Physics that might be on interest for EuPRAXIA)

SG @ ELI-NP
Simulation Group

Paolo Tomassini and Domenico Doria

Extreme Light Infrastructure (ELI-NP), Str. Reactorului no.30, P.O. box MG-6, Bucharest - Magurele, Romania

Theory @ LDED

Cautionary note 1:
PT is not a nuclear physicist

Cautionary note 2:
PT was one of the proponents of the EUROGAMMAS consortium

We acknowledge support from **ELI-RO project ELI-RO/5.9/14 2924-2027**
[Project Director P. Tomassini]

The structure of the talk

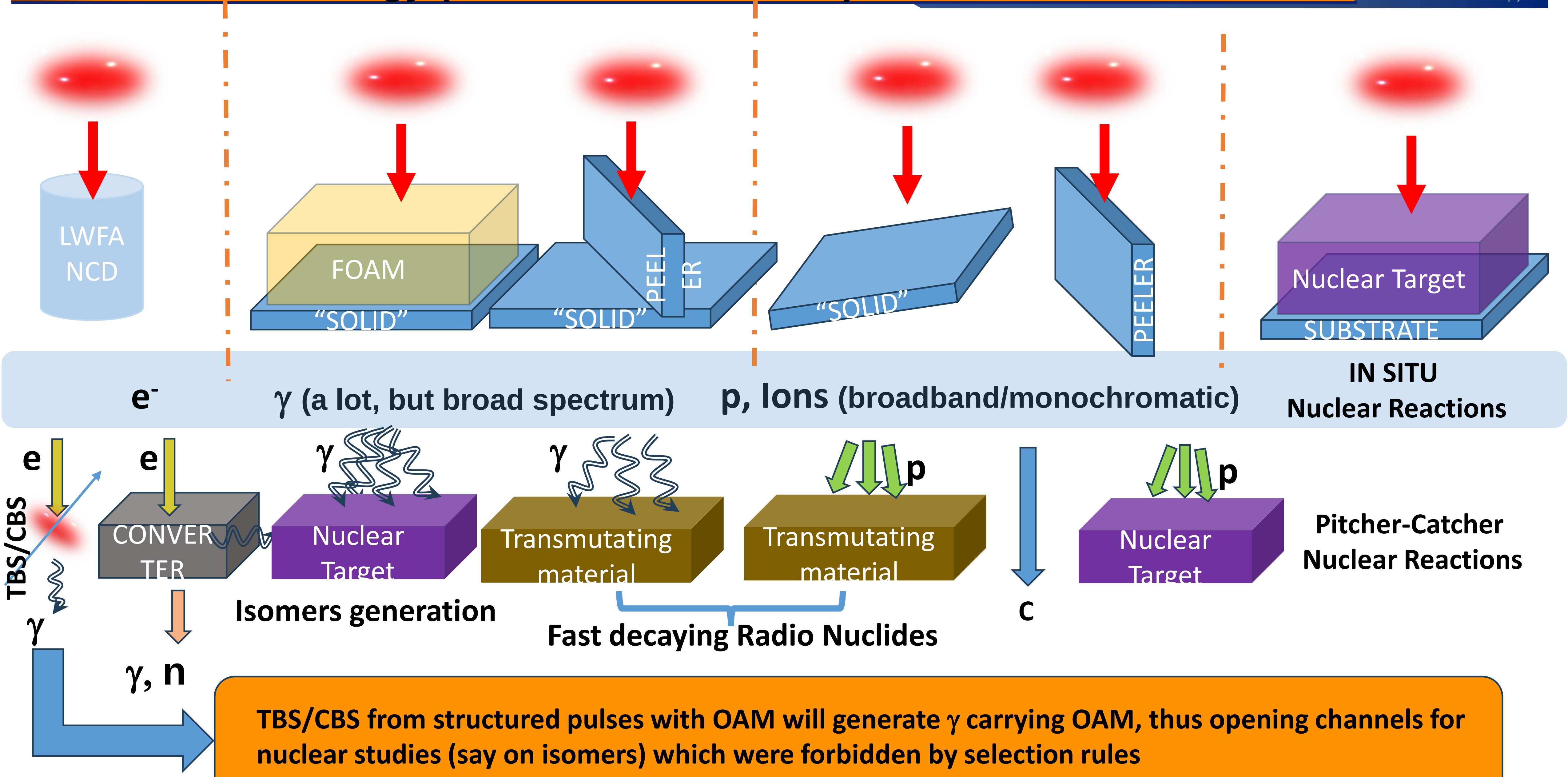
Two distinct talks merged here:

“Laser-matter interactions”
[As we come from different research areas this was meant as an introduction and a survey on the main laser-plasma interactions that are/can be used in NP so as to trigger ideas for the discussion]

Some of the topics have been already described by Alessio Del Dotto on yesterday

“Nuclear physics with laser”
[This part was presented in the last EuPRAXIA workshop in Elba. It’s mostly about what we are doing (or we might do) at ELI-NP]

Interaction zoology (useful for NP studies)



LWFA NCD

FOAM

"SOLID"

"SOLID"

PEELER

"SOLID"

PEELER

Nuclear Target

SUBSTRATE

e^-

γ (a lot, but broad spectrum)

p, Ions (broadband/monochromatic)

IN SITU
Nuclear Reactions

e

TBS/CBS

γ

e

CONVERTER

γ, n

γ

Nuclear Target

Isomers generation

γ

Transmutating material

p

Transmutating material

Fast decaying Radio Nuclides

C

p

Nuclear Target

Pitcher-Catcher
Nuclear Reactions

TBS/CBS from structured pulses with OAM will generate γ carrying OAM, thus opening channels for nuclear studies (say on isomers) which were forbidden by selection rules

The structure of the talk

Sections:

1. A survey on laser-matter interaction
2. What’s going on at ELI-NP (experimentally wide)
3. Some NP applications of laser-matter interactions

High-Intensity laser-plasma interactions (a target density view)

For a given laser (wavelength, intensity), a characteristic (electron plasma) density setting the interplay between ***a transparent*** and an ***absorbing/reflecting*** target **is the critical density**, at which the longitudinal plasma oscillation frequency (ω_p) equals the pulse frequency (ω_0)

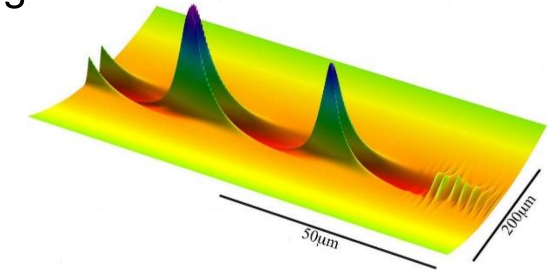
$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_e \gamma_0}}$$

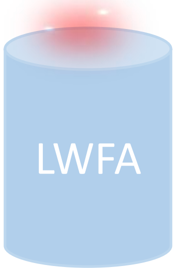
Quivering

$$n_c = \frac{1{,}1 \cdot 10^{21}}{\lambda_0^2} \gamma_0 \; [cm^{-3}]$$

UNDERDENSE (LWFA) $n_e \ll n_c$

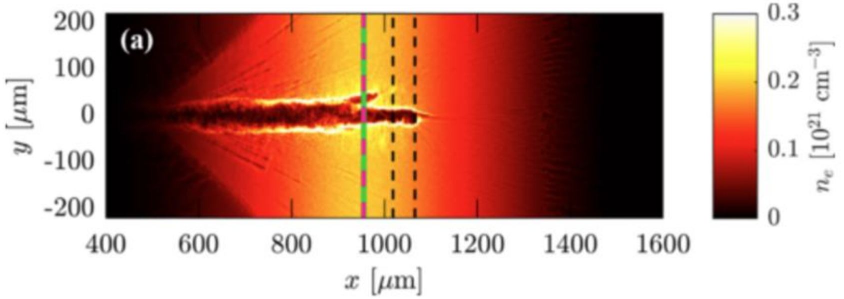
Might be of 10's of cm overall scale

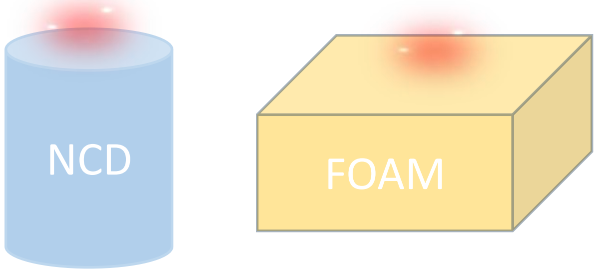




NEAR CRITICAL (DLA) $n_e \approx n_c$

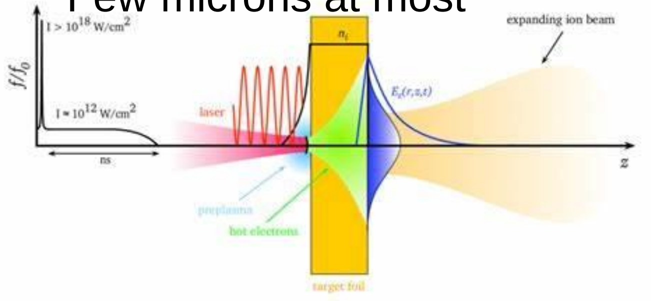
Few tens/hunderds of microns at most

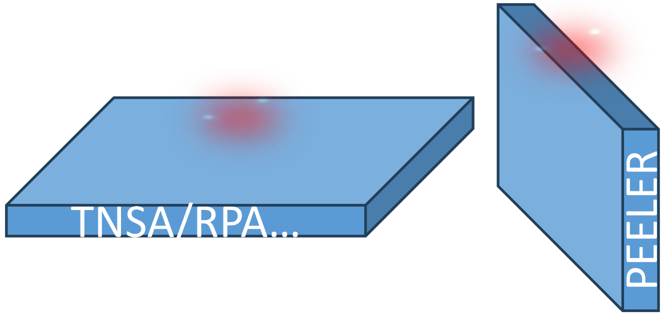




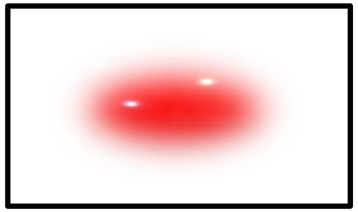
"SOLID" DENSITY (TNSA/RPA...) $n_e \gg n_c$

Few microns at most





High-Intensity laser matter interactions (the laser view)



The main laser parameter in ultraintense laser-electron interaction (we forget about QED effects here) is the normalized amplitude

$$a_0 = \frac{eA_0}{mc^2} = 8.5\cdot 10^{-10}\sqrt{I\lambda_0^2}$$

I : in W/cm^2

λ_0 : in μm

which measures the amplitude of the electron transverse momentum oscillation while the particle is quivering in the laser field

$$\delta u_\perp = \frac{\delta p_\perp}{mc} \cong a_0$$

and therefore sets a threshold for relativistic effects in the electron dynamics in the laser field at $a_0 \approx 1$

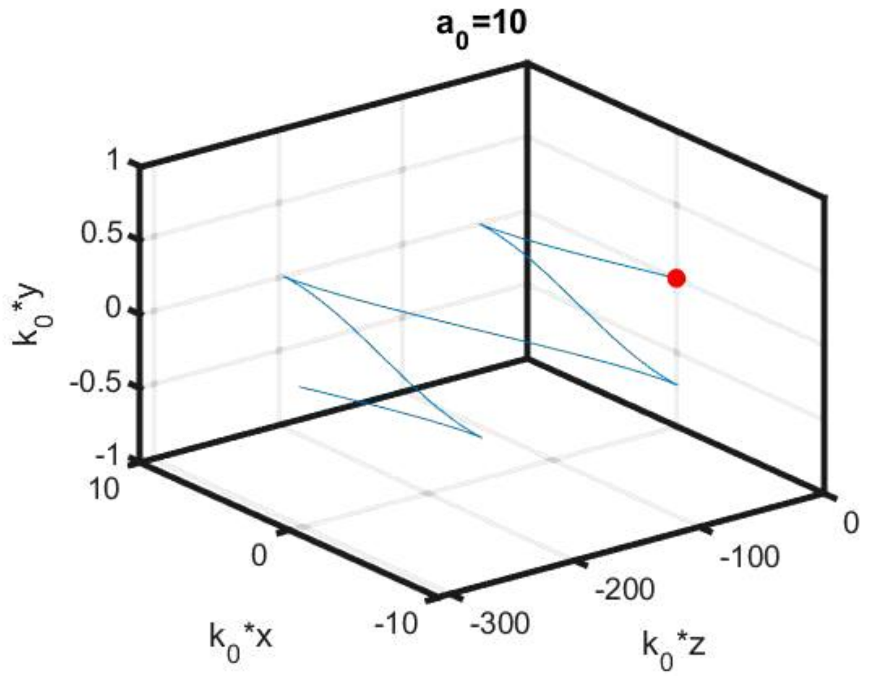
$a_0 \sim 1 \quad I \sim 10^{18}$ W/cm^2

$\lambda_0 = 0.8\,\mu$m

$$\gamma_0 = \sqrt{1 + a_0^2/2}$$

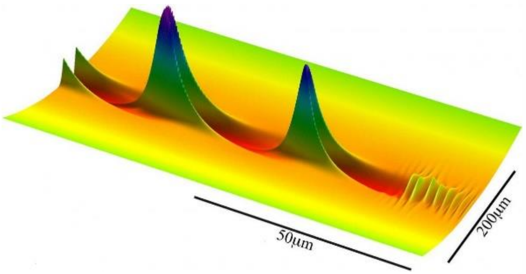
* L.P.

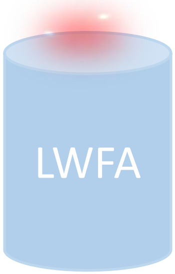
Characteristic γ of the e^-



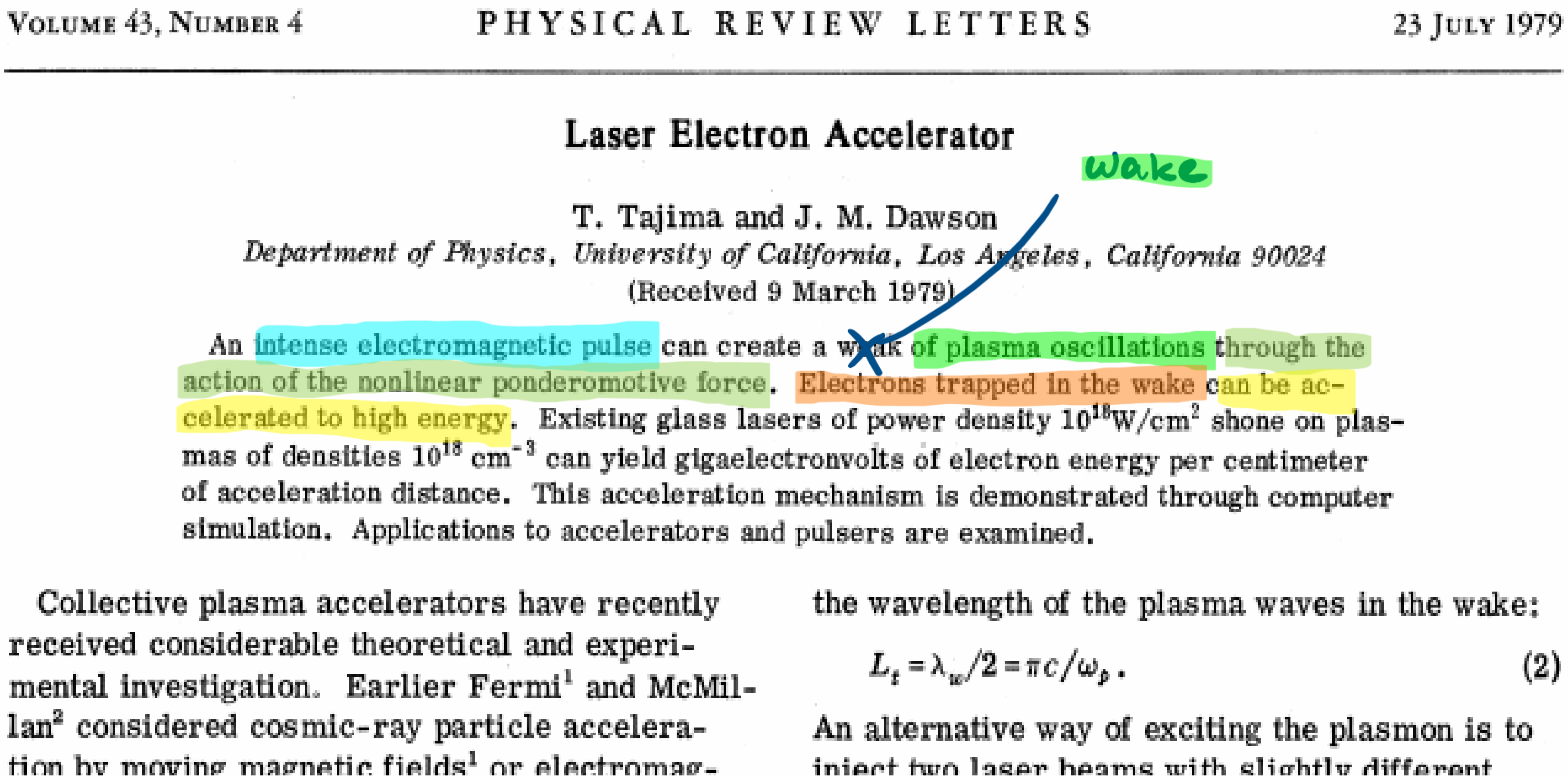
The Laser Wake Field Acceleration (LWFA)

UNDERDENSE (LWFA)





The original idea of Laser driven acceleration



Volume 43, Number 4 PHYSICAL REVIEW LETTERS 23 July 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

An intense electromagnetic pulse can create a ~~weak~~ wake of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromag-

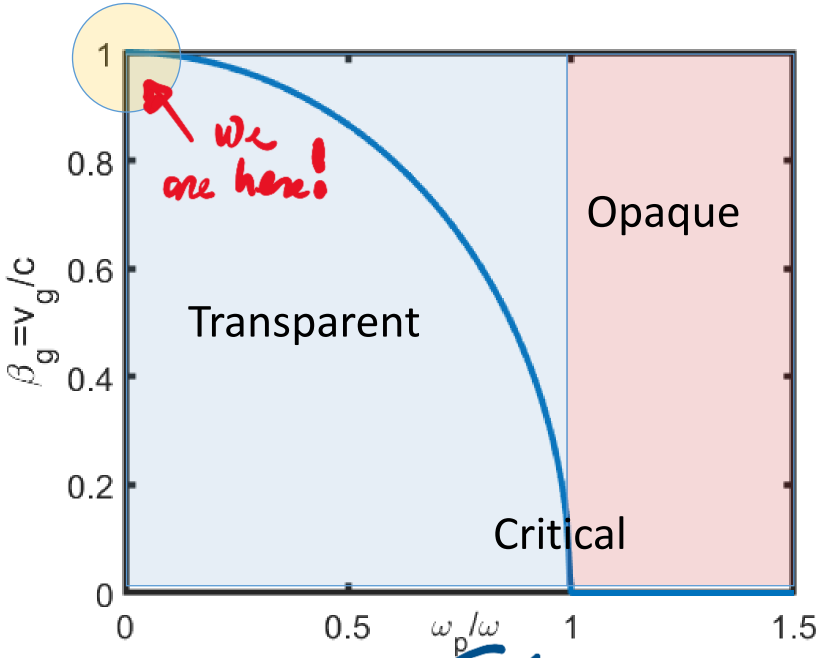
the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p . \quad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different

The Laser Wake Field Acceleration (LWFA)

In LWFA the electron density is so small that the laser pulse propagates in a transparent medium, at speed very close to c

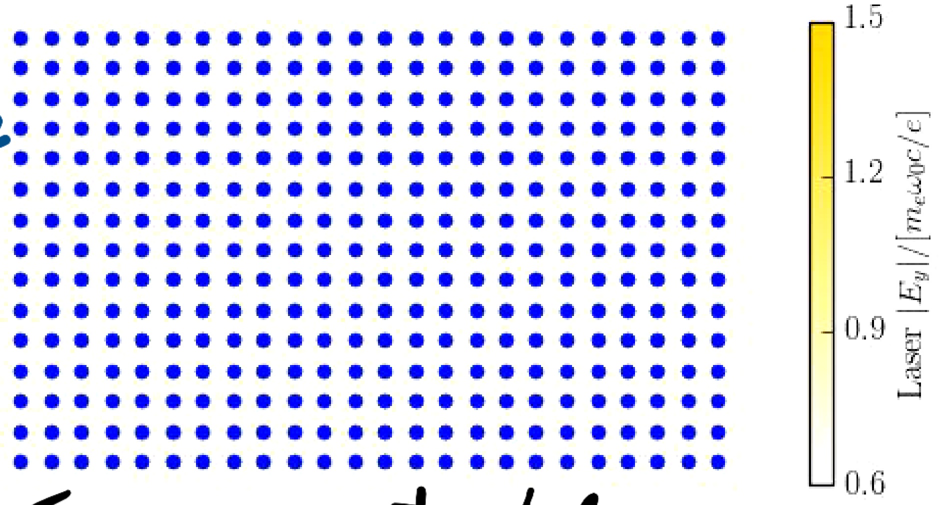


$= \sqrt{n_e/n_c}$

$n_e \sim 10^{17} - 10^{19}\ cm^{-3}$

$$\frac{n_e}{n_c} = \left(\frac{\omega_p}{\omega_0}\right)^2 \approx 10^{-4} \div 10^{-2}$$

$$\gamma_g = \sqrt{\frac{n_c}{n_e}} : 10 \div 100$$



Ions remain at rest!

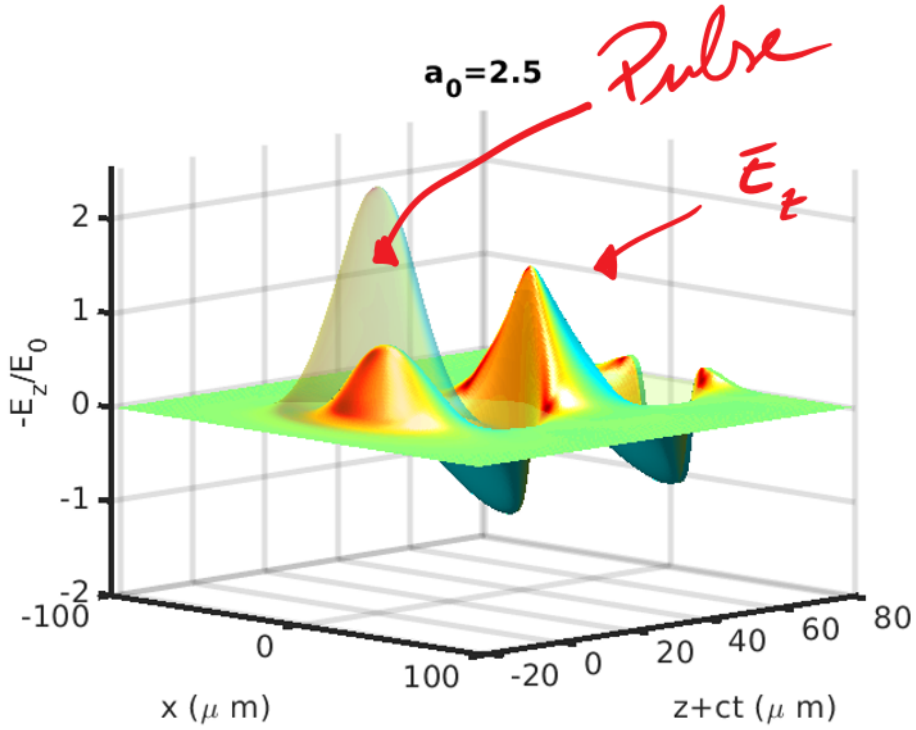
The pulse excites a longitudinal plasma wave through its ponderomotive force. $\vec{F}_p \propto -\vec{\nabla}\gamma$ ← Quivering energy

The phase speed of the plasma wave is the same of the group laser speed

The Laser Wake Field Acceleration (LWFA)

We are mostly interested in the **“blow-out” or “bubble”** deep nonlinear and in the quasi-linear regimes

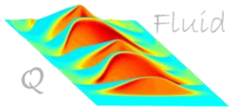
Quasilinear/weakly nonlinear

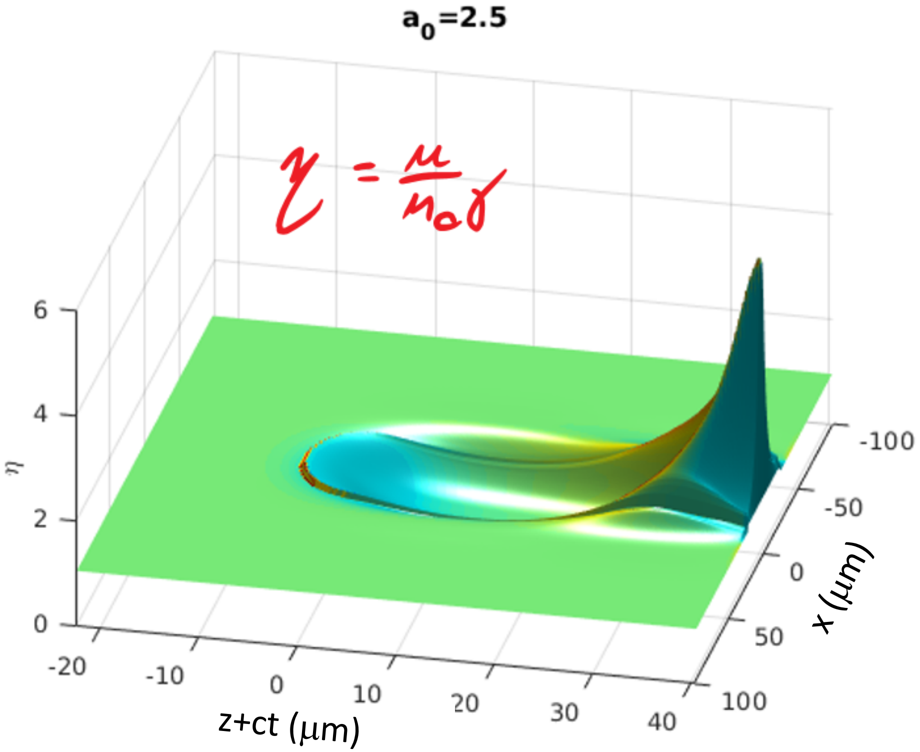


Pulse

E_z

What accelerated electrons see





$$\eta = \frac{n}{n_0 \gamma}$$

What laser pulses see

The Laser Wake Field Acceleration (LWFA)

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e^- beam

n_e

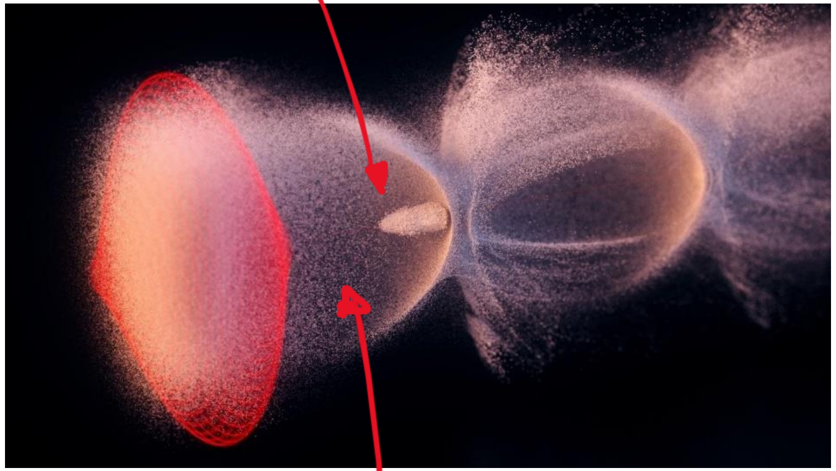
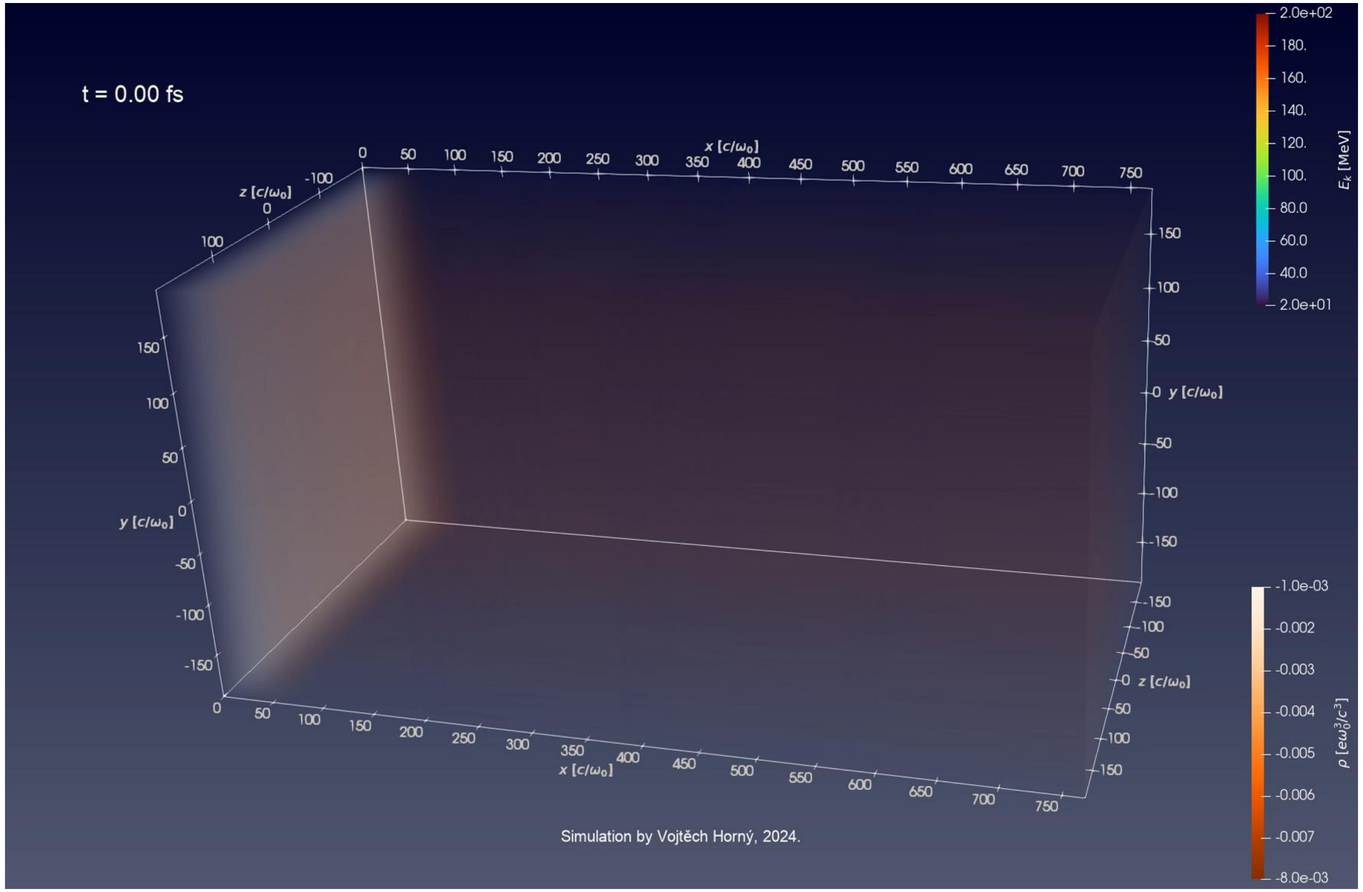


Image credits: DESY

Total evacuation of the electrons behind the pulse

Blow-out/bubble regime

V. Horny/LDED/TheoryGroup

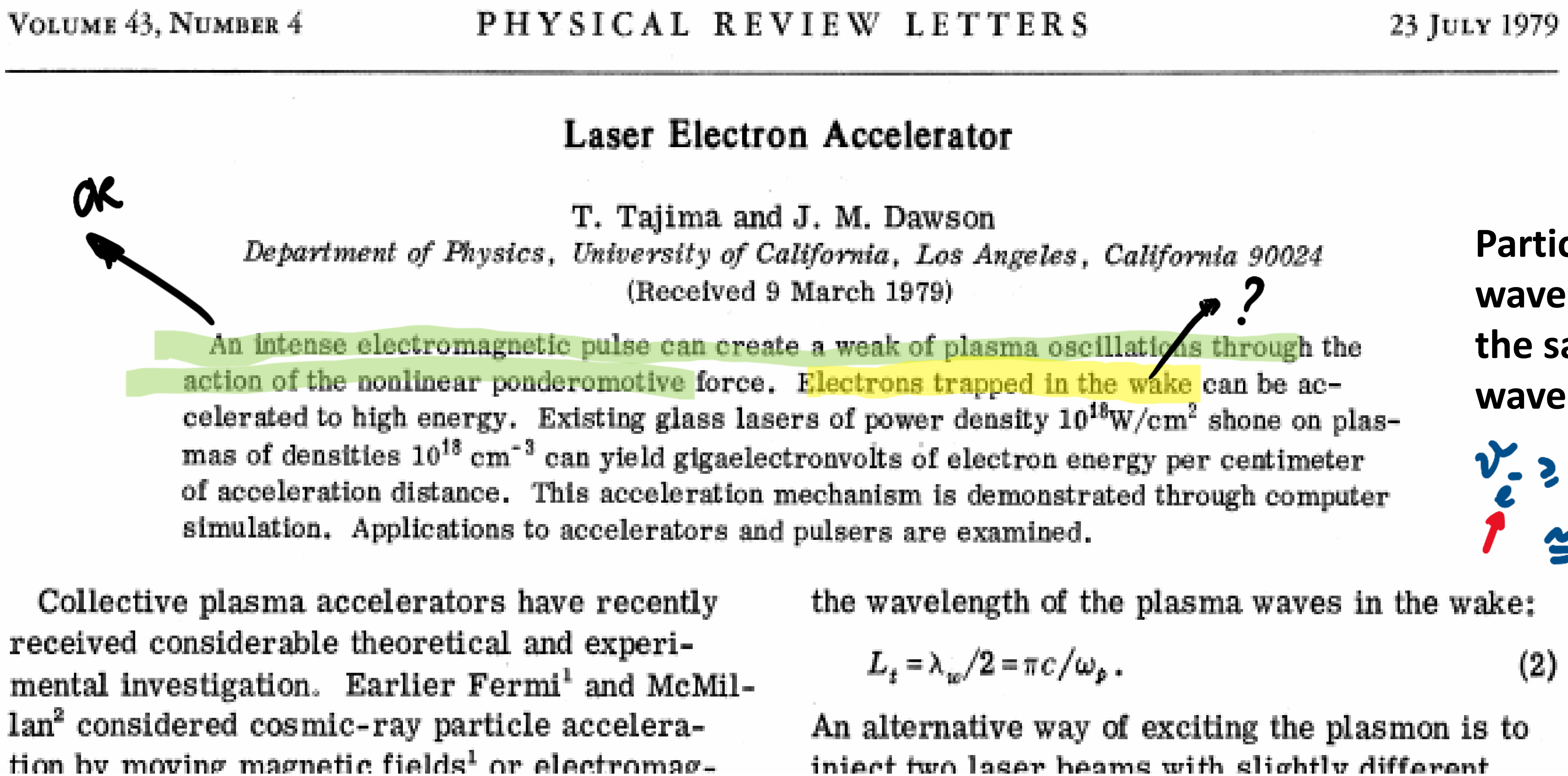


Simulation by Vojtěch Horný, 2024.

SG @ ELI-NP
Simulation Group

Theory @ LDED

The Laser Wake Field Acceleration (LWFA)



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the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p . \qquad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different

Particles are trapped in a wave when they reach the same speed of the wave

$v_{e^-} \simeq v_\phi$ (plasma wake)

$\cong v_g$ (laser pulse)

$\gamma_e \simeq \gamma_g \simeq \sqrt{\frac{n_c}{n_e}}$

10 ÷ 100

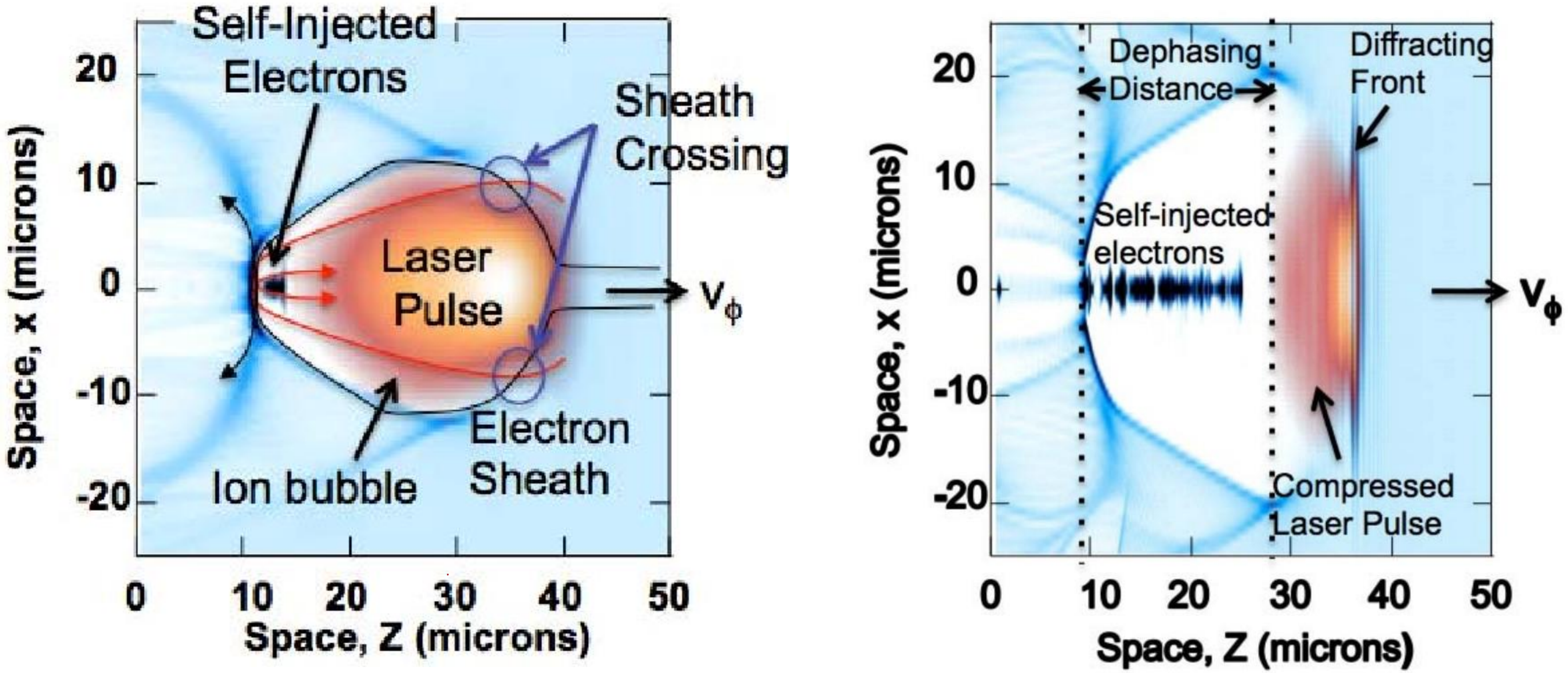
The Laser Wake Field Acceleration (LWFA)

“Self” trapping in the bubble regime

🙂 Automatic process, once the threshold is reached.

☹ Usually the beam quality is poor

C. Joshi, IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 45, NO. 12, DECEMBER 2017



Beam Quality

- **Compactness** in phase-space (low energy spread, divergence…)
- High charge or high current
- **Linear correlation** in the transverse x-u_x and y-u_y planes (low emittance)

$$u = p/mc$$

Normalized emittance

$$\epsilon_n^2 = \langle x^2\rangle\langle u_x^2\rangle - (\langle x \cdot u_x\rangle)^2$$

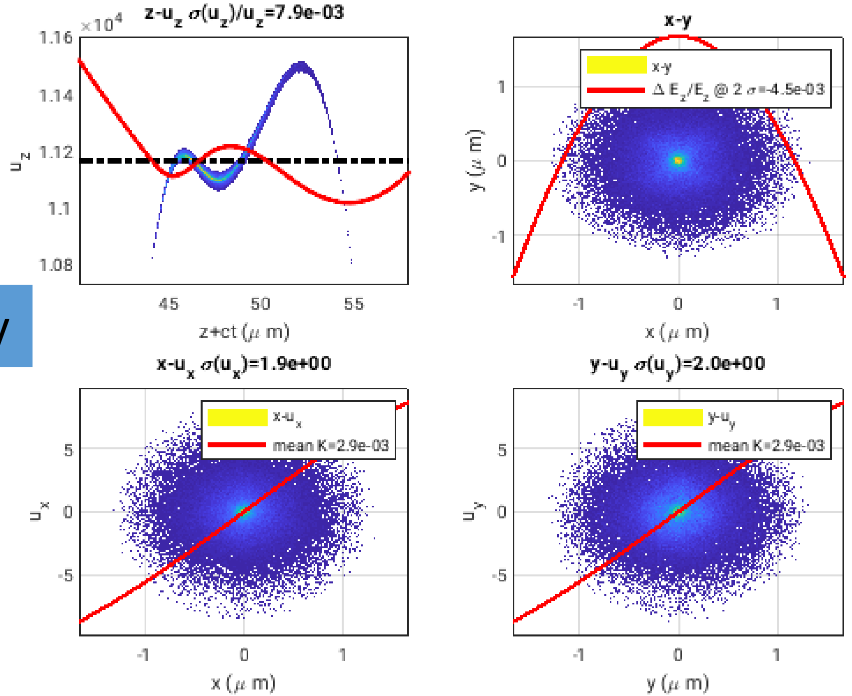
Normalized Brighness (5D)

$$B_{n,5D} = \frac{2}{\pi^2}\frac{I}{\epsilon_{n,x}\epsilon_{n,y}} \quad A/(m\times rad)^2$$

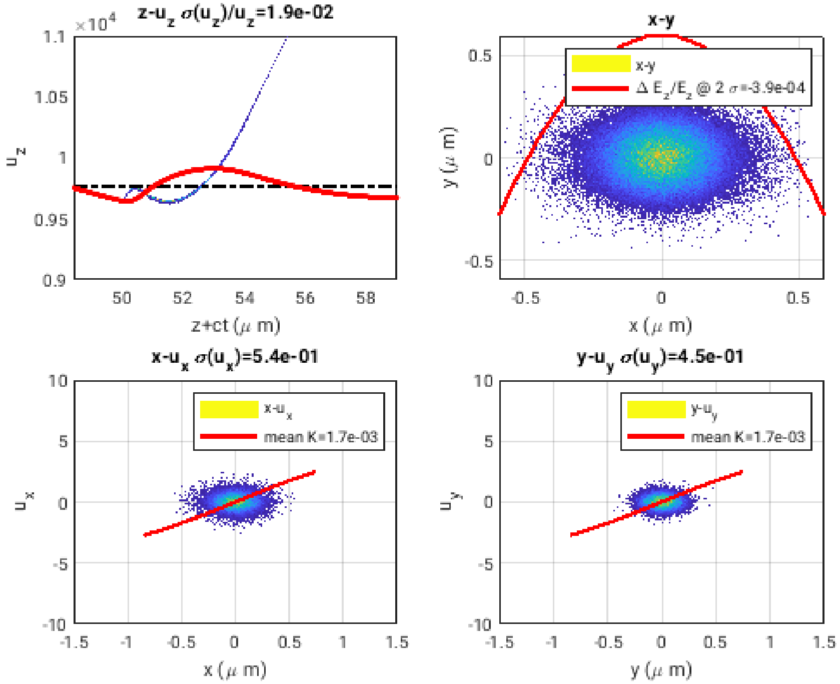
Normalized Brighness (6D)

$$B_{n,6D} = \frac{B_{n,5D}}{\delta E/E}$$

$$B_{n,6D} = \frac{B_{n,5D}}{\delta E/E/0.1\%}$$



Good Quality



Excellent Quality

High-Quality injection schemes (some of)

- **Colliding pulses injection (E. Esarey et al., 1997; M.Chen et al, 2014) by ponderomotive assisted trapping**

E. Esarey et al., Phys. Rev. Lett. 79, 2682 (1997)
M. Chen et al., Phys. Rev. ST Accel. Beams 17, 051303 (2014)
Malka et al., PoP, DOI:10.1063/1.3079486 (2014)

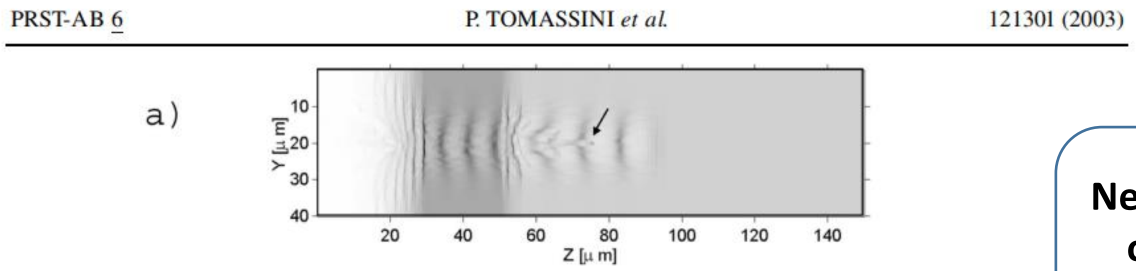
- **Density downramp** injection (**S. Bulanov et al., 1998**). Inje decrease of the wave speed and this is obtained with a suc plasma density. **First 2D PIC simulations (P. Tomassini et a very low emittances (ε_n=0.2 mm mrad) can be obtained ir**


Article

Free-electron lasing at 27 nanometres based on a laser wakefield accelerator

https://doi.org/10.1038/s41586-021-03678-x
Received: 5 August 2020
Accepted: 28 May 2021

Wentao Wang[1,4]✉, Ke Feng[1,4], Lintong Ke[1,2], Changhai Yu[1], Yi Xu[1], Rong Qi[1], Yu Chen[1], Zhiyong Qin[1], Zhijun Zhang[1], Ming Fang[1], Jiaqi Liu[1], Kangnan Jiang[1,3], Hao Wang[1], Cheng Wang[1], Xiaojun Yang[1], Fenxiang Wu[1], Yuxin Leng[1], Jiansheng Liu[1]✉, Ruxin Li[1,3]✉ & Zhizhan Xu[1]



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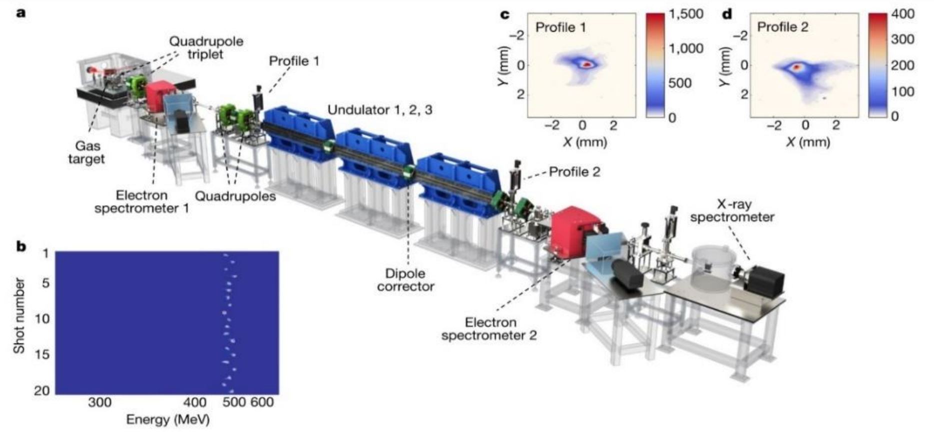
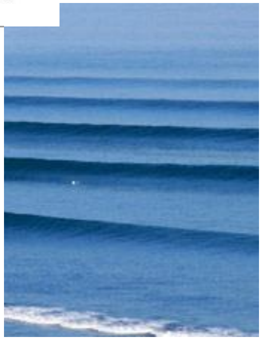


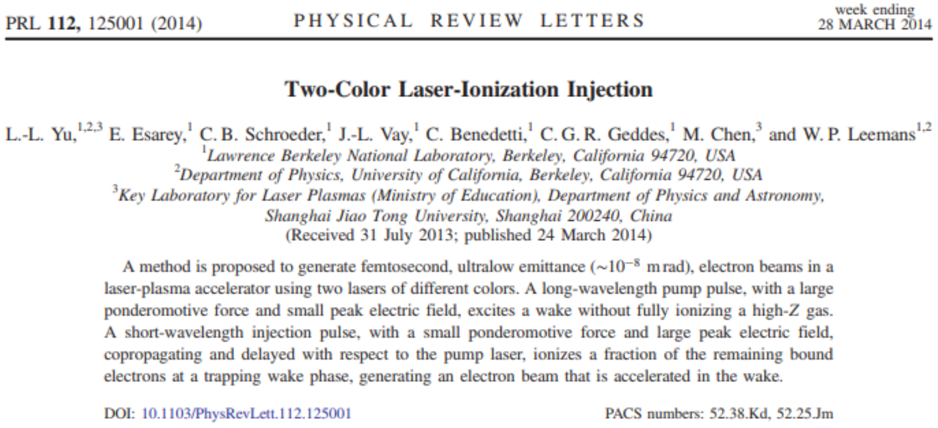


- **Two Color and ReMPI injection (L. L. Yu et al., 2014, P. Tomassini, 2017) look very promising (more on next slides).**

The Laser Wake Field Acceleration (LWFA)

Two Color and ReMPI Injections

-



PRL 112, 125001 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

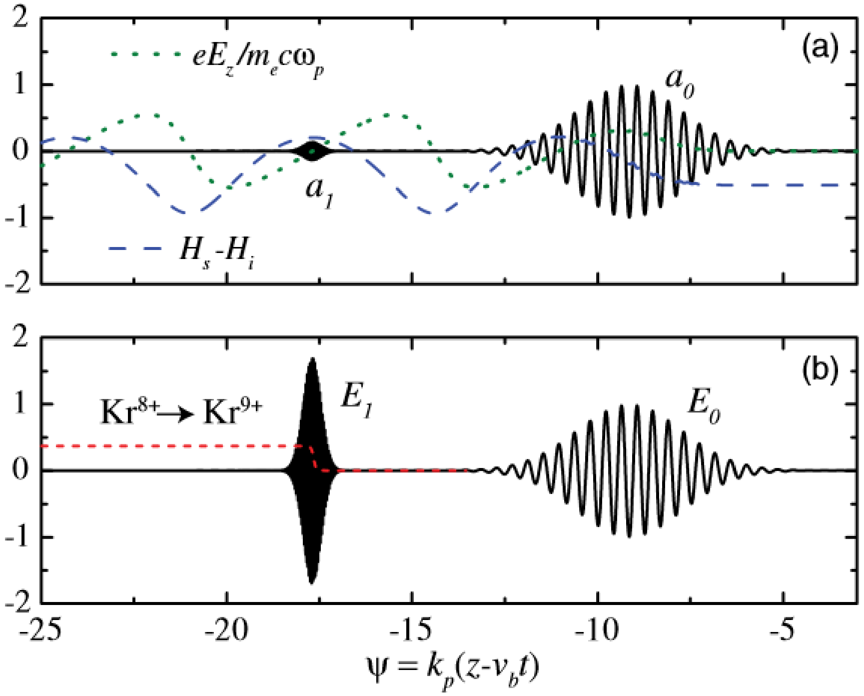
Two-Color Laser-Ionization Injection

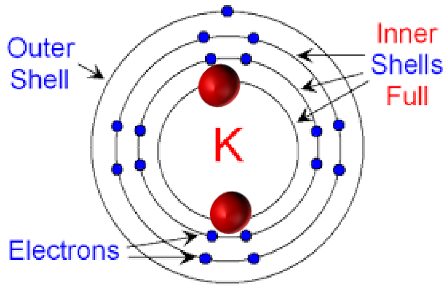
L.-L. Yu,[1,2,3] E. Esarey,[1] C. B. Schroeder,[1] J.-L. Vay,[1] C. Benedetti,[1] C. G. R. Geddes,[1] M. Chen,[3] and W. P. Leemans[1,2]
[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
[3]*Key Laboratory for Laser Plasmas (Ministry of Education), Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*

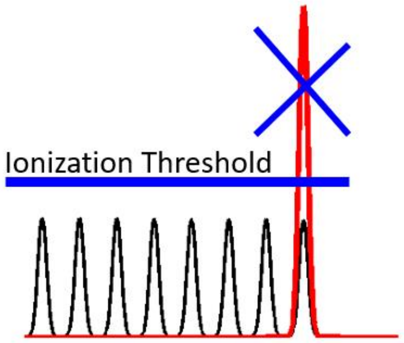
(Received 31 July 2013; published 24 March 2014)

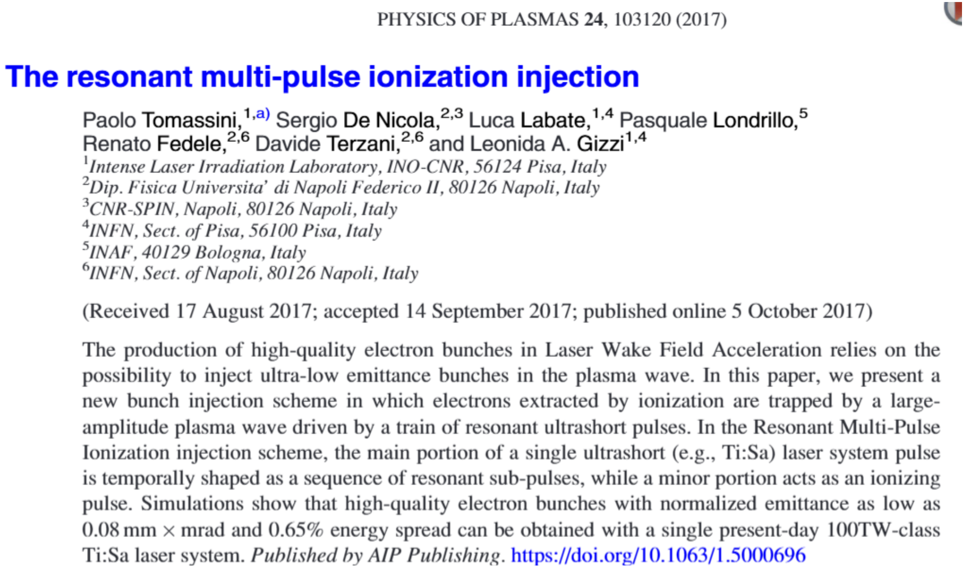
A method is proposed to generate femtosecond, ultralow emittance ($\sim 10^{-8}$ m rad), electron beams in a laser-plasma accelerator using two lasers of different colors. A long-wavelength pump pulse, with a large ponderomotive force and small peak electric field, excites a wake without fully ionizing a high-Z gas. A short-wavelength injection pulse, with a small ponderomotive force and large peak electric field, copropagating and delayed with respect to the pump laser, ionizes a fraction of the remaining bound electrons at a trapping wake phase, generating an electron beam that is accelerated in the wake.

DOI: 10.1103/PhysRevLett.112.125001 PACS numbers: 52.38.Kd, 52.25.Jm









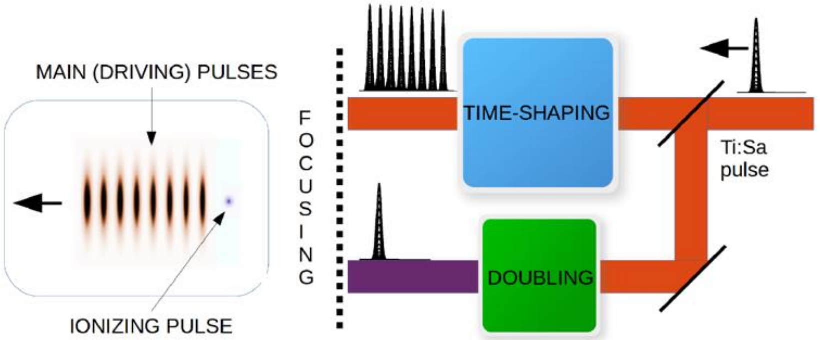
PHYSICS OF PLASMAS 24, 103120 (2017)

The resonant multi-pulse ionization injection

Paolo Tomassini,[1,a)] Sergio De Nicola,[2,3] Luca Labate,[1,4] Pasquale Londrillo,[5] Renato Fedele,[2,6] Davide Terzani,[2,6] and Leonida A. Gizzi[1,4]
[1]*Intense Laser Irradiation Laboratory, INO-CNR, 56124 Pisa, Italy*
[2]*Dip. Fisica Universita' di Napoli Federico II, 80126 Napoli, Italy*
[3]*CNR-SPIN, Napoli, 80126 Napoli, Italy*
[4]*INFN, Sect. of Pisa, 56100 Pisa, Italy*
[5]*INAF, 40129 Bologna, Italy*
[6]*INFN, Sect. of Napoli, 80126 Napoli, Italy*

(Received 17 August 2017; accepted 14 September 2017; published online 5 October 2017)

The production of high-quality electron bunches in Laser Wake Field Acceleration relies on the possibility to inject ultra-low emittance bunches in the plasma wave. In this paper, we present a new bunch injection scheme in which electrons extracted by ionization are trapped by a large-amplitude plasma wave driven by a train of resonant ultrashort pulses. In the Resonant Multi-Pulse Ionization injection scheme, the main portion of a single ultrashort (e.g., Ti:Sa) laser system pulse is temporally shaped as a sequence of resonant sub-pulses, while a minor portion acts as an ionizing pulse. Simulations show that high-quality electron bunches with normalized emittance as low as 0.08 mm × mrad and 0.65% energy spread can be obtained with a single present-day 100TW-class Ti:Sa laser system. *Published by AIP Publishing.* https://doi.org/10.1063/1.5000696



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Two Color and ReMPI Injections

PRL **112,** 125001 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

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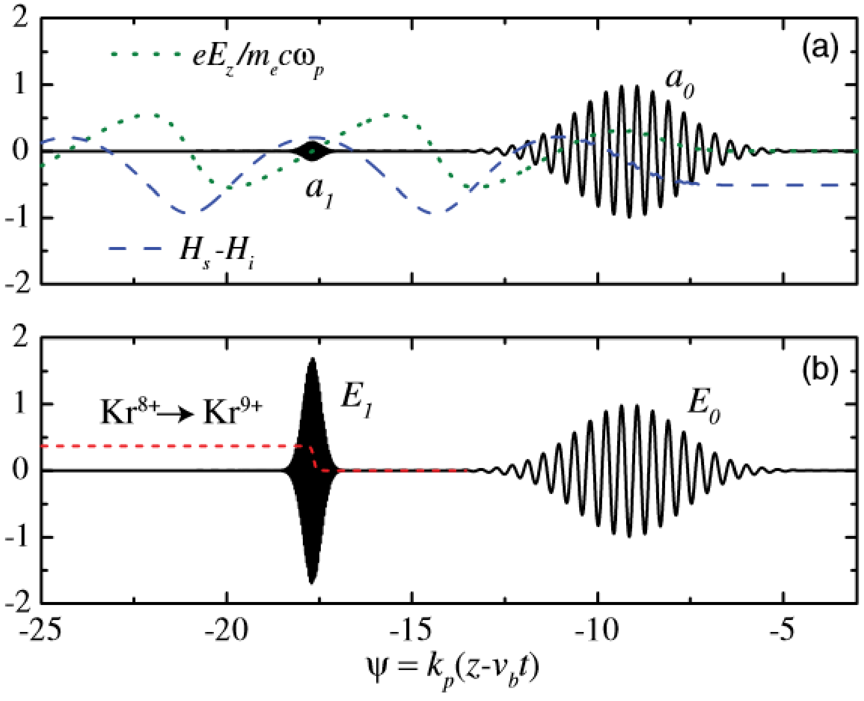

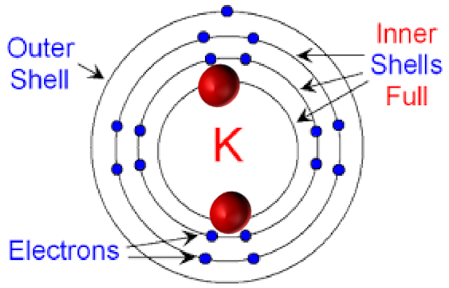

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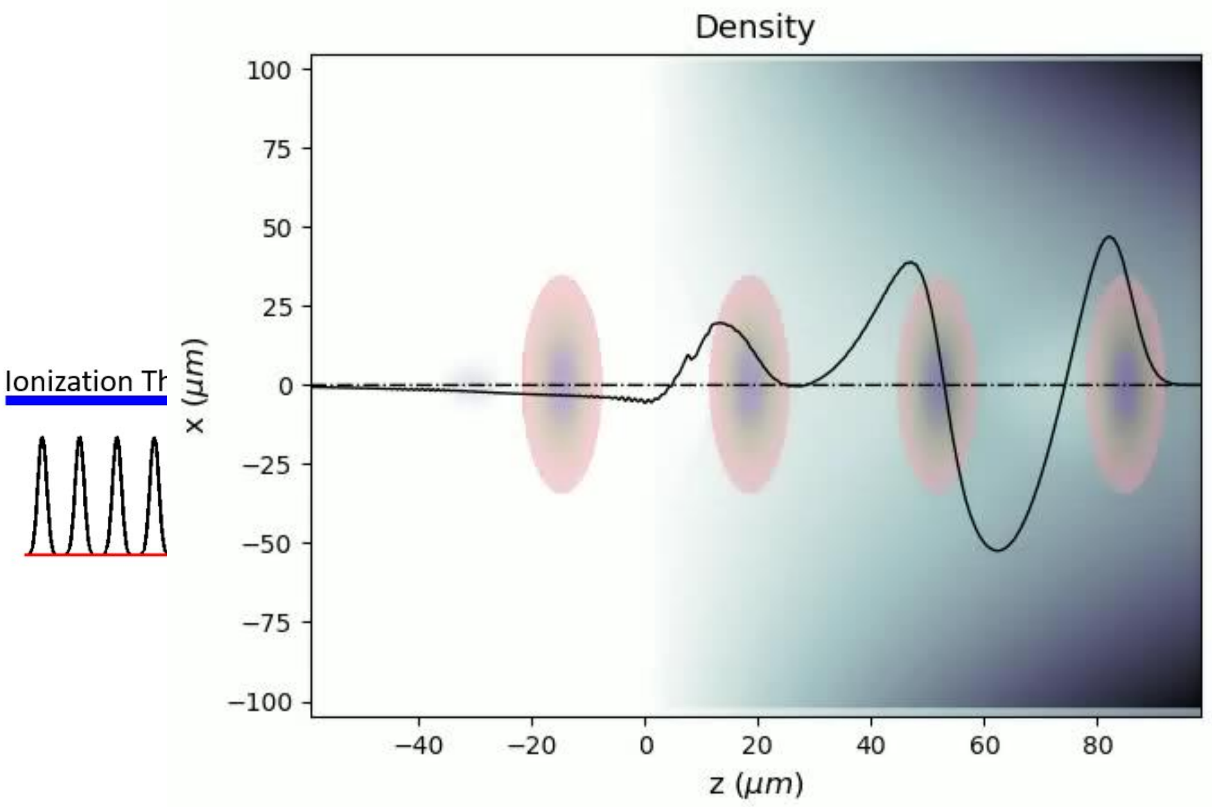
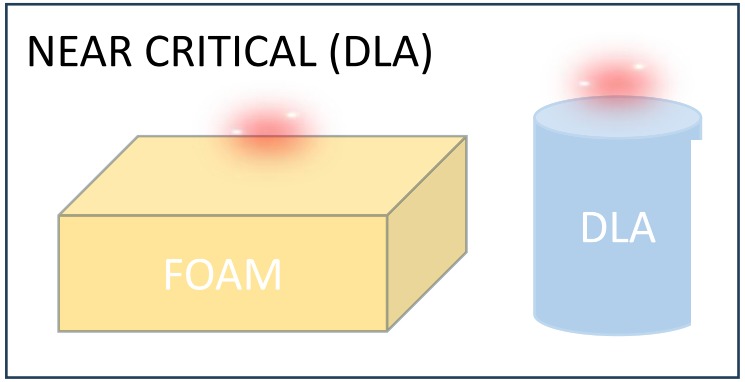
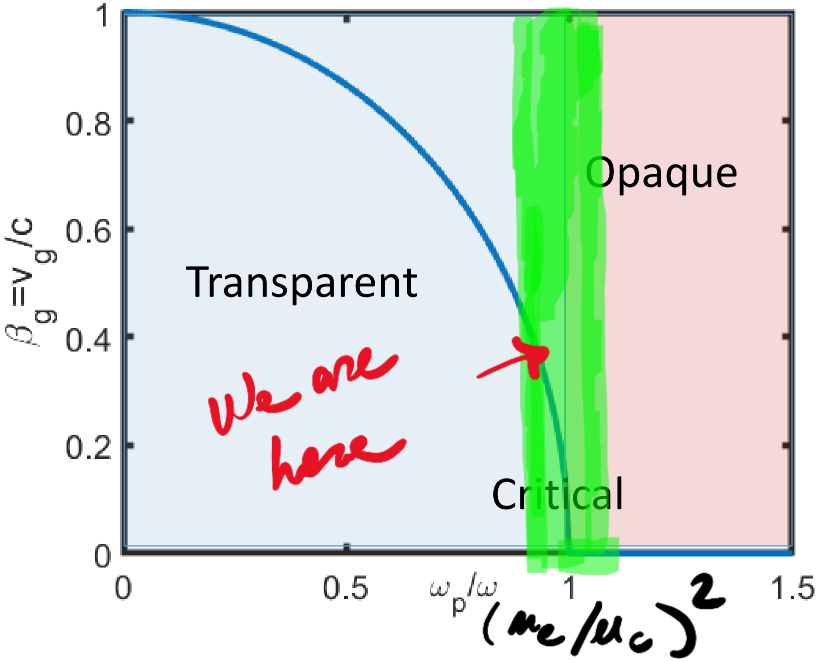
[6]*INFN, Sect. of Napoli, 80126 Napoli, Italy*

(Received 17 August 2017; accepted 14 September 2017; published online 5 October 2017)

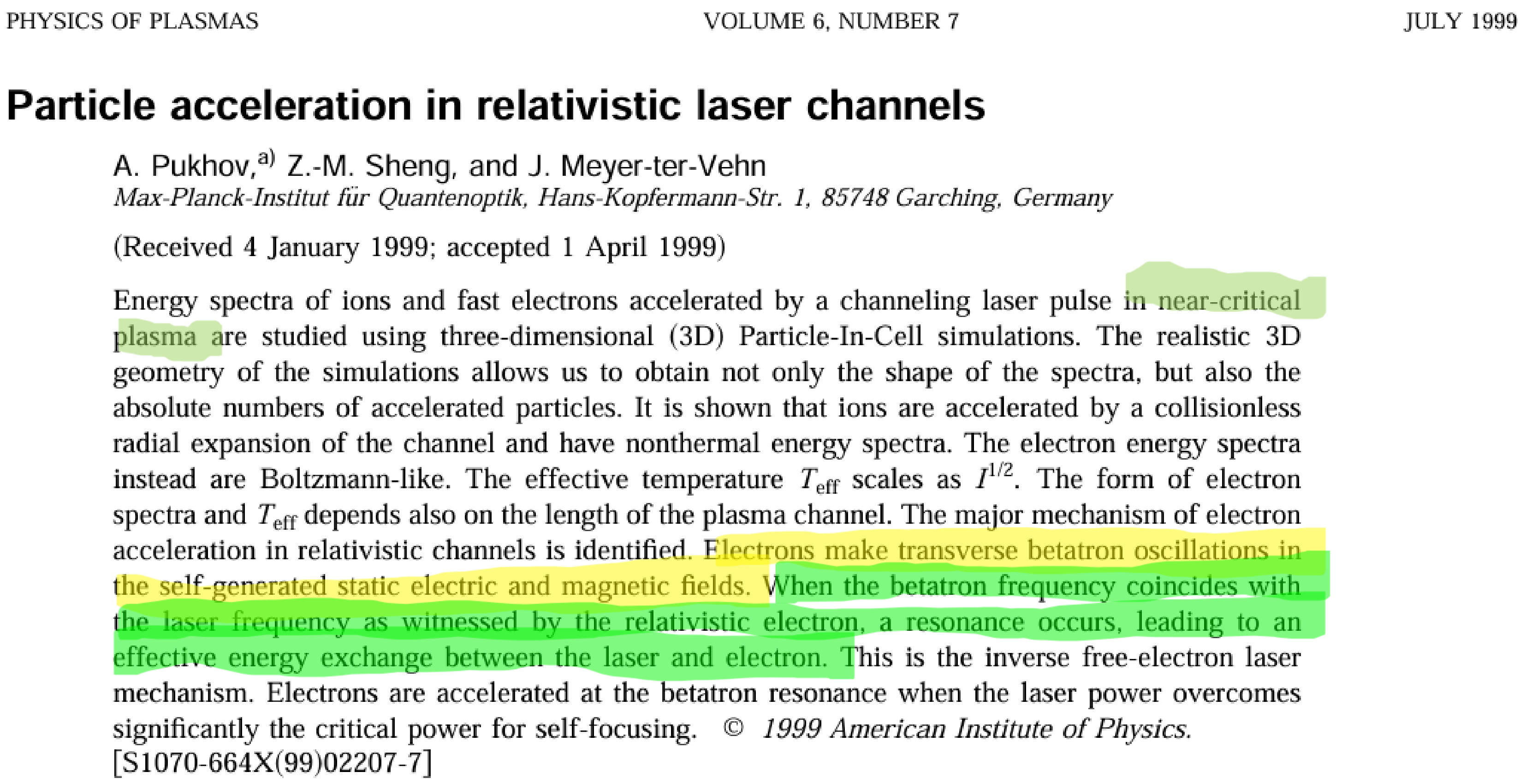


The Direct Laser Acceleration in plasmas (DLA) –[NOT in vacuum]





The original idea of Direct Laser Acceleration in plasmas



PHYSICS OF PLASMAS VOLUME 6, NUMBER 7 JULY 1999

Particle acceleration in relativistic laser channels

A. Pukhov,[a] Z.-M. Sheng, and J. Meyer-ter-Vehn
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

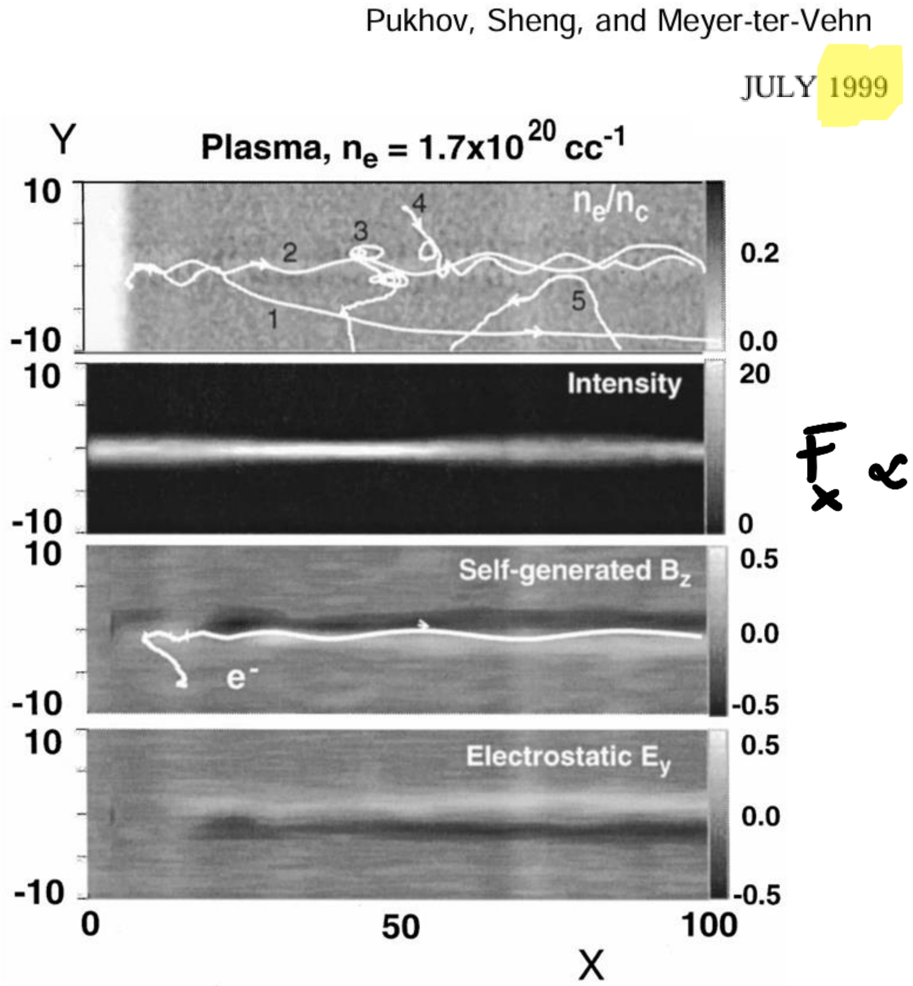
(Received 4 January 1999; accepted 1 April 1999)

Energy spectra of ions and fast electrons accelerated by a channeling laser pulse in near-critical plasma are studied using three-dimensional (3D) Particle-In-Cell simulations. The realistic 3D geometry of the simulations allows us to obtain not only the shape of the spectra, but also the absolute numbers of accelerated particles. It is shown that ions are accelerated by a collisionless radial expansion of the channel and have nonthermal energy spectra. The electron energy spectra instead are Boltzmann-like. The effective temperature T_{eff} scales as $I^{1/2}$. The form of electron spectra and T_{eff} depends also on the length of the plasma channel. The major mechanism of electron acceleration in relativistic channels is identified. Electrons make transverse betatron oscillations in the self-generated static electric and magnetic fields. When the betatron frequency coincides with the laser frequency as witnessed by the relativistic electron, a resonance occurs, leading to an effective energy exchange between the laser and electron. This is the inverse free-electron laser mechanism. Electrons are accelerated at the betatron resonance when the laser power overcomes significantly the critical power for self-focusing.
[S1070-664X(99)02207-7]

Main message: as the density is more than 100x the one we have in LWFA, **a huge amount of charge can be generated (nC + class)**, but **the spectrum** of the- bursts **is broadband** and the **divergence is very high**.

The Direct Laser Acceleration in plasmas (DLA) –[NOT in vacuum]

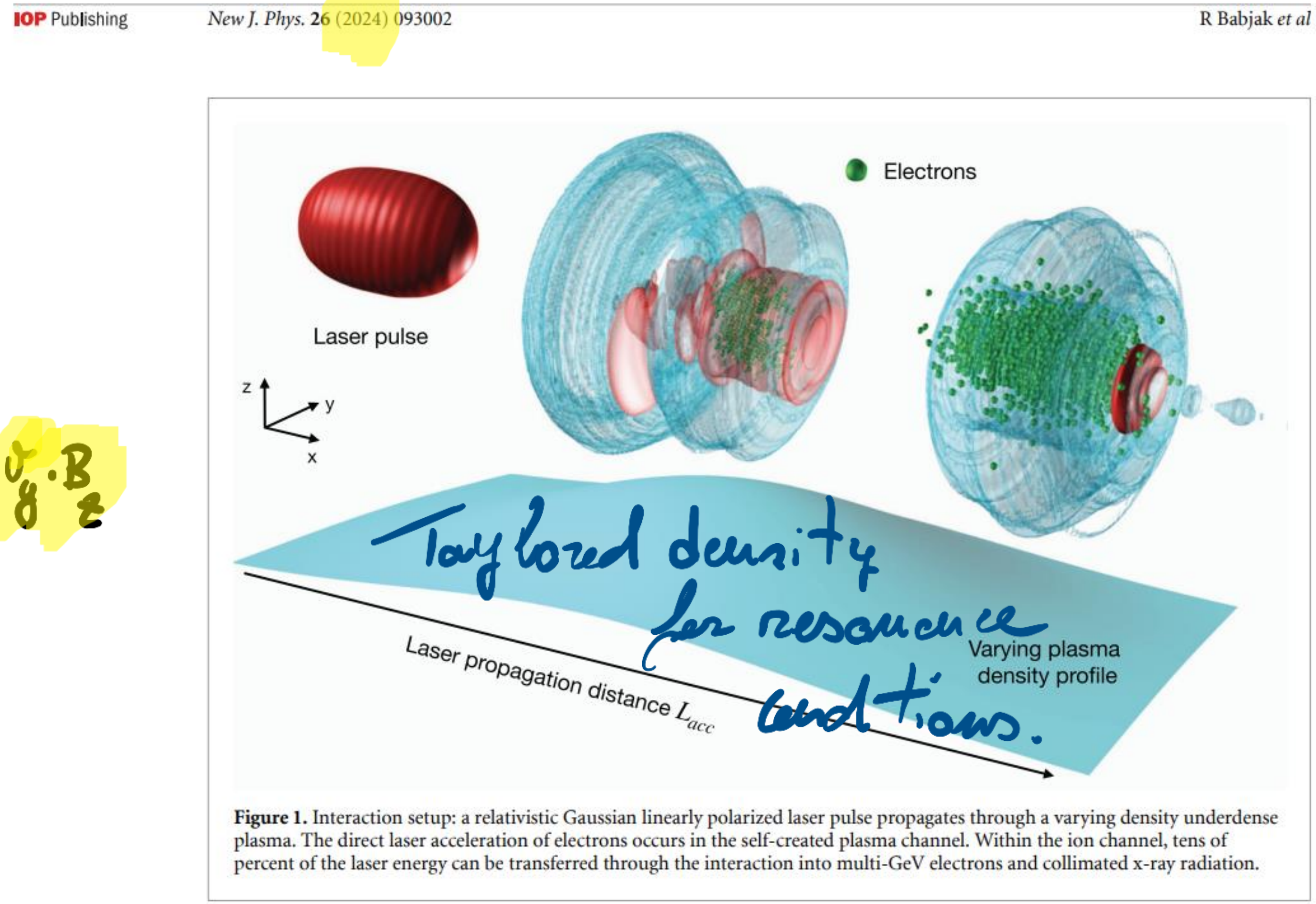
The evolution of Direct Laser Acceleration in plasmas



Pukhov, Sheng, and Meyer-ter-Vehn

JULY 1999

$$F_x \propto E_x + v_y \cdot B_z$$



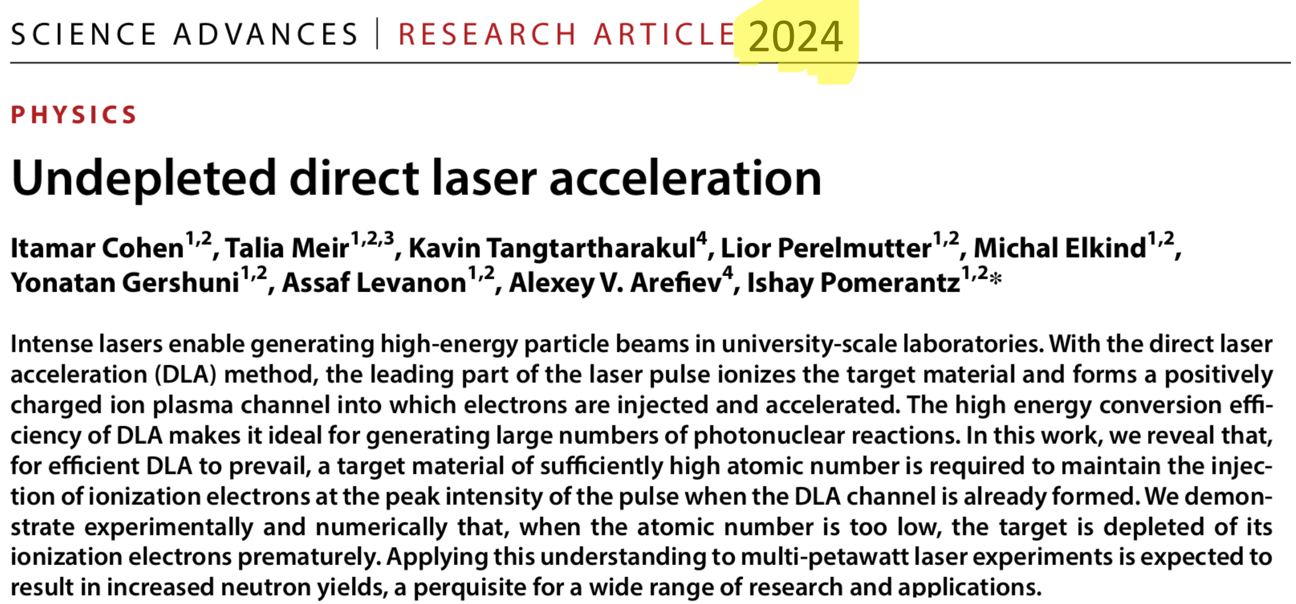
IOP Publishing New J. Phys. 26 (2024) 093002 R Babjak et al

Taylored density for resonance conditions.

Figure 1. Interaction setup: a relativistic Gaussian linearly polarized laser pulse propagates through a varying density underdense plasma. The direct laser acceleration of electrons occurs in the self-created plasma channel. Within the ion channel, tens of percent of the laser energy can be transferred through the interaction into multi-GeV electrons and collimated x-ray radiation.

The Direct Laser Acceleration in plasmas (DLA) –[NOT in vacuum]

Latest results in Direct Laser Acceleration in plasmas



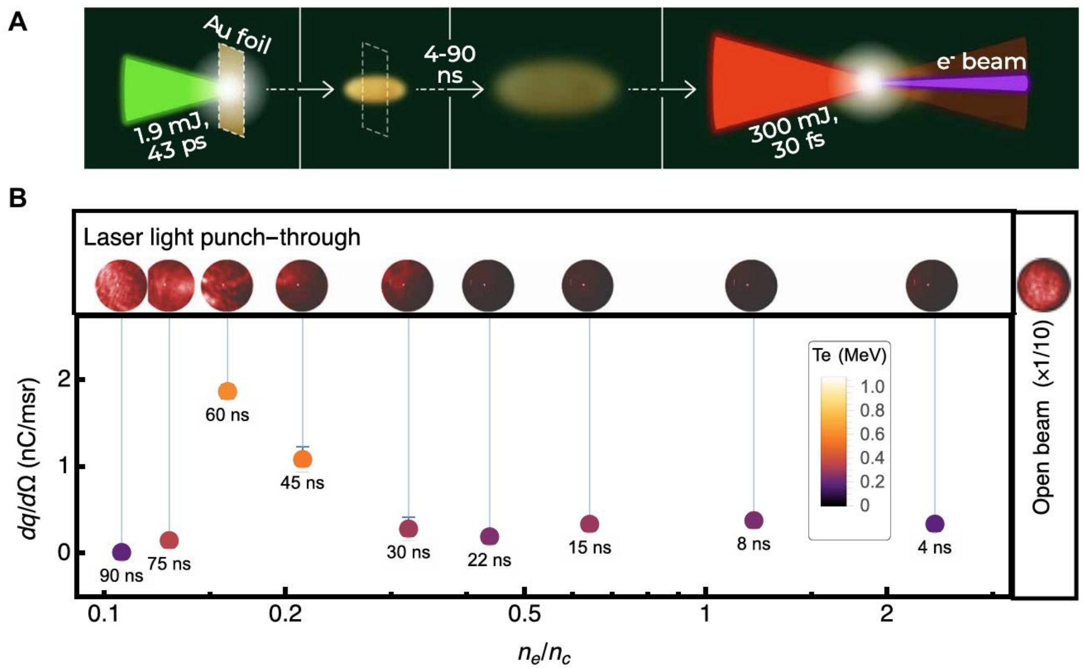
SCIENCE ADVANCES | RESEARCH ARTICLE 2024

PHYSICS

Undepleted direct laser acceleration

Itamar Cohen[1,2], Talia Meir[1,2,3], Kavin Tangtartharakul[4], Lior Perelmutter[1,2], Michal Elkind[1,2], Yonatan Gershuni[1,2], Assaf Levanon[1,2], Alexey V. Arefiev[4], Ishay Pomerantz[1,2]*

Intense lasers enable generating high-energy particle beams in university-scale laboratories. With the direct laser acceleration (DLA) method, the leading part of the laser pulse ionizes the target material and forms a positively charged ion plasma channel into which electrons are injected and accelerated. The high energy conversion efficiency of DLA makes it ideal for generating large numbers of photonuclear reactions. In this work, we reveal that, for efficient DLA to prevail, a target material of sufficiently high atomic number is required to maintain the injection of ionization electrons at the peak intensity of the pulse when the DLA channel is already formed. We demonstrate experimentally and numerically that, when the atomic number is too low, the target is depleted of its ionization electrons prematurely. Applying this understanding to multi-petawatt laser experiments is expected to result in increased neutron yields, a perquisite for a wide range of research and applications.



Experiments done with a 20TW system

Direct application on neutron generation are foreseen (see after in the presentation)

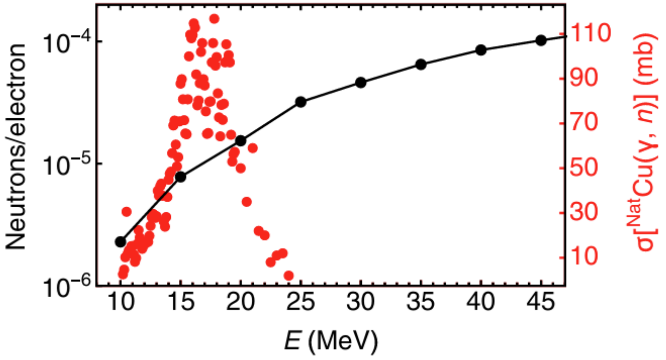
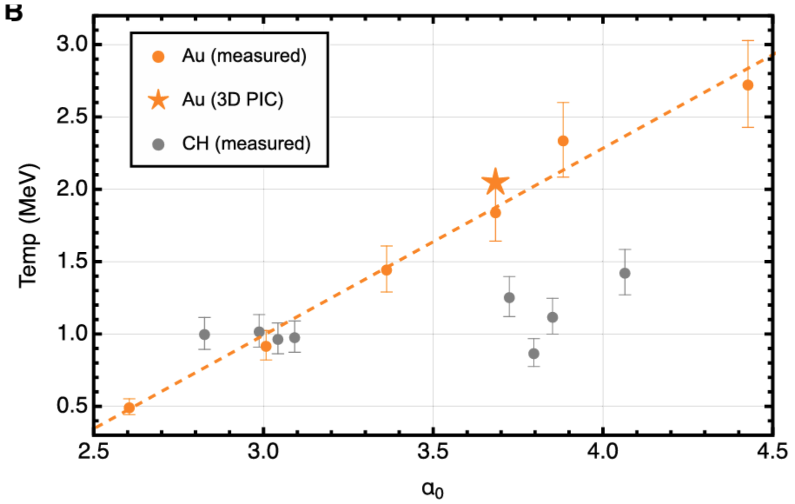
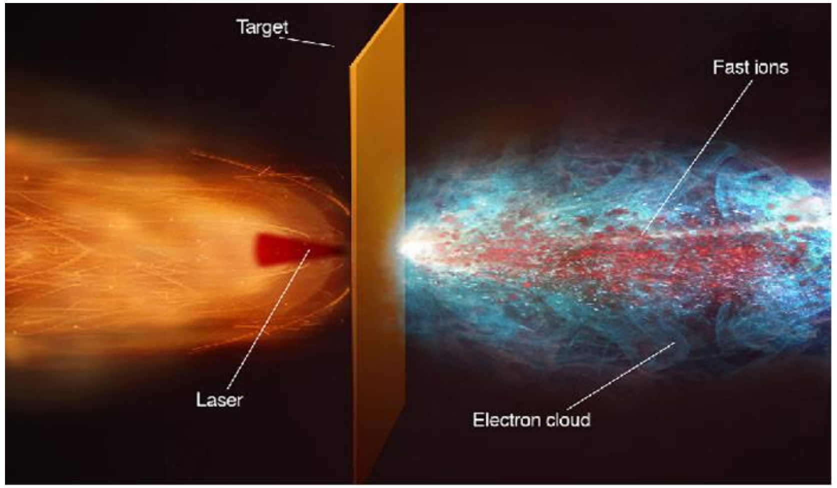


Fig. 6. The efficiency of photoneutron generation using mega–electron volt–level electron beams. Each data point (black) represents the results of a particle transport simulation of a monoenergetic electron beam impinging on a 10-cm-thick Cu block. Shown in red are measured cross sections (48) of the $^{Nat}Cu(\gamma, n)$ reaction.



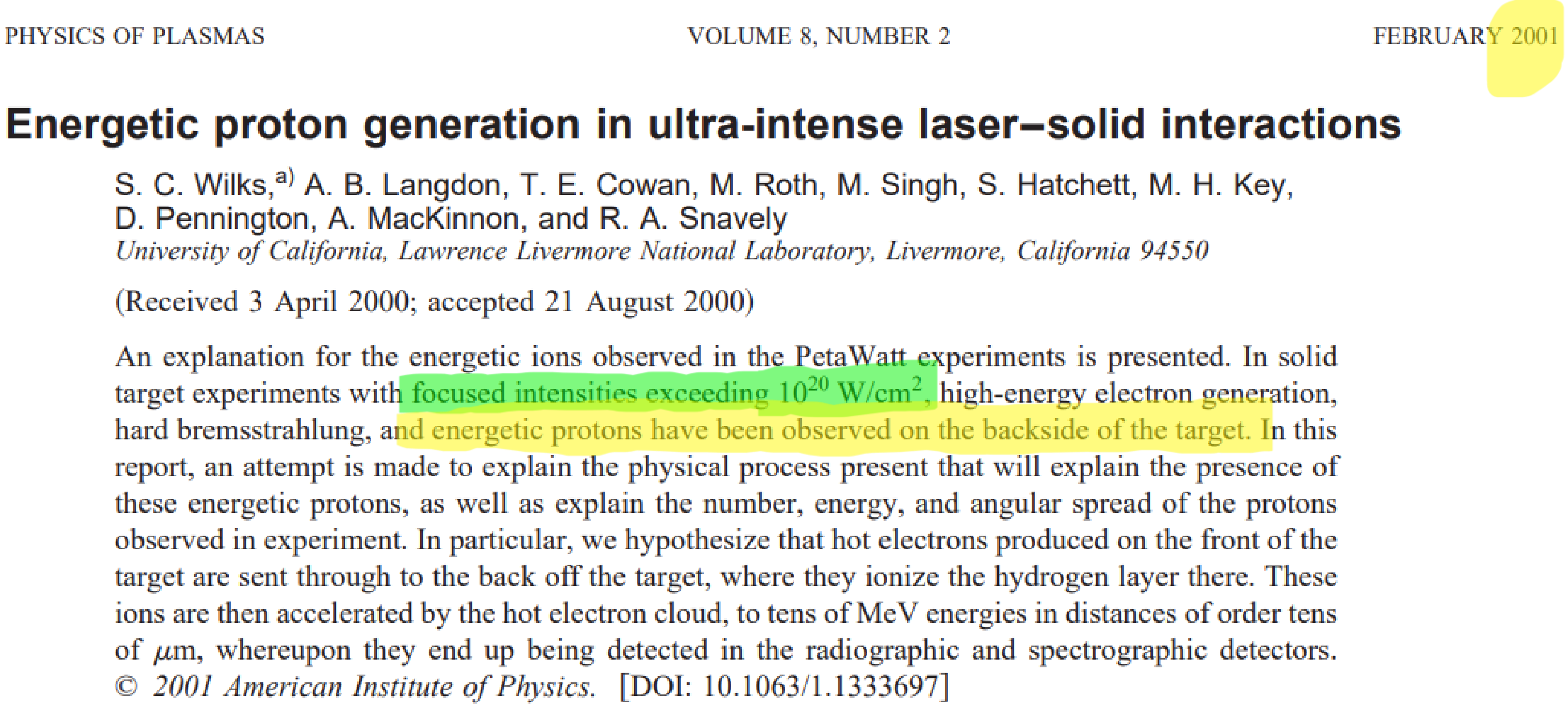
The laser-”solid” interaction

OVER DENSE (TNSA)



https://lasers.llnl.gov/news/powerful-new-source-high-energy-protons

The basis: the **<u>T</u>arget <u>N</u>ormal <u>S</u>heath <u>A</u>cceleration** of protons and ions



PHYSICS OF PLASMAS VOLUME 8, NUMBER 2 FEBRUARY 2001

Energetic proton generation in ultra-intense laser–solid interactions

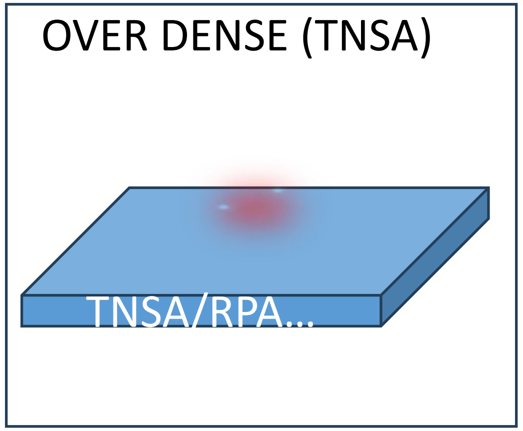
S. C. Wilks,[a] A. B. Langdon, T. E. Cowan, M. Roth, M. Singh, S. Hatchett, M. H. Key, D. Pennington, A. MacKinnon, and R. A. Snavely
University of California, Lawrence Livermore National Laboratory, Livermore, California 94550

(Received 3 April 2000; accepted 21 August 2000)

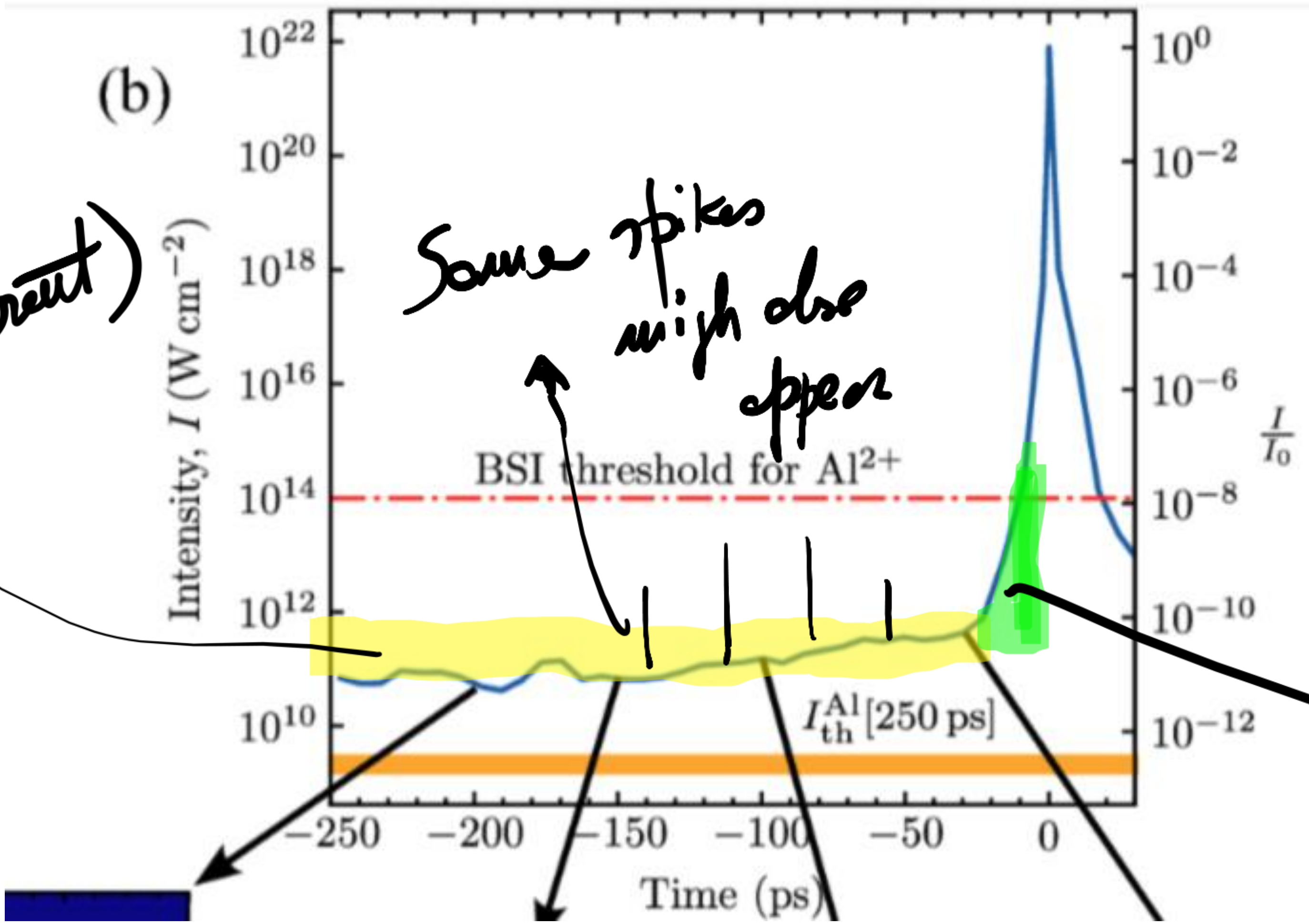
An explanation for the energetic ions observed in the PetaWatt experiments is presented. In solid target experiments with focused intensities exceeding 10^{20} W/cm^2, high-energy electron generation, hard bremsstrahlung, and energetic protons have been observed on the backside of the target. In this report, an attempt is made to explain the physical process present that will explain the presence of these energetic protons, as well as explain the number, energy, and angular spread of the protons observed in experiment. In particular, we hypothesize that hot electrons produced on the front of the target are sent through to the back off the target, where they ionize the hydrogen layer there. These ions are then accelerated by the hot electron cloud, to tens of MeV energies in distances of order tens of μm, whereupon they end up being detected in the radiographic and spectrographic detectors. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1333697]

See the presentation by Alessio Del Dotto on yesterday

The laser-"solid" interaction



PREPULSE/PEDESTAL

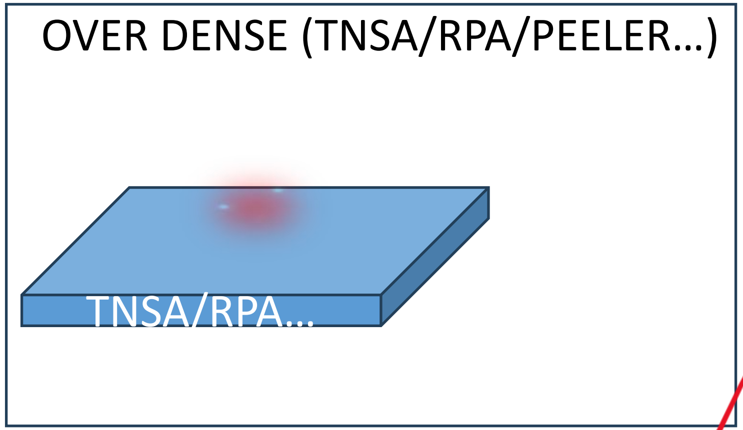


ASE (NOT coherent)
Prepulse

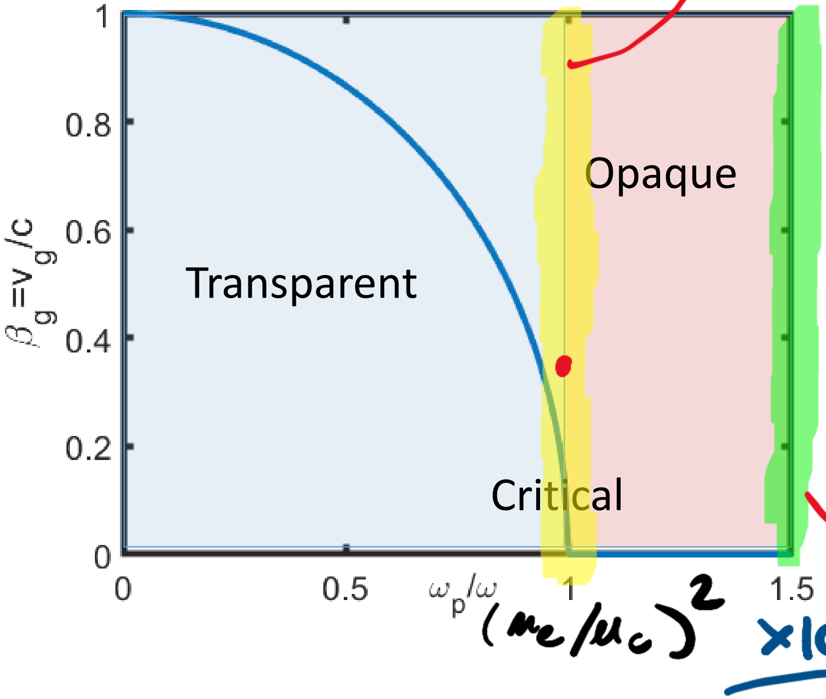
Some spikes
might also
appear

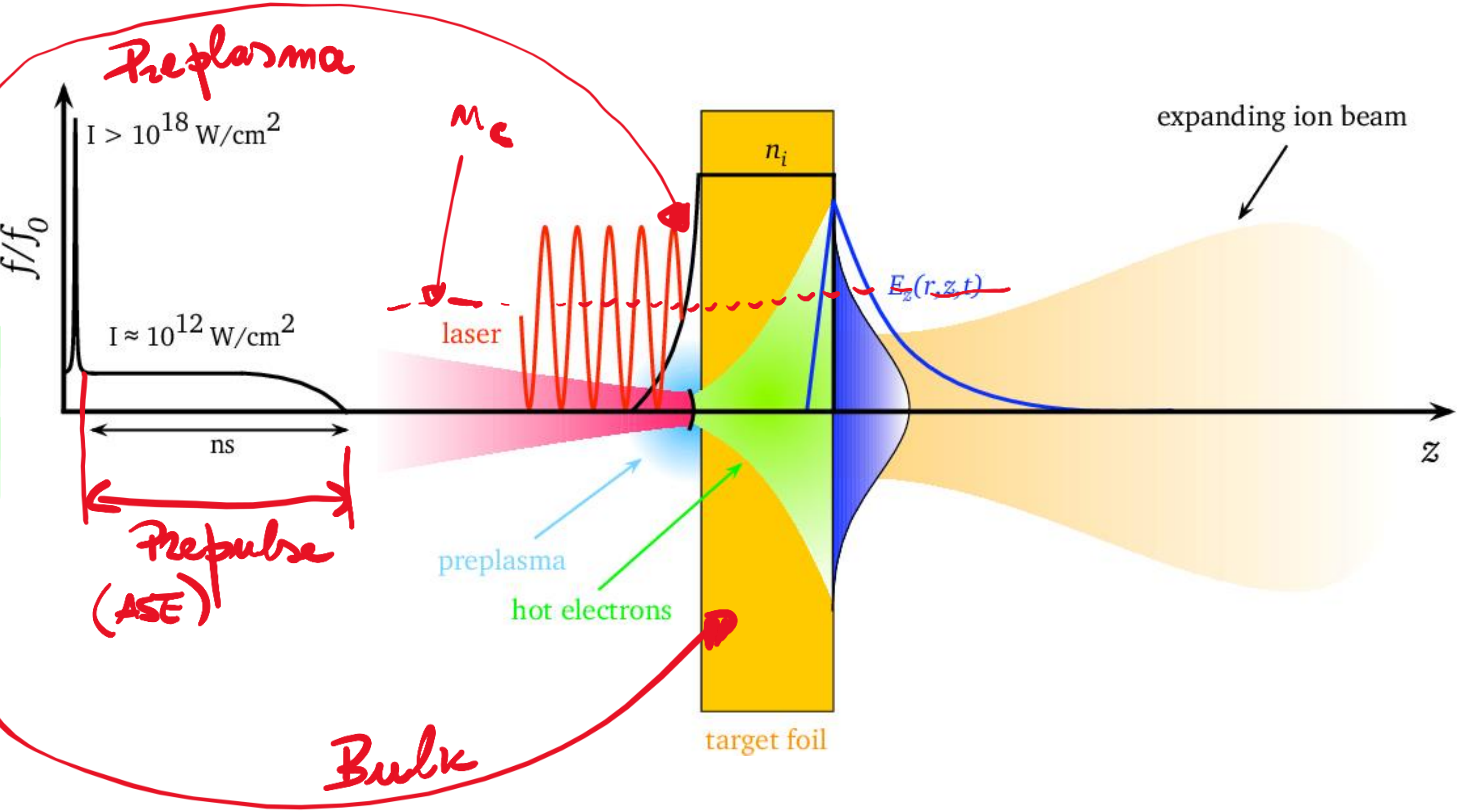
Pedestal
(coherent)

The laser-”solid” interaction



The basis: the **T**arget **N**ormal **S**heath **A**cceleration of protons and ions





We are in both the conditions!

M. Roth and M . Shollmeier, **Ion Acceleration - Target Normal Sheath Acceleration,** DOI:10.5170/CERN-2016-001.231

The laser-”solid” interaction

OVER DENSE (TNSA)

The basis: the **Target Normal Sheath Acceleration** of protons and ions

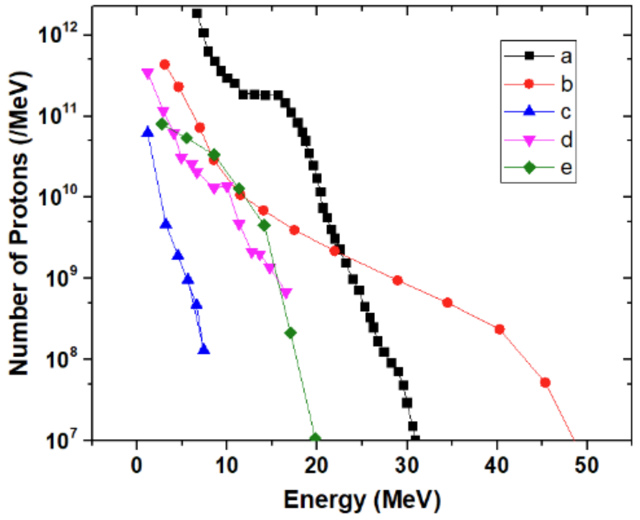
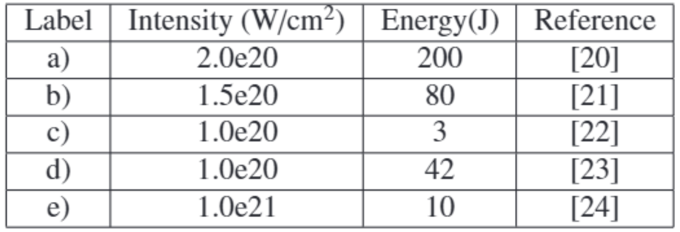


Figure 1: Comparison of proton spectrum emerging in different experiments. For the symbol caption see the Table 1



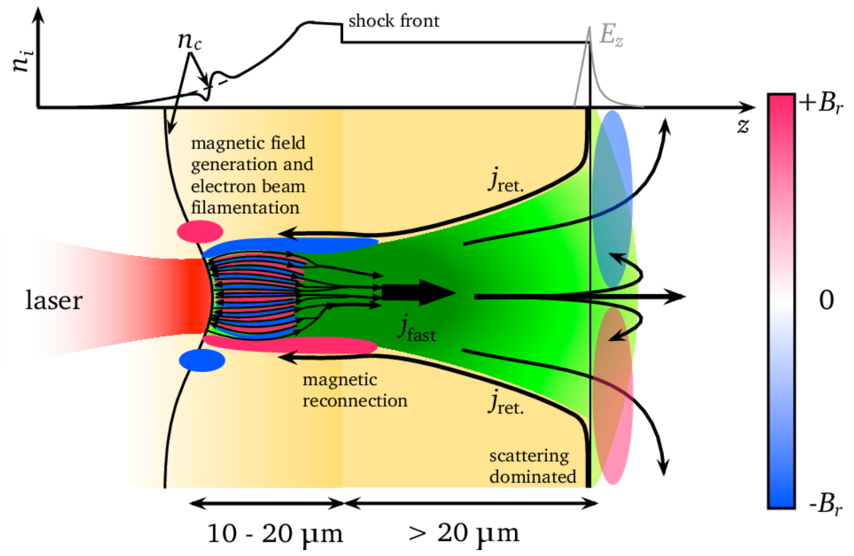
Label	Intensity (W/cm^2)	Energy(J)	Reference
a)	2.0e20	200	[20]
b)	1.5e20	80	[21]
c)	1.0e20	3	[22]
d)	1.0e20	42	[23]
e)	1.0e21	10	[24]

ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 909, 12 November 2018, Pages 323-326

A complementary compact laser based neutron source

A. Cianchi [a b], C. Andreani [a b c d], R. Bedogni [e], G. Festa [c], O. Sans-Planell [e], R. Senesi [a b c d]



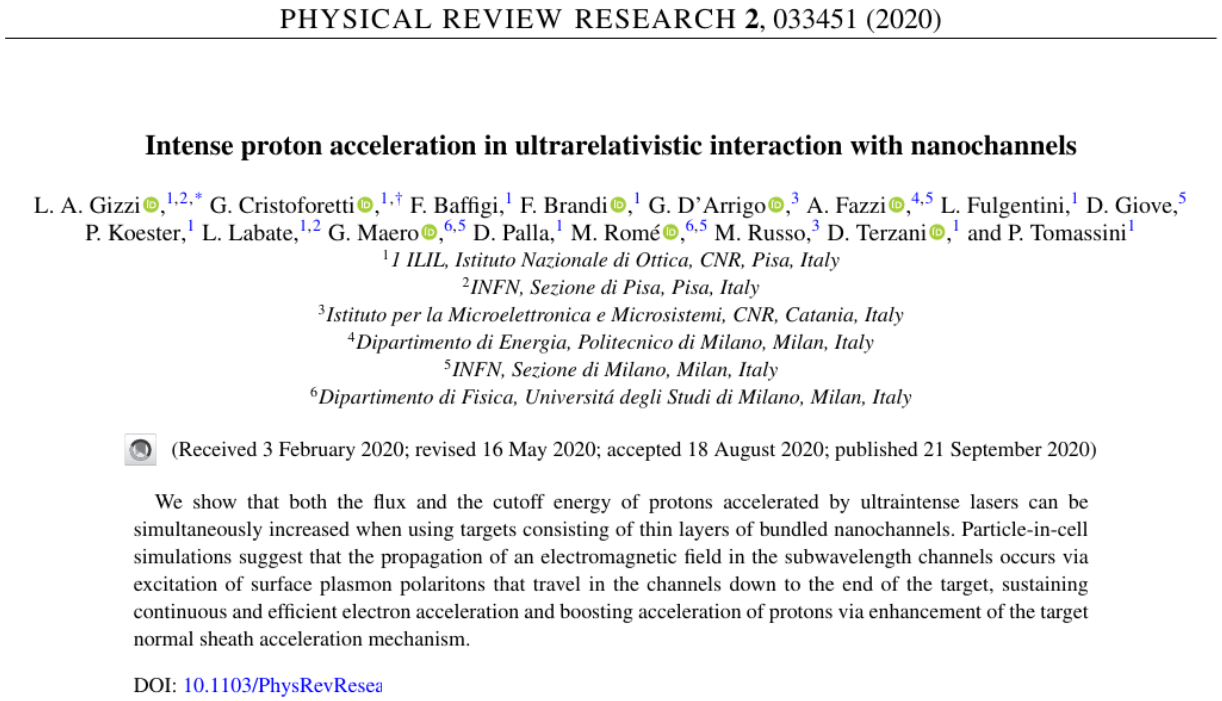
M. Roth and M . Shollmeier, **Ion Acceleration - Target Normal Sheath Acceleration,** DOI:10.5170/CERN-2016-001.231

The laser-”solid” interaction

OVER DENSE (TNSA)

The basis: the **Target Normal Sheath Acceleration** of protons and ions

NANO STRUCTURED TARGETS


PHYSICAL REVIEW RESEARCH **2**, 033451 (2020)

Intense proton acceleration in ultrarelativistic interaction with nanochannels

L. A. Gizzi,[1,2,*] G. Cristoforetti,[1,†] F. Baffigi,[1] F. Brandi,[1] G. D’Arrigo,[3] A. Fazzi,[4,5] L. Fulgentini,[1] D. Giove,[5] P. Koester,[1] L. Labate,[1,2] G. Maero,[6,5] D. Palla,[1] M. Romé,[6,5] M. Russo,[3] D. Terzani,[1] and P. Tomassini[1]
[1] *1 ILIL, Istituto Nazionale di Ottica, CNR, Pisa, Italy*
[2] *INFN, Sezione di Pisa, Pisa, Italy*
[3] *Istituto per la Microelettronica e Microsistemi, CNR, Catania, Italy*
[4] *Dipartimento di Energia, Politecnico di Milano, Milan, Italy*
[5] *INFN, Sezione di Milano, Milan, Italy*
[6] *Dipartimento di Fisica, Universitá degli Studi di Milano, Milan, Italy*

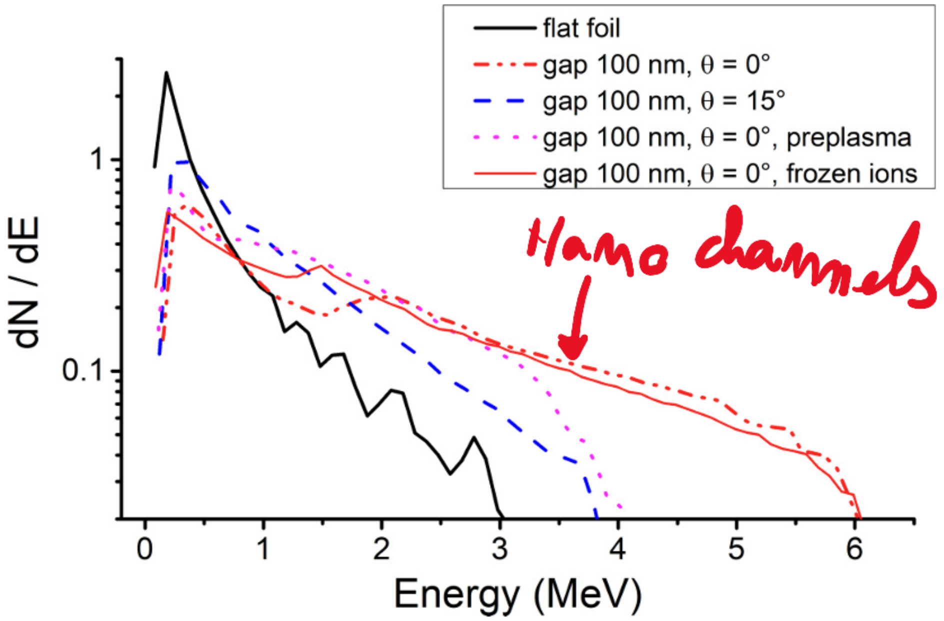
(Received 3 February 2020; revised 16 May 2020; accepted 18 August 2020; published 21 September 2020)

We show that both the flux and the cutoff energy of protons accelerated by ultraintense lasers can be simultaneously increased when using targets consisting of thin layers of bundled nanochannels. Particle-in-cell simulations suggest that the propagation of an electromagnetic field in the subwavelength channels occurs via excitation of surface plasmon polaritons that travel in the channels down to the end of the target, sustaining continuous and efficient electron acceleration and boosting acceleration of protons via enhancement of the target normal sheath acceleration mechanism.

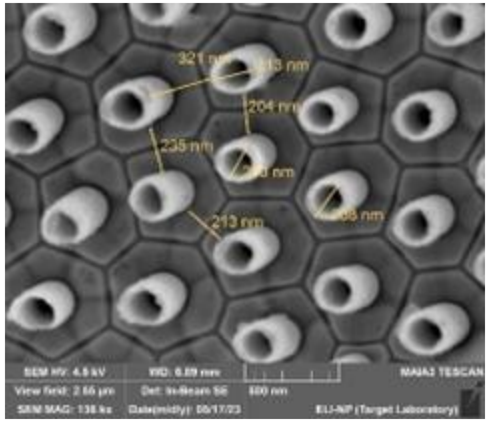
DOI: 10.1103/PhysRevResea

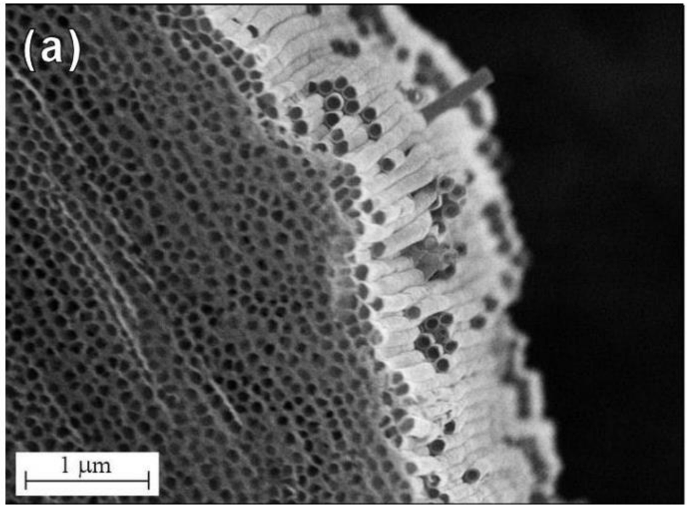
100TW experiment in CNR-INO

L. A. GIZZI *et al.*



Nano channels

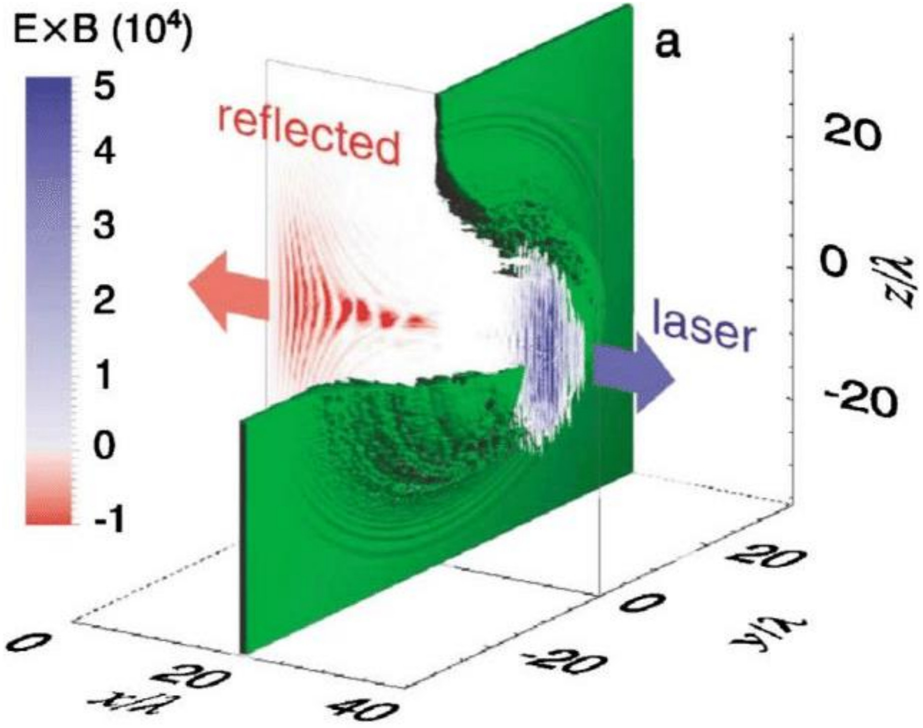




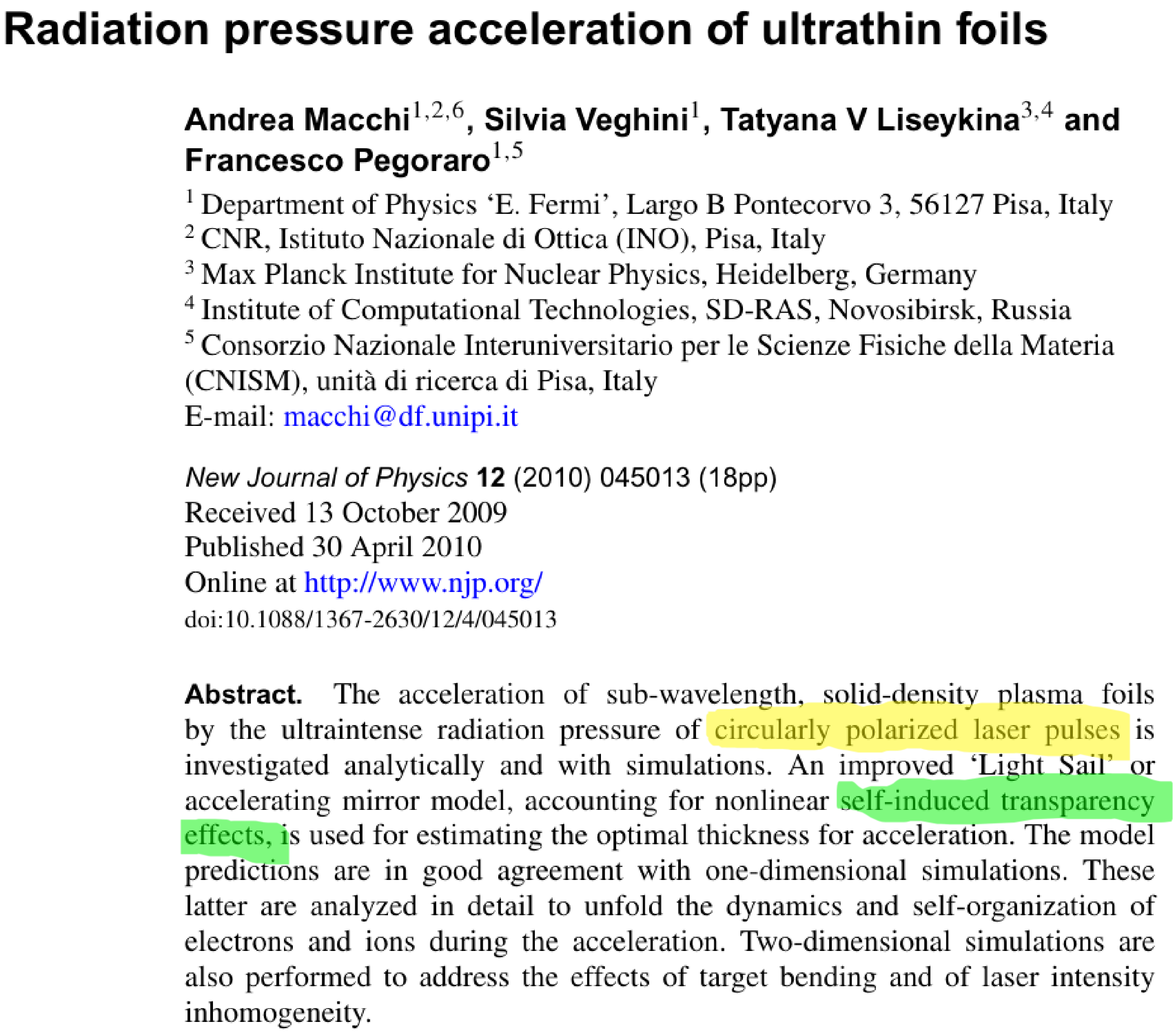
The laser-"solid" interaction

OVER DENSE (TNSA/RPA)

Next level: the **<u>Radiation Pressure Acceleration/Light Sail</u>** of protons and ions



A. Macchi CNR-INO Pisa



Radiation pressure acceleration of ultrathin foils

Andrea Macchi[1,2,6], **Silvia Veghini**[1], **Tatyana V Liseykina**[3,4] and **Francesco Pegoraro**[1,5]

[1] Department of Physics 'E. Fermi', Largo B Pontecorvo 3, 56127 Pisa, Italy
[2] CNR, Istituto Nazionale di Ottica (INO), Pisa, Italy
[3] Max Planck Institute for Nuclear Physics, Heidelberg, Germany
[4] Institute of Computational Technologies, SD-RAS, Novosibirsk, Russia
[5] Consorzio Nazionale Interuniversitario per le Scienze Fisiche della Materia (CNISM), unità di ricerca di Pisa, Italy
E-mail: macchi@df.unipi.it

New Journal of Physics **12** (2010) 045013 (18pp)
Received 13 October 2009
Published 30 April 2010
Online at http://www.njp.org/
doi:10.1088/1367-2630/12/4/045013

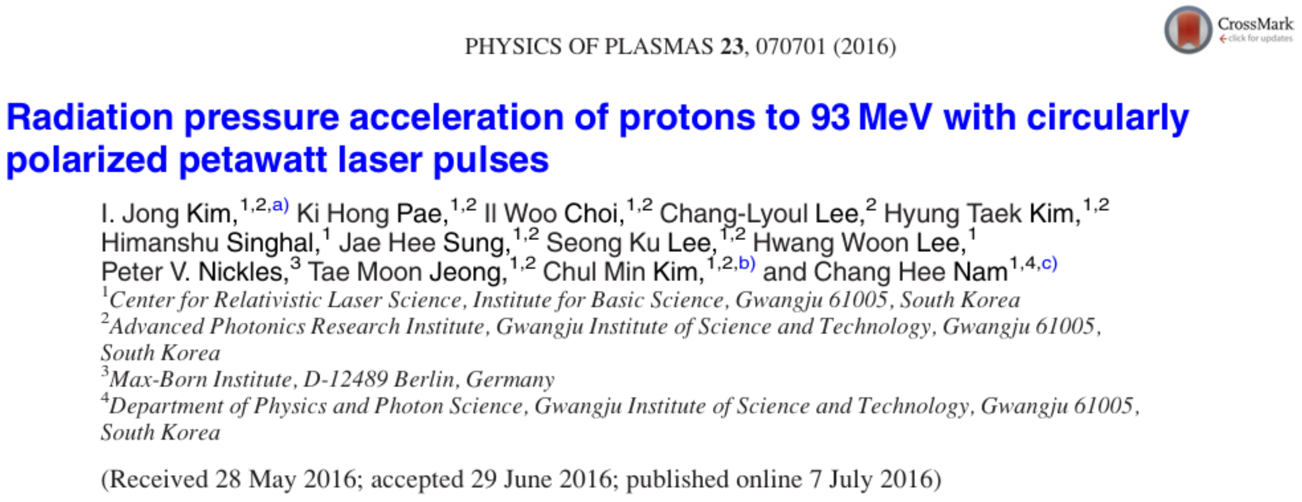
Abstract. The acceleration of sub-wavelength, solid-density plasma foils by the ultraintense radiation pressure of circularly polarized laser pulses is investigated analytically and with simulations. An improved 'Light Sail' or accelerating mirror model, accounting for nonlinear self-induced transparency effects, is used for estimating the optimal thickness for acceleration. The model predictions are in good agreement with one-dimensional simulations. These latter are analyzed in detail to unfold the dynamics and self-organization of electrons and ions during the acceleration. Two-dimensional simulations are also performed to address the effects of target bending and of laser intensity inhomogeneity.

The laser-”solid” interaction

OVER DENSE (TNSA/RPA)

Next level: the **Radiation Pressure Acceleration/Light Sail** of protons and io

Experimental results a CoRELS

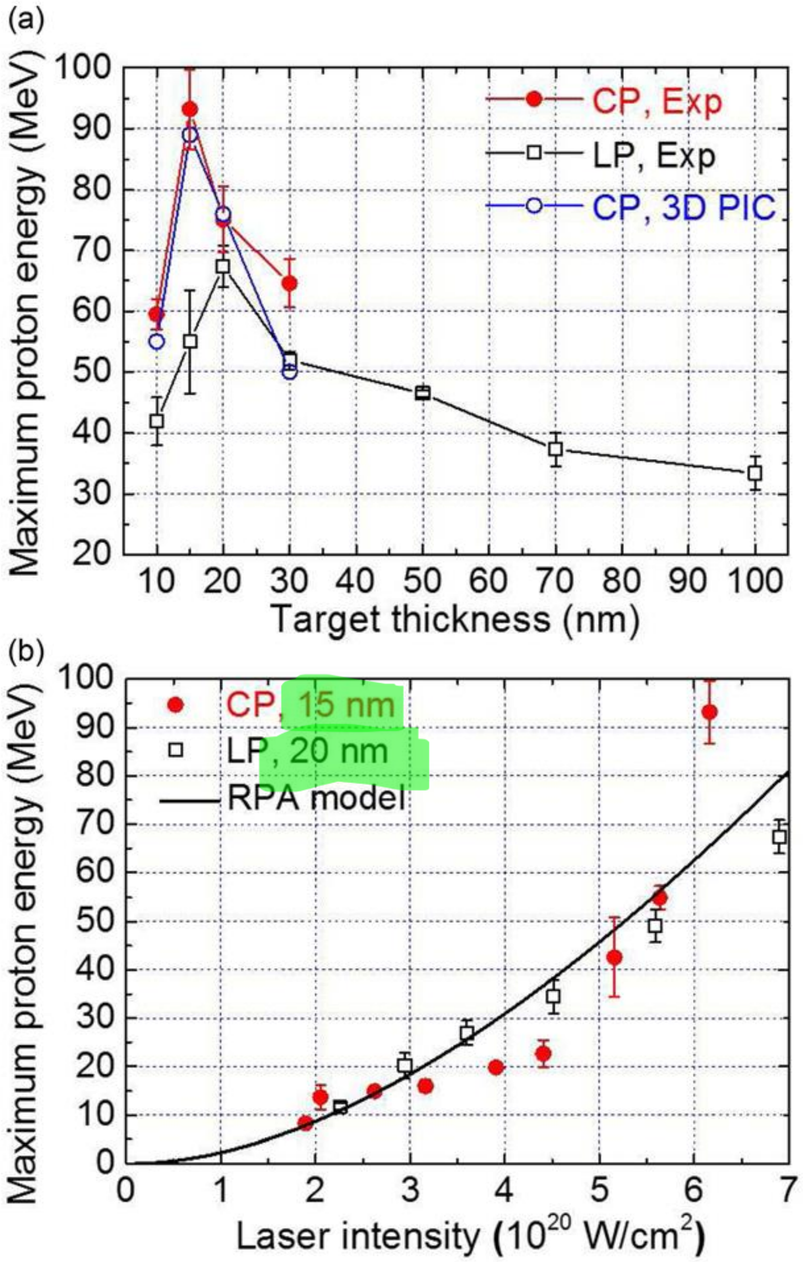


PHYSICS OF PLASMAS **23**, 070701 (2016)

Radiation pressure acceleration of protons to 93 MeV with circularly polarized petawatt laser pulses

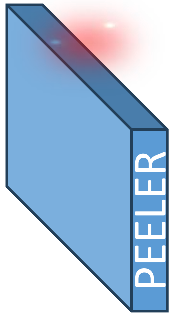
I. Jong Kim,[1,2,a)] Ki Hong Pae,[1,2] Il Woo Choi,[1,2] Chang-Lyoul Lee,[2] Hyung Taek Kim,[1,2]
Himanshu Singhal,[1] Jae Hee Sung,[1,2] Seong Ku Lee,[1,2] Hwang Woon Lee,[1]
Peter V. Nickles,[3] Tae Moon Jeong,[1,2] Chul Min Kim,[1,2,b)] and Chang Hee Nam[1,4,c)]
[1]*Center for Relativistic Laser Science, Institute for Basic Science, Gwangju 61005, South Korea*
[2]*Advanced Photonics Research Institute, Gwangju Institute of Science and Technology, Gwangju 61005, South Korea*
[3]*Max-Born Institute, D-12489 Berlin, Germany*
[4]*Department of Physics and Photon Science, Gwangju Institute of Science and Technology, Gwangju 61005, South Korea*

(Received 28 May 2016; accepted 29 June 2016; published online 7 July 2016)



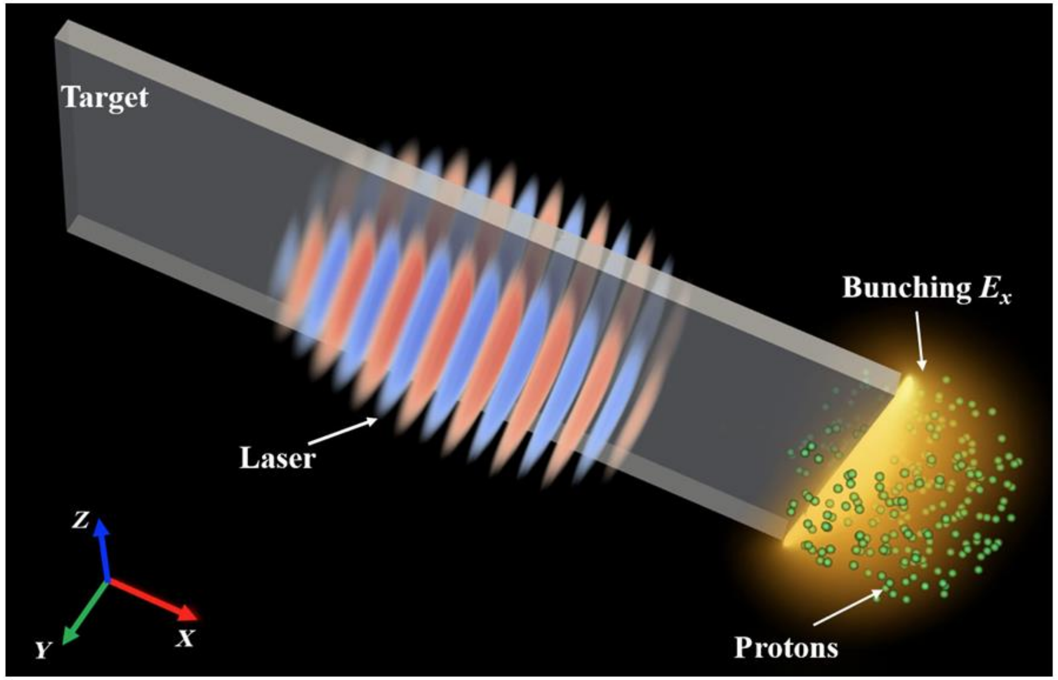
The laser-”solid” interaction

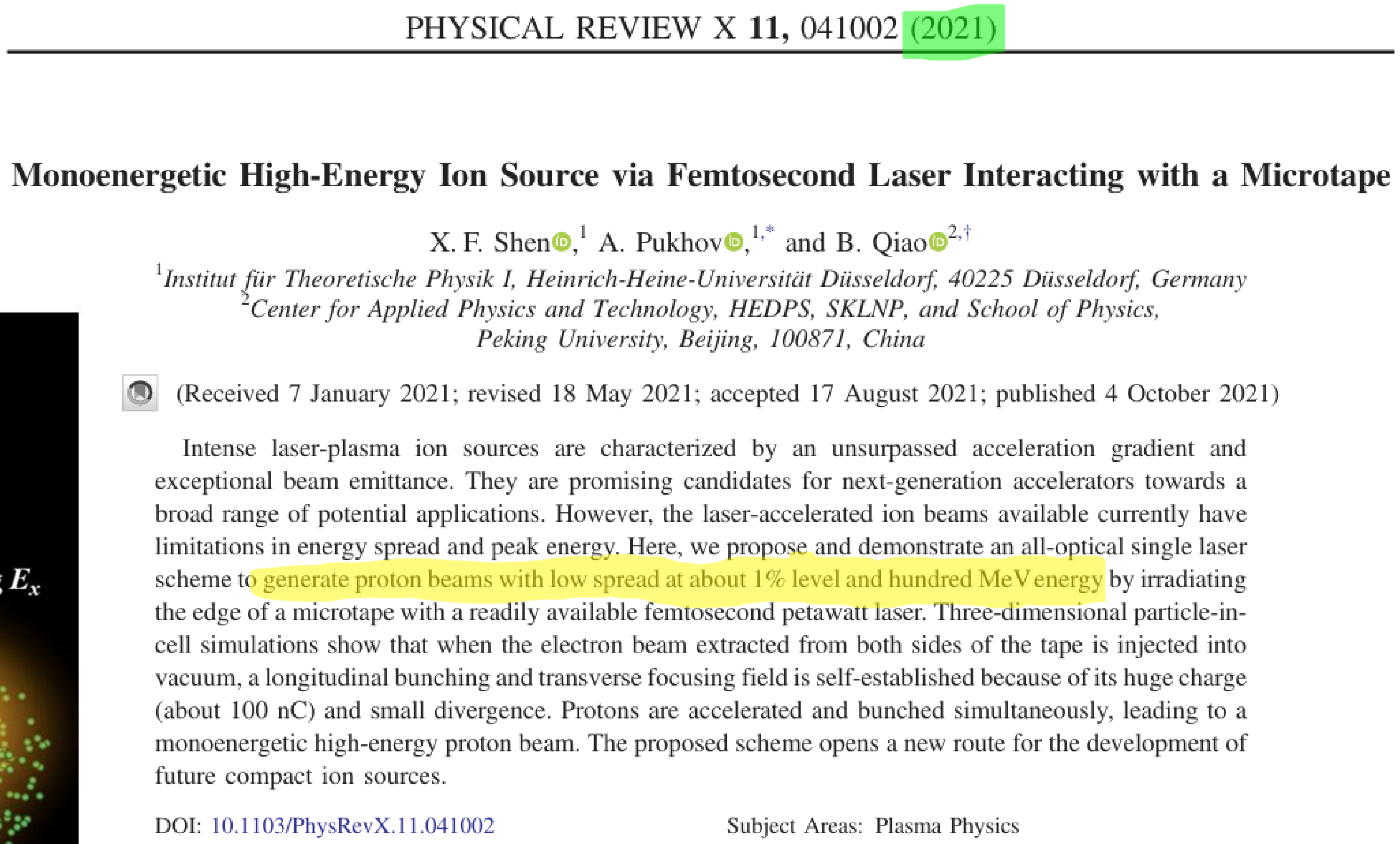
OVER DENSE (PEELER)



Next next level: the

<u>PEELER acceleration</u>





PHYSICAL REVIEW X **11,** 041002 (2021)

Monoenergetic High-Energy Ion Source via Femtosecond Laser Interacting with a Microtape

X. F. Shen,[1] A. Pukhov,[1,*] and B. Qiao[2,†]

[1]*Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany*
[2]*Center for Applied Physics and Technology, HEDPS, SKLNP, and School of Physics, Peking University, Beijing, 100871, China*

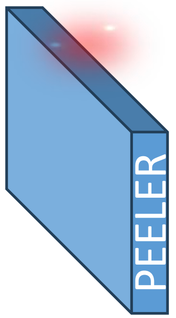
(Received 7 January 2021; revised 18 May 2021; accepted 17 August 2021; published 4 October 2021)

Intense laser-plasma ion sources are characterized by an unsurpassed acceleration gradient and exceptional beam emittance. They are promising candidates for next-generation accelerators towards a broad range of potential applications. However, the laser-accelerated ion beams available currently have limitations in energy spread and peak energy. Here, we propose and demonstrate an all-optical single laser scheme to generate proton beams with low spread at about 1% level and hundred MeV energy by irradiating the edge of a microtape with a readily available femtosecond petawatt laser. Three-dimensional particle-in-cell simulations show that when the electron beam extracted from both sides of the tape is injected into vacuum, a longitudinal bunching and transverse focusing field is self-established because of its huge charge (about 100 nC) and small divergence. Protons are accelerated and bunched simultaneously, leading to a monoenergetic high-energy proton beam. The proposed scheme opens a new route for the development of future compact ion sources.

DOI: 10.1103/PhysRevX.11.041002 Subject Areas: Plasma Physics

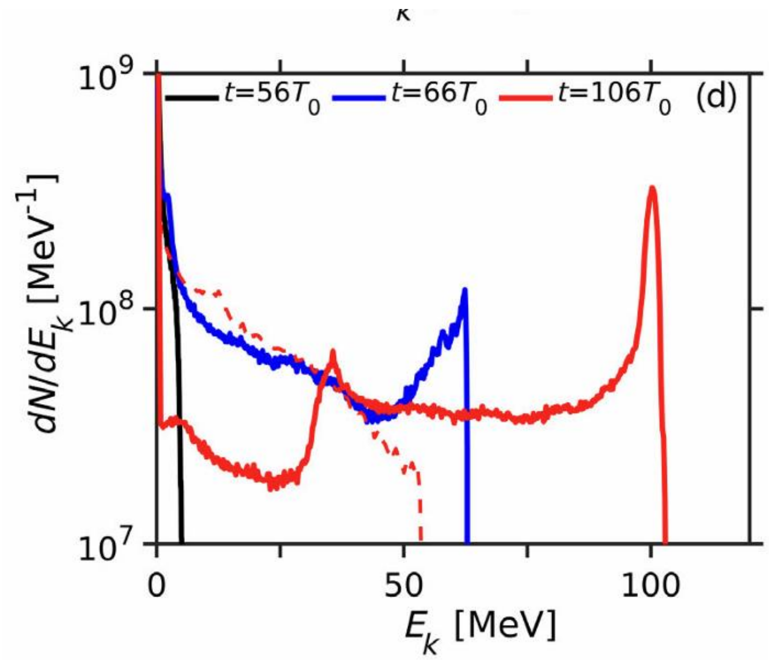
The laser-”solid” interaction

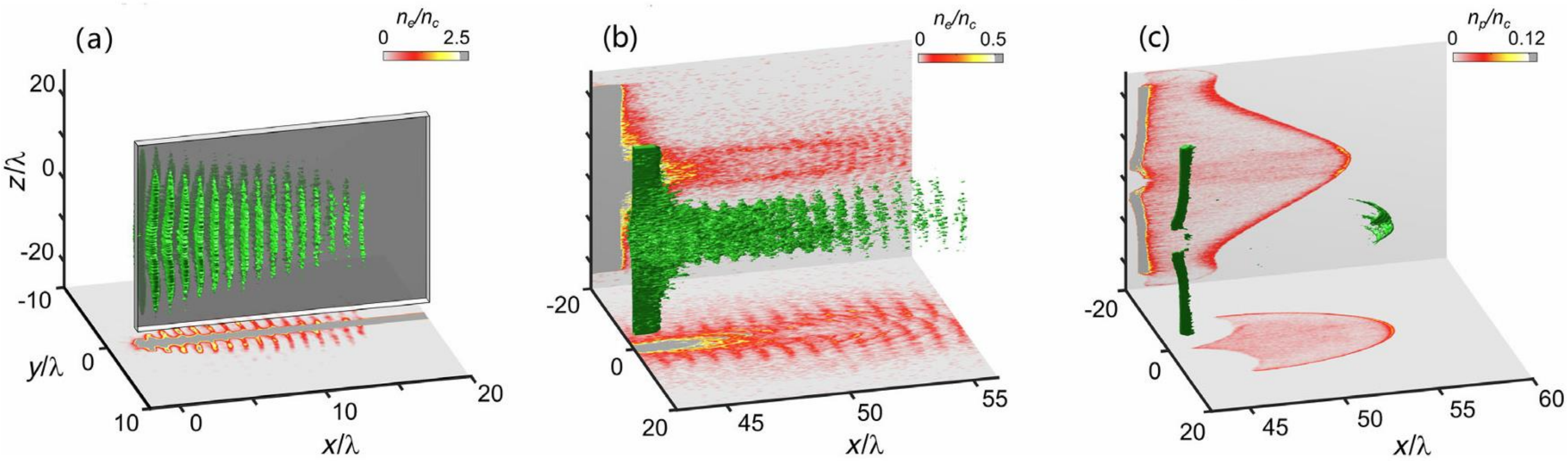
OVER DENSE (PEELER)



Next next level: the **PEELER acceleration**

200TW 3D PIC simulation



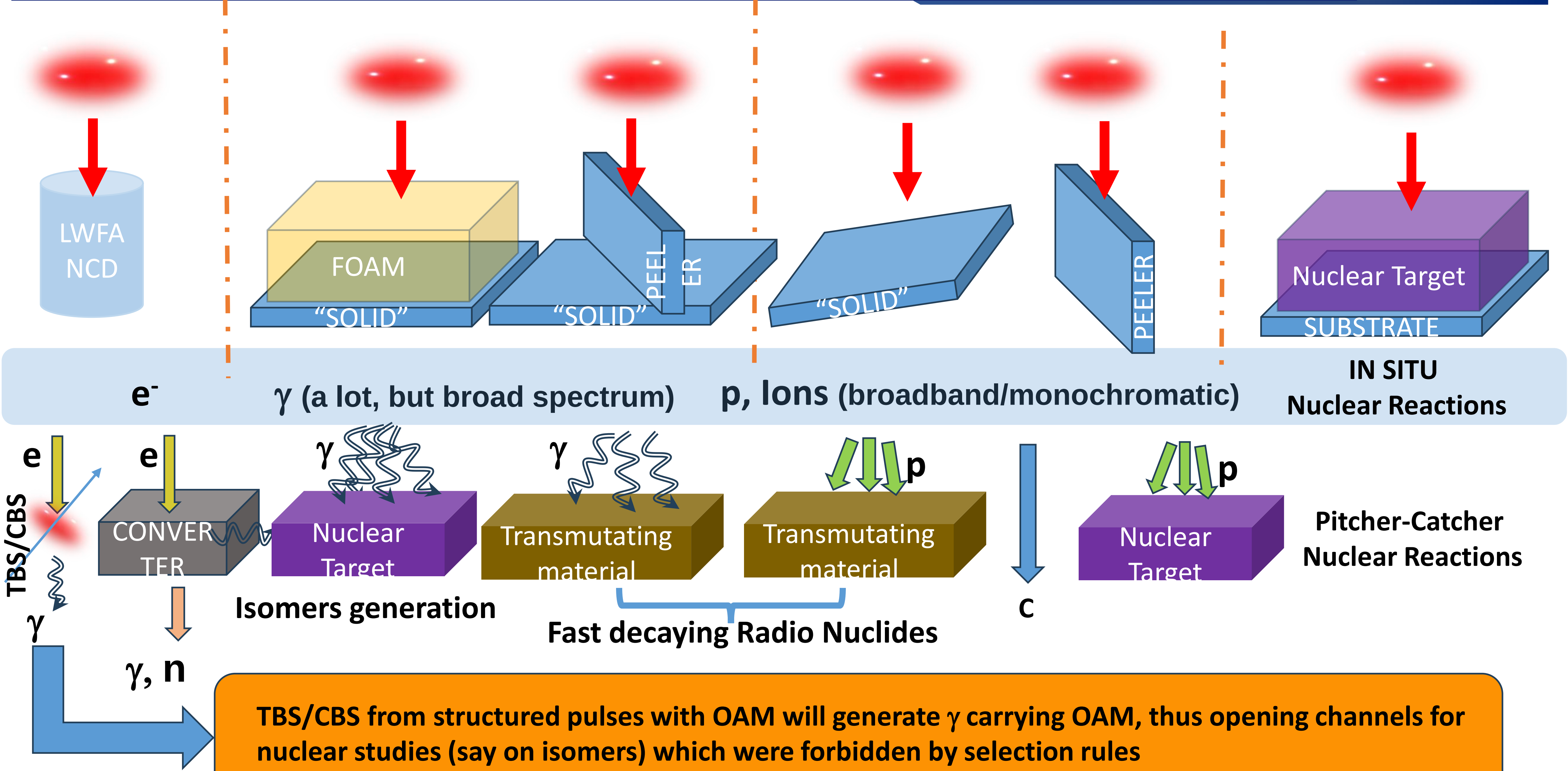


The structure of the talk

Sections:

1. A survey on laser-matter interaction
2. **What’s going on at ELI-NP**
3. Some NP applications of laser-matter interactions

Interaction zoology (useful for NP studies) at ELI-NP



TBS/CBS from structured pulses with OAM will generate γ carrying OAM, thus opening channels for nuclear studies (say on isomers) which were forbidden by selection rules

Theory/Simulations

ELI-NP/LDED

SG @ ELI-NP
Simulation Group

Theory @ LDED

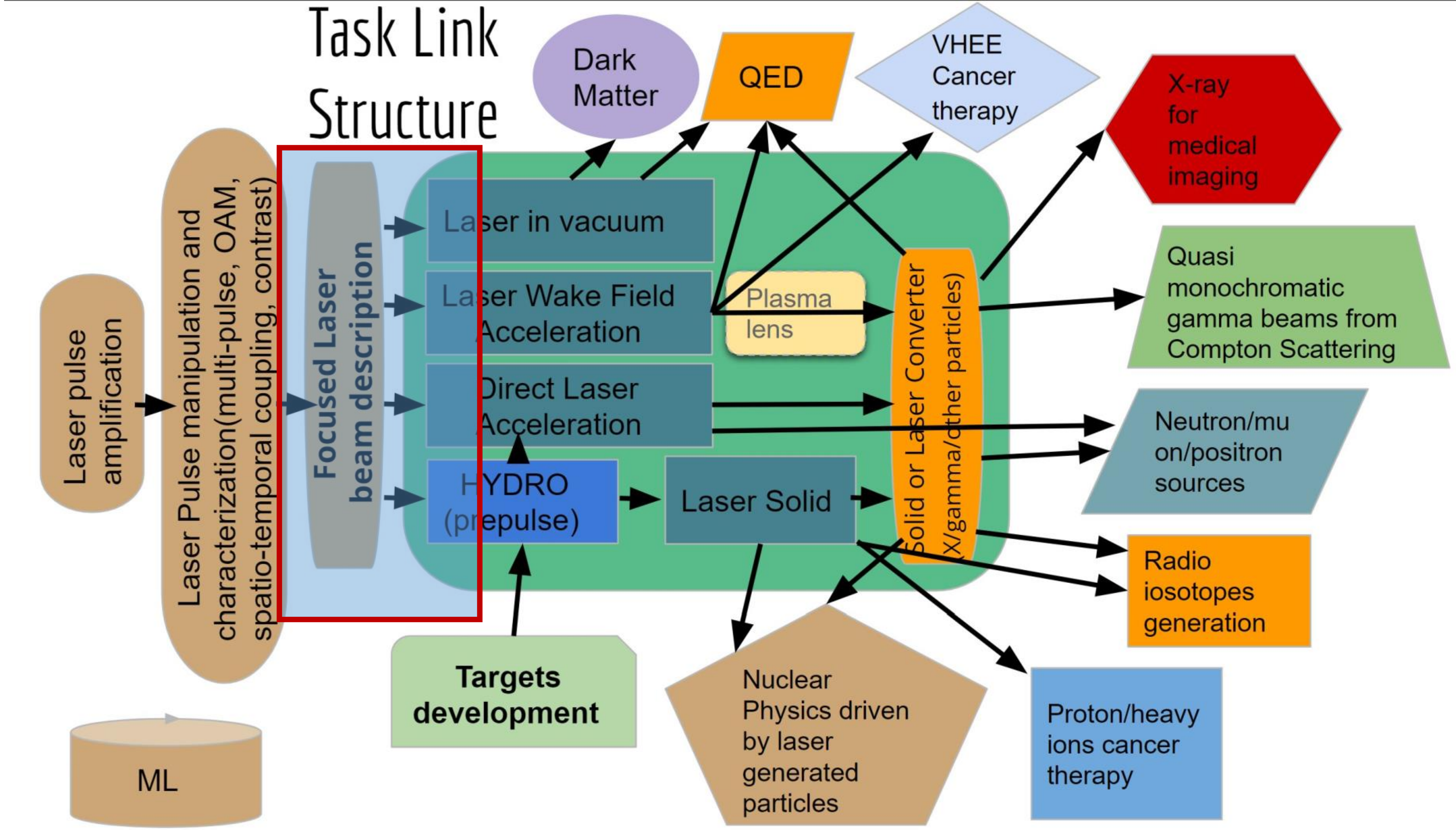
The Simulation Group of ELI-NP

The SG@ELI-NP Simulation Group of the ELI-NP pillar was created (along with the other transversal groups) in March 2023 under initiative of the **Scientific Director, V. Malka**

Group Coordinator
P. Tomassini

Performs simulation researches and drives research for the whole ELI-NP pillar

SG @ ELI-NP
Simulation Group



The Theory/Simulation Group of LDED Laser Driven Experiments Dep in ELI-NP

Theory@LDED

The group is part of the **LDED** (Department Head: **Domenico Doria**)

Group Coordinator
P. Tomassini

Performs theory and simulation researches (mostly) for LDED

- Nuclar Physics
- Laser Solid
- LWFA/DLA
- Radiation and secondary sources

Paolo Tomassini
Head of Research

Nuclear Physicist

Chieh-Jen Yang
Young Researcher

Vojtech Horny
Young Researcher

Dragana Dreghici
Ph. D. student

Bogdan Corobean
Ph. D. student

Federico Avella
Ph. D. student@CNR-INO
(co tutoring)

High-fidelity PIC simulations with aberrated/structured pulses

Virtual Lab Infrastructure **VLI-LPIC package (VLI-Laser to PIC interface)**

(P. Tomassini, F. Avella)

SG @ ELI-NP
Simulation Group

CNR INO
CONSIGLIO NAZIONALE DELLE RICERCHE
ISTITUTO NAZIONALE DI OTTICA

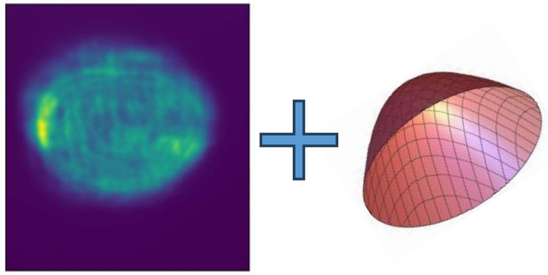
TO PIC (OUTPUT)

Federico Avella
Ph. D. student@INO
(co tutoring)

Solve the Helmoltz equation for the propagation

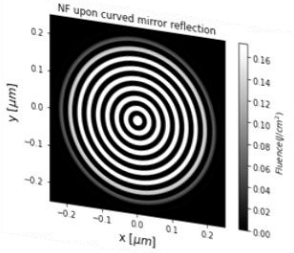
$$2ik_0\partial_z\hat{E}(x,y,z)=\nabla_\perp^2\hat{E}(x,y,z)$$

INPUT



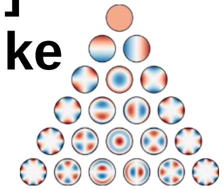
NF Image

Add Masks

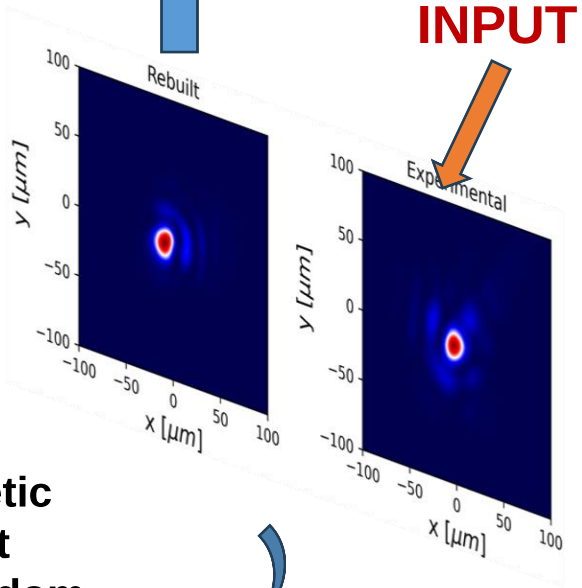


Add aberrations

$Z=[z_1,\ldots,z_{28}]$
List of Zernike Polinomial coefficients



INPUT



P. Tomassini, F. Avella et al., “Automatic reconstruction of the laser transverse intensity and phase structures near the focal plane for advanced Particle In Cell modelling”, to be submitted **on J. Comp. Physics**

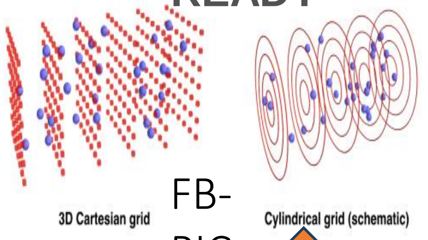
Optimization

Currently a genetic algorithm + pivot preceded by random sampling of the 28th dimensional space

High-fidelity PIC simulations with aberrated/structured pulses

Virtual Lab Infrastructure   VLI-LPIC package (VLI-Laser to PIC interface)

READY



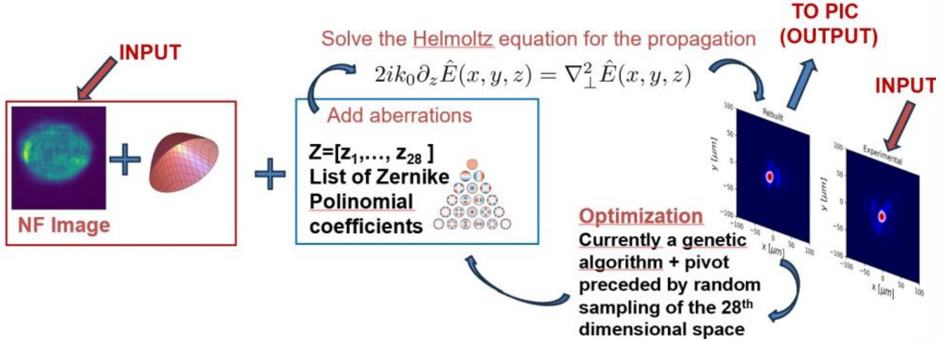
FB-PIC

READY

+ SMILEI + EPOCH +….

Federico Avella
Ph. D. student@INO
(co tutoring)

3D rebuilt pulse directly sent to PIC codes



Solve the Helmoltz equation for the propagation

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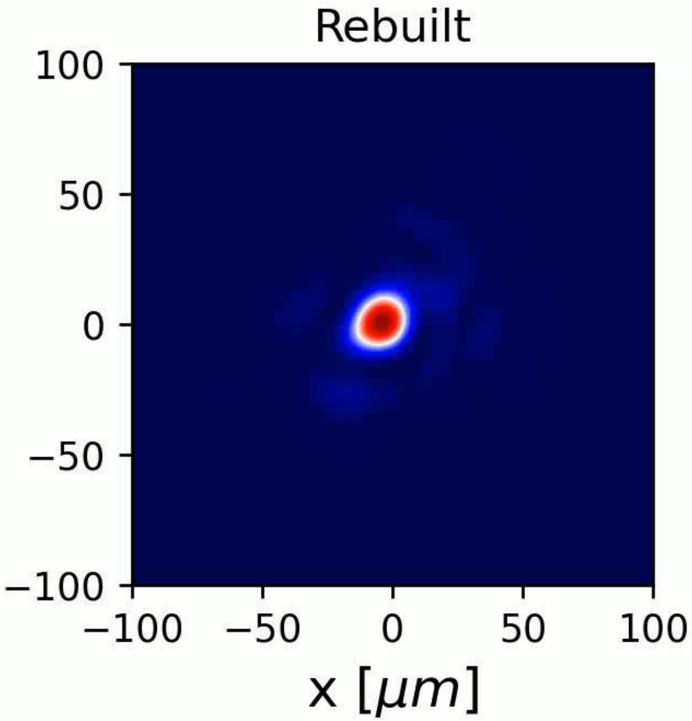
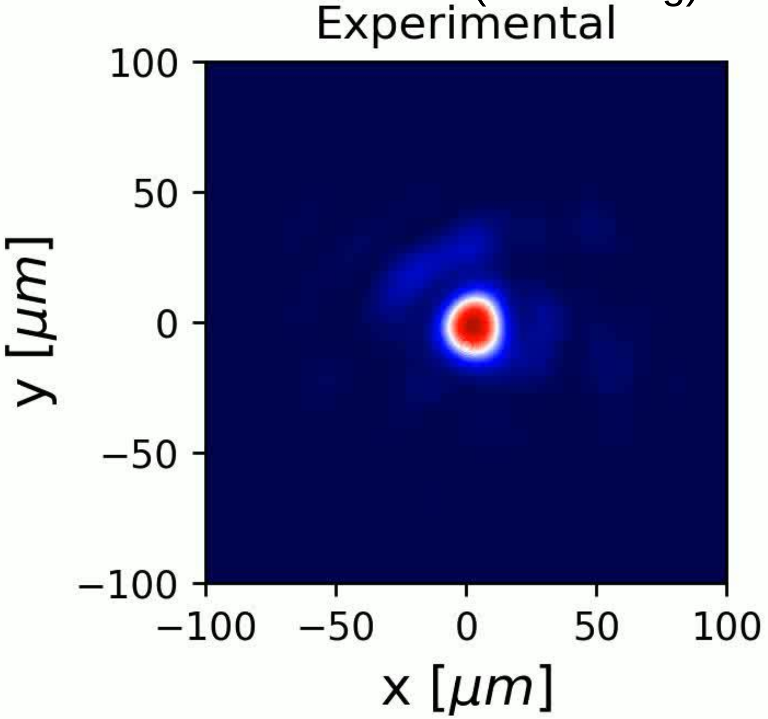
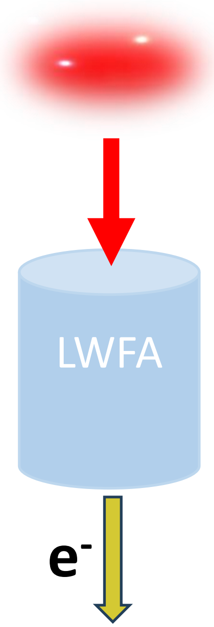




Interaction zoology at ELI-NP: LWFA

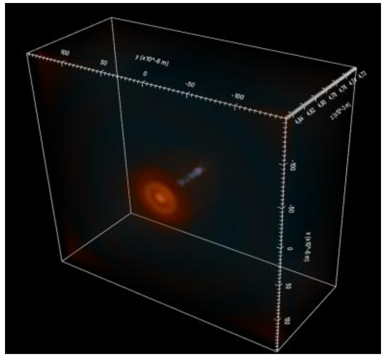


- <1PW **High-brightness** 1-2GeV **w/wo ultrashort** (sub fs) option with a two-subpulses **ReMPI** scheme (P. Tomassini, L.A.Gizzi+CNR-INO, D. Doria)

FEL X and TBS quasi monochromatic γ beams

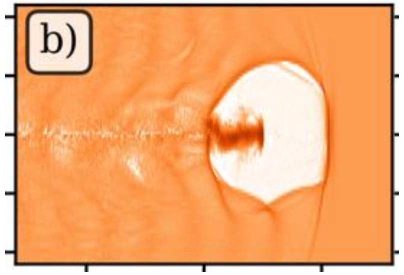
- 1PW/10PW standard acceleration for **high charge** (nC class)/**high energy** (multi GeV) beams [***guiding needed for E>5GeV, working on that***] (P. Ghenuche, D. Doria, V. Malka, P. Tomassini)

Broad Band γ and μ generation
[see G. Sarri, D. Doria]



- 100TW scale**/10/100Hz multi nC low energy beams** with the **high-efficiency** LWFA regime **<u>(efficiency of 50%)</u>** employing post-compressed pulses (V. Horny, G. Bleotu, D. Ursescu, V. Malka, P. Tomassini)

Broad band X/γ, VHEE, n, RadioIsotopes

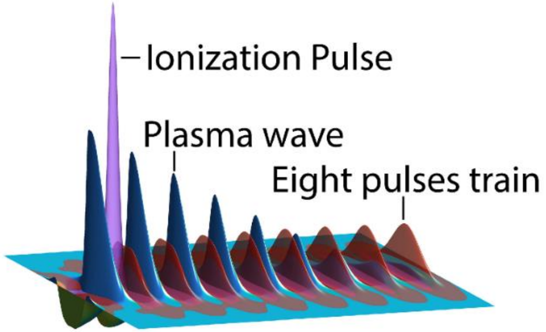


Interaction zoology at ELI-NP: LWFA + High Brightness beams

The first FEL compliant version of ReMPI for 5GeV suffered from “gigantism”.

8 pulses

(1PW, EuPRAXIA)



30 pC

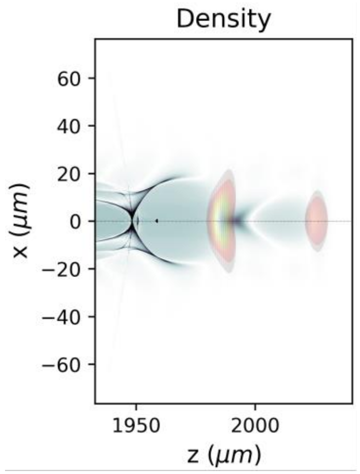
$$\epsilon_n \simeq 80nmrad$$

P. Tomassini et al., High-quality 5GeV electron bunches with the resonant multi-pulse ionization injection, PPCF P 62 (2020) 014010

P. Tomassini et al., BRILLIANT X-RAY FREE ELECTRON LASER DRIVEN BY RESONANT MULTI-PULSE IONIZATION INJECTION ACCELERATOR, proc. FEL 2022 conference, Trieste.

(200TW)

2 pulses

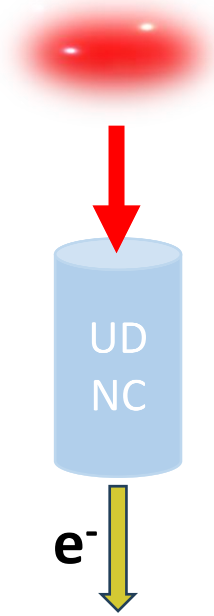


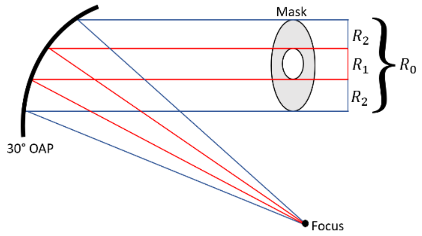
5-30 pC

$$\epsilon_{n,x} \simeq 120nmrad$$
$$\epsilon_{n,y} \simeq 60nmrad$$

P. Tomassini et al., High-Brightness e-beams with the ReMPI scheme employing two driver pulses, in preparation

Interaction zoology at ELI-NP: LWFA + High Brightness beams

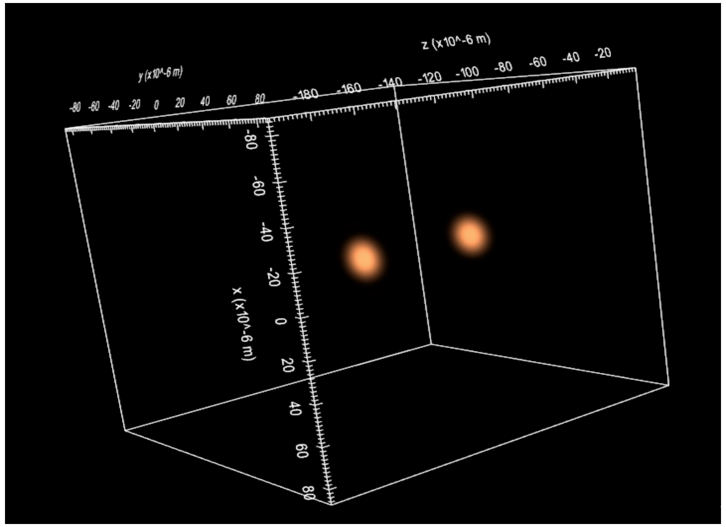




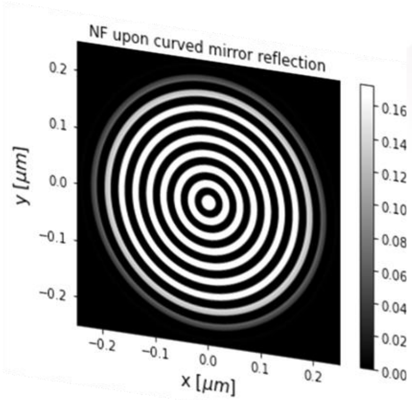
N=1 ring (efficiency 70%)

VLI-LPIC to FB-PIC

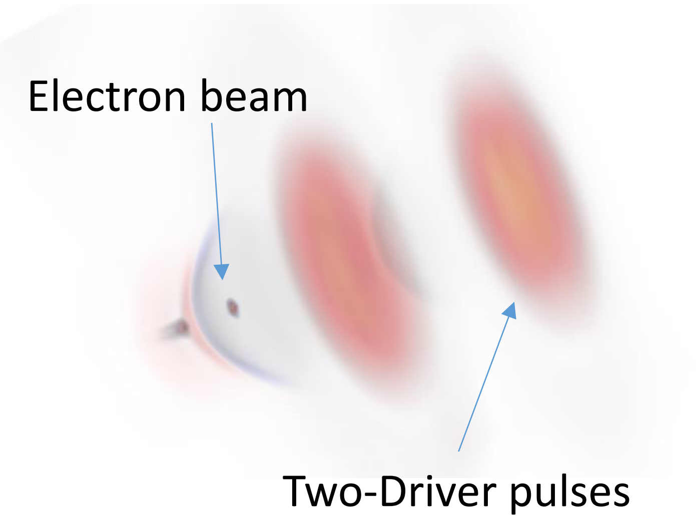
Full pulse description
including aberrations
(with **F. Avella** CNR-INO)

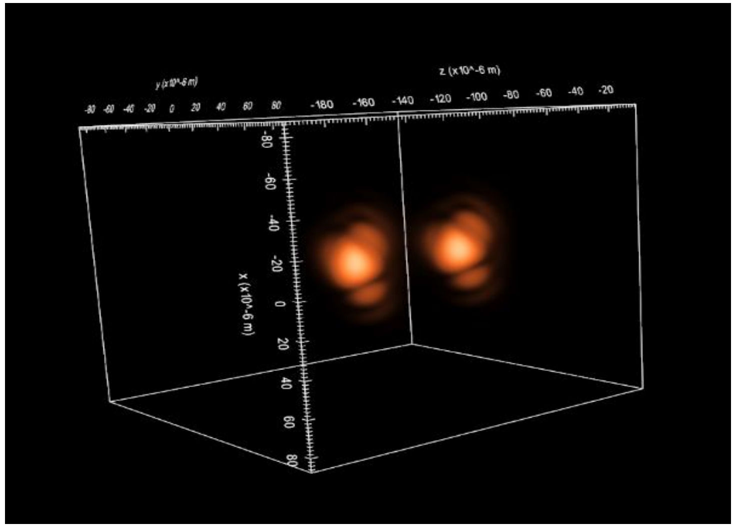


($N\theta$=5 modes: no aberrations, with a lot of aberrations)



N=20 rings (efficiency 50

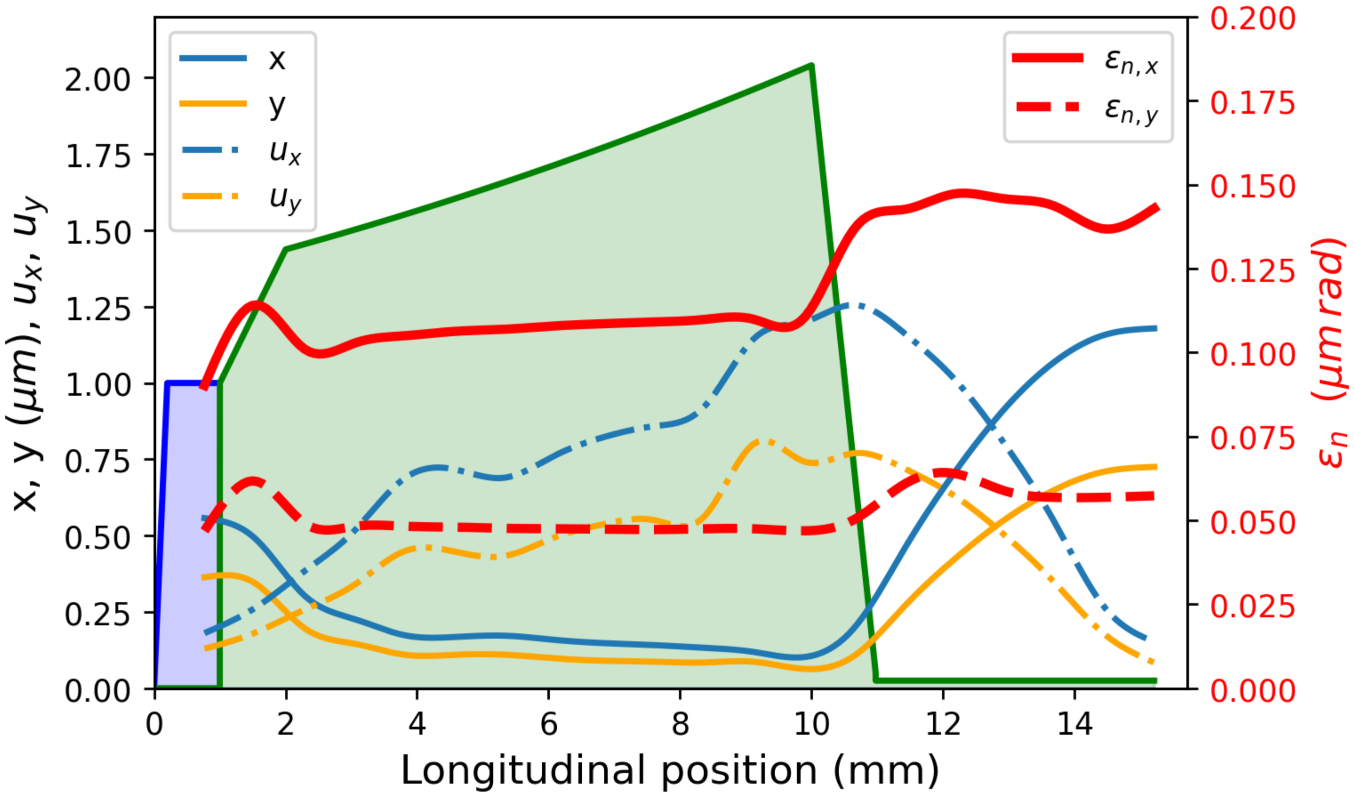




Interaction zoology at ELI-NP: LWFA + High Brightness beams

SINGLE Ti:Sa 200TW/300TW laser system, Circularly Polarised pulses

- 2x 23fs FWHM pulses, w0=30 μm , total 4.2J on TEM00,
- 1x 30fs FWHM ionization pulse **in III** harmonics, w0=3.5 μm, on TEM00, 20mJ



- **100%Ar (8+) plasma, n0=0.75e18 1/cm^3,**
- **1mm plateau + 100He 10mm accelerating structure, guided pulse with radially parabolic density profile**

Plasma lens after the downramp to reduce beam divergence

Interaction zoology at ELI-NP: LWFA + High Brightness beams

FB-PIC q3D simulation Nθ=3

Projected, Q=20pC

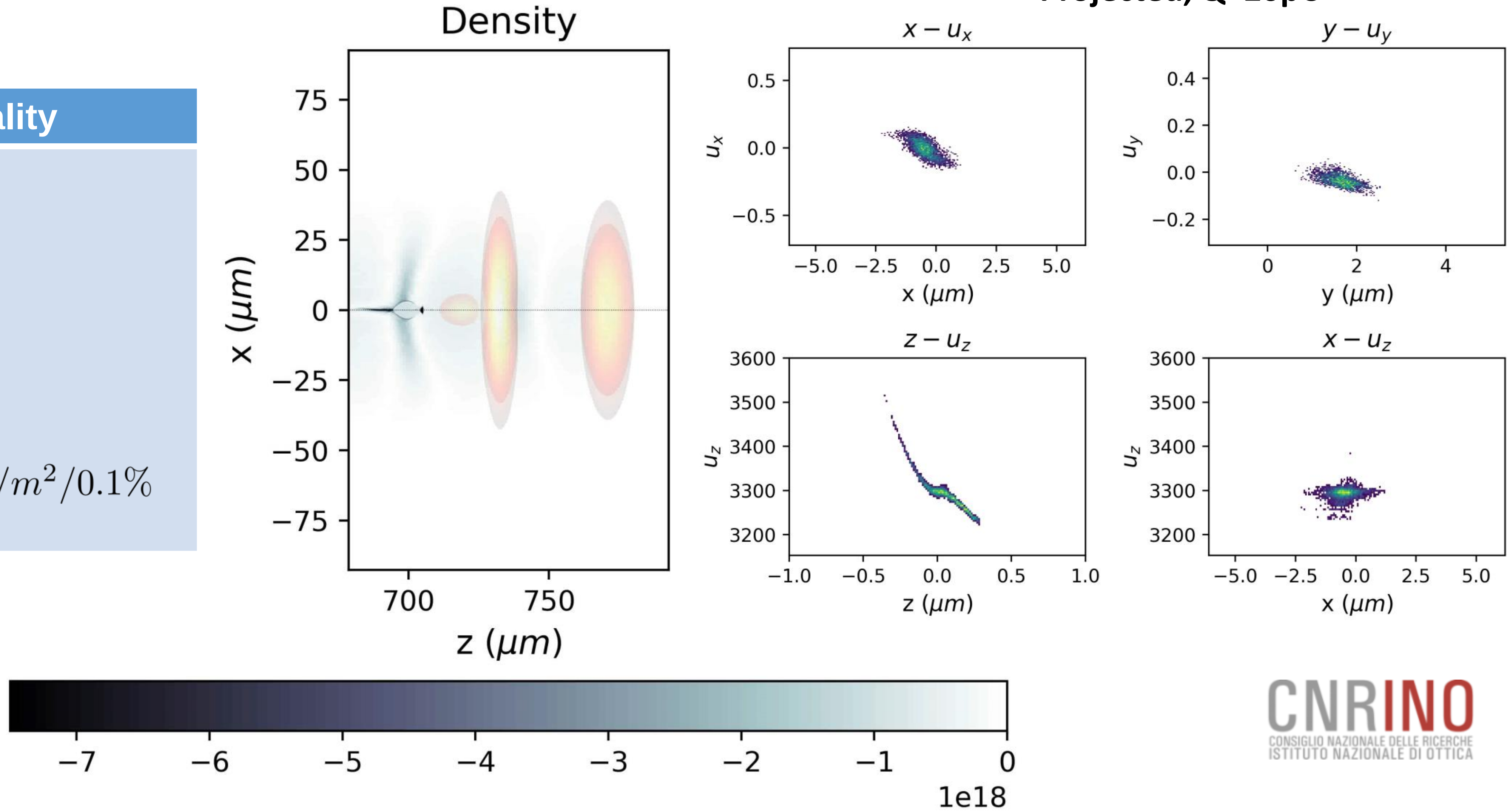
Projected Quality

δE/E (rms) 0.7%

ε_n = 0.09 μmrad
(geom. mean)

L = 0.2 μm

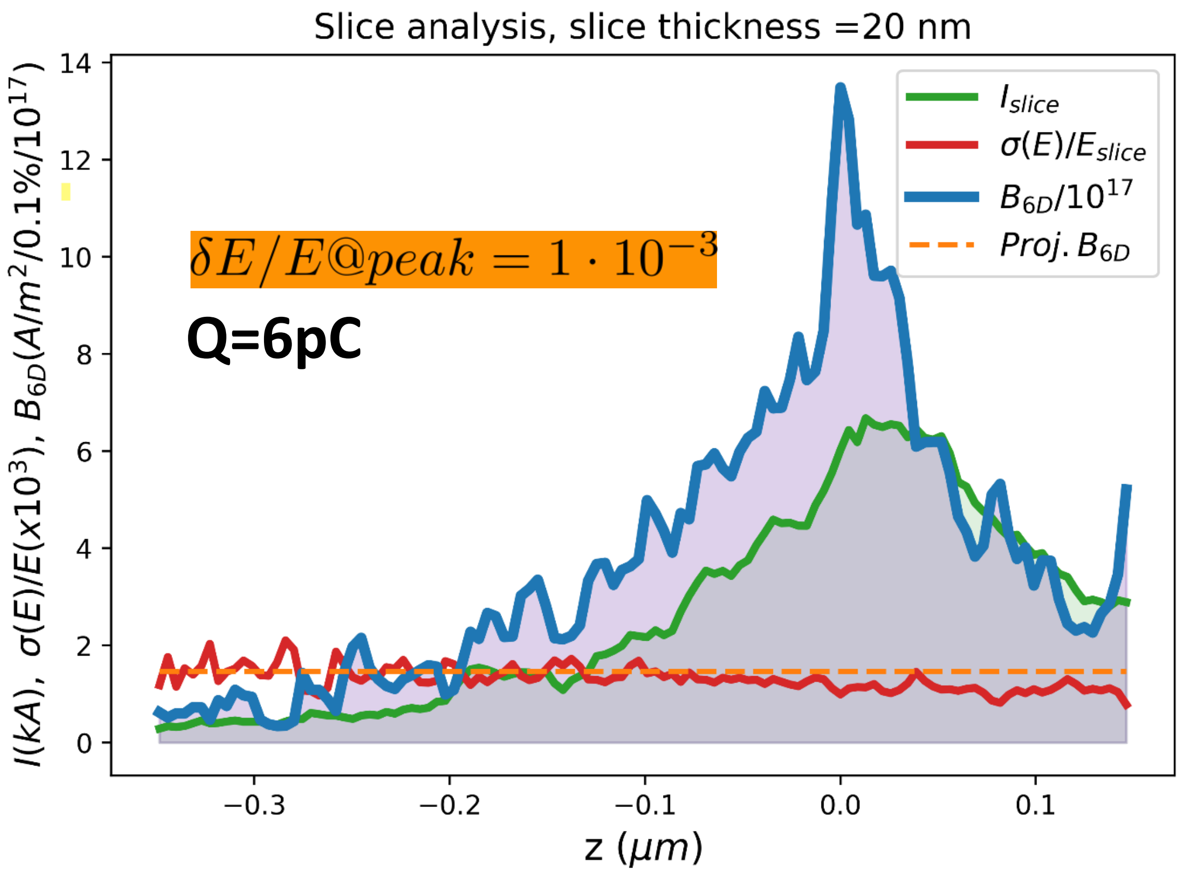
B6D = $5 \cdot 10^{17} A/m^2/0.1\%$



Interaction zoology at ELI-NP: LWFA + High Brightness beams

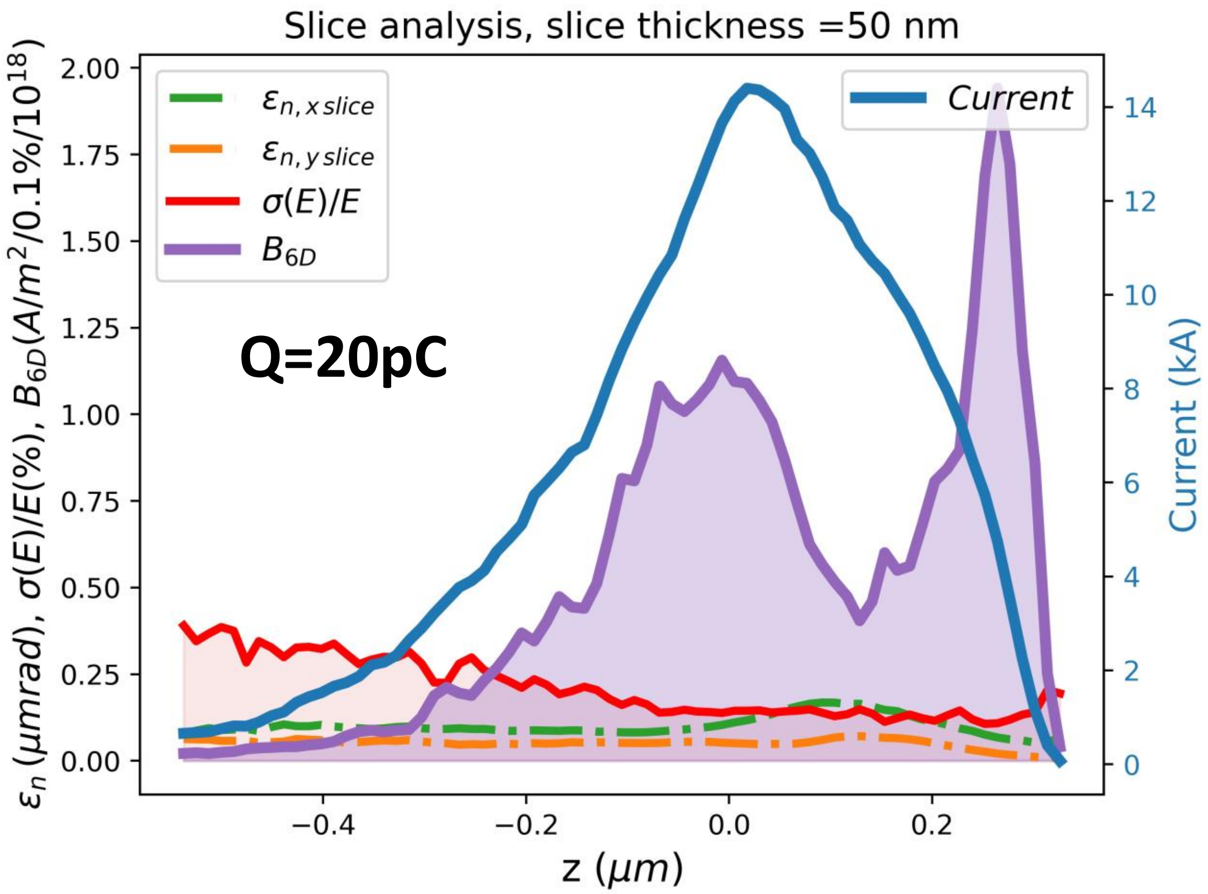
Duration (rms)	Projected Brighthess 6D	δE/E (rms)
250 as	$1.5 \cdot 10^{17} A/m^2/0.1\%$	0.6%

Duration (rms)	Projected Brighthess 6D	δE/E (rms)
600 as	$5 \cdot 10^{17} A/m^2/0.1\%$	0.7%


Slice analysis, slice thickness =20 nm

$\delta E/E@peak = 1 \cdot 10^{-3}$

Q=6pC

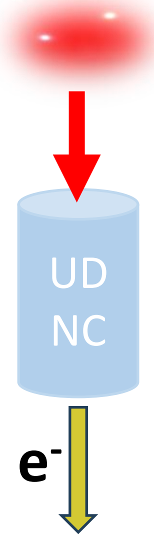

Slice analysis, slice thickness =50 nm

Q=20pC

FEL-oriented

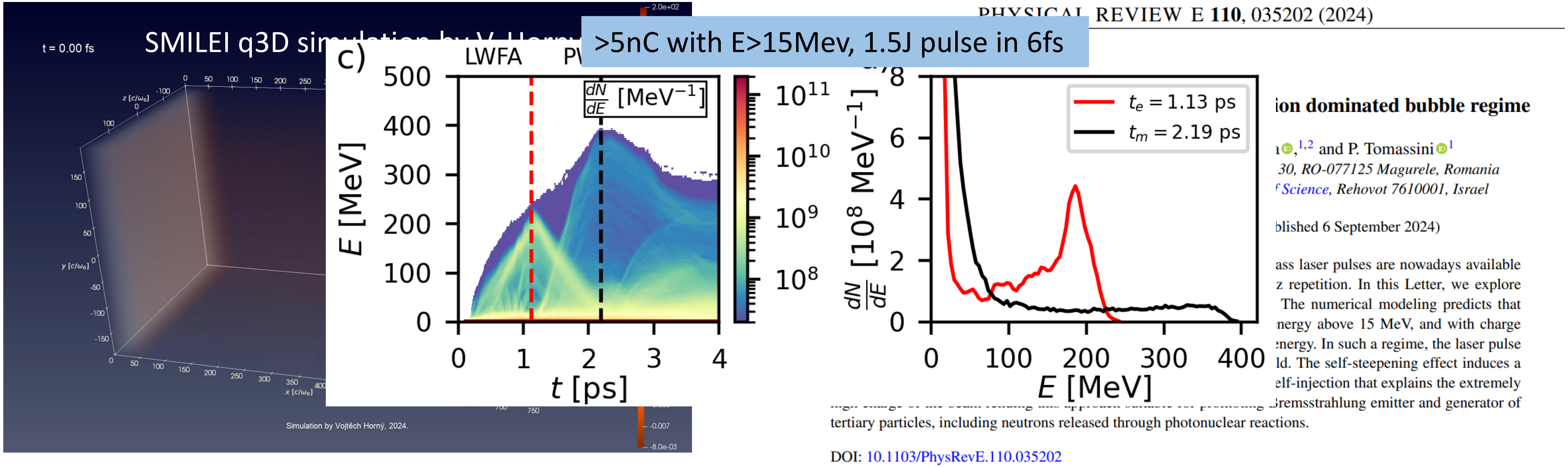
Thomson BS oriented

Interaction zoology at ELI-NP: LWFA



1. <1PW **High-brightness** 1-2GeV **w/wo ultrashort** (sub fs) option with a two-subpulses **ReMPI** sc
2. 1PW/10PW standard acceleration for **high charge** (nC class)/**high energy** (multi GeV), beams [*q*
   needed for E>5GeV, working on that]
3. 100TW scale**/10/100Hz multi nC low energy beams** with the **high-efficiency** LWFA regime **(efficiency of 50%)** employing post-compressed pulses

Vojtech Horny
Young Researcher



>5nC with E>15Mev, 1.5J pulse in 6fs

PHYSICAL REVIEW E **110**, 035202 (2024)

ion dominated bubble regime

,[1,2] and P. Tomassini[1]

30, RO-077125 Magurele, Romania

f Science, Rehovot 7610001, Israel

blished 6 September 2024)

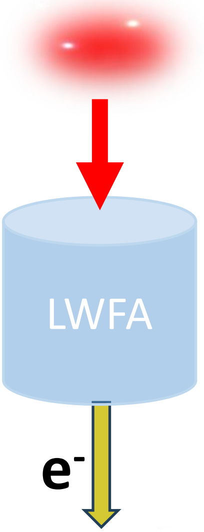
ass laser pulses are nowadays available
z repetition. In this Letter, we explore
The numerical modeling predicts that
nergy above 15 MeV, and with charge
energy. In such a regime, the laser pulse
ld. The self-steepening effect induces a
elf-injection that explains the extremely
Bremsstrahlung emitter and generator of
tertiary particles, including neutrons released through photonuclear reactions.

DOI: 10.1103/PhysRevE.110.035202

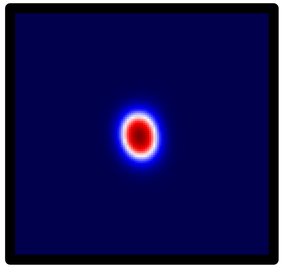
Interaction zoology at ELI-NP: LWFA

100TW scale**/10/100Hz multi nC low energy beams** with the **high-efficiency** LWFA regime employing post-compressed pulses

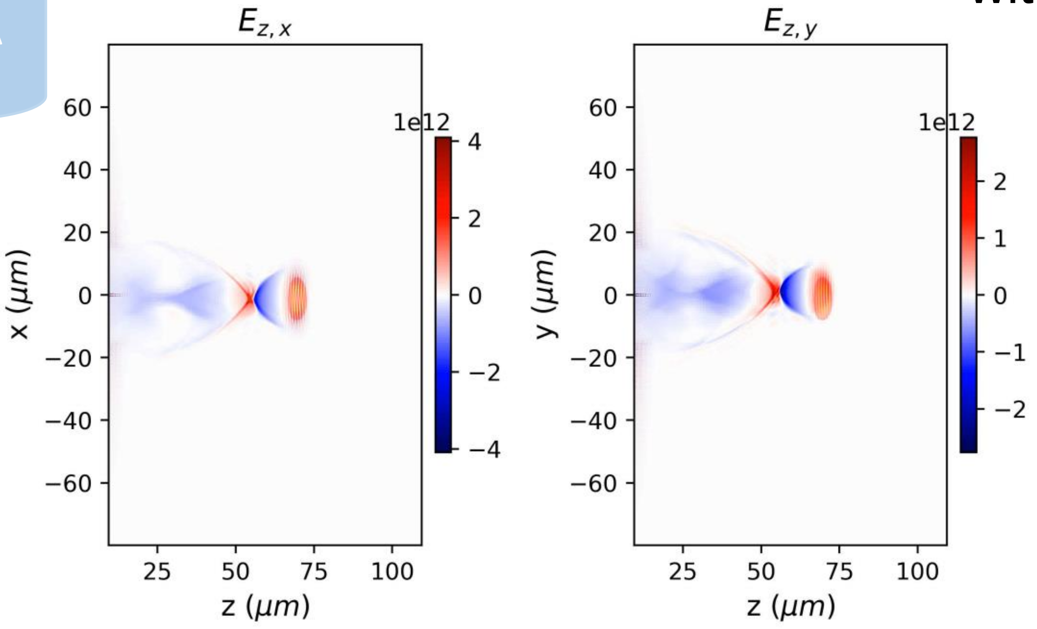
Examples: towards start-to-end simulations with post compressed Joulse-scale pulses (<u>11fs FWHM, 1J</u>)

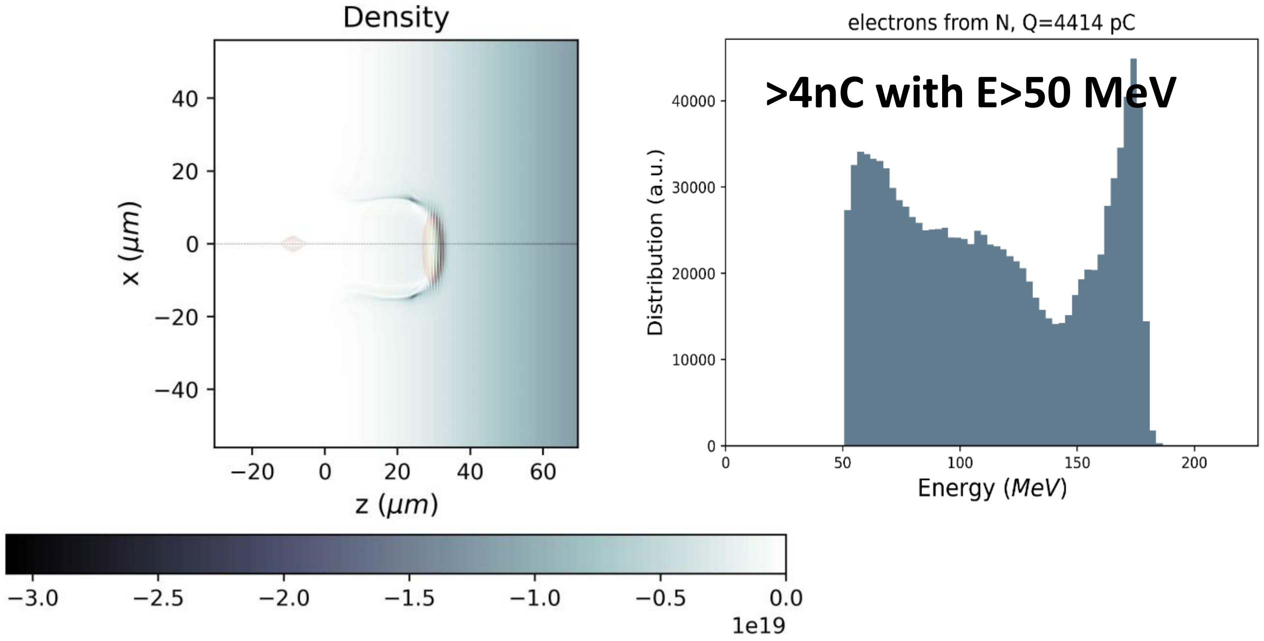


Virtual Lab Infrastructure   **VLI-LPIC package (VLI-Laser to PIC interface)**



q3D simulations
with FBPIC



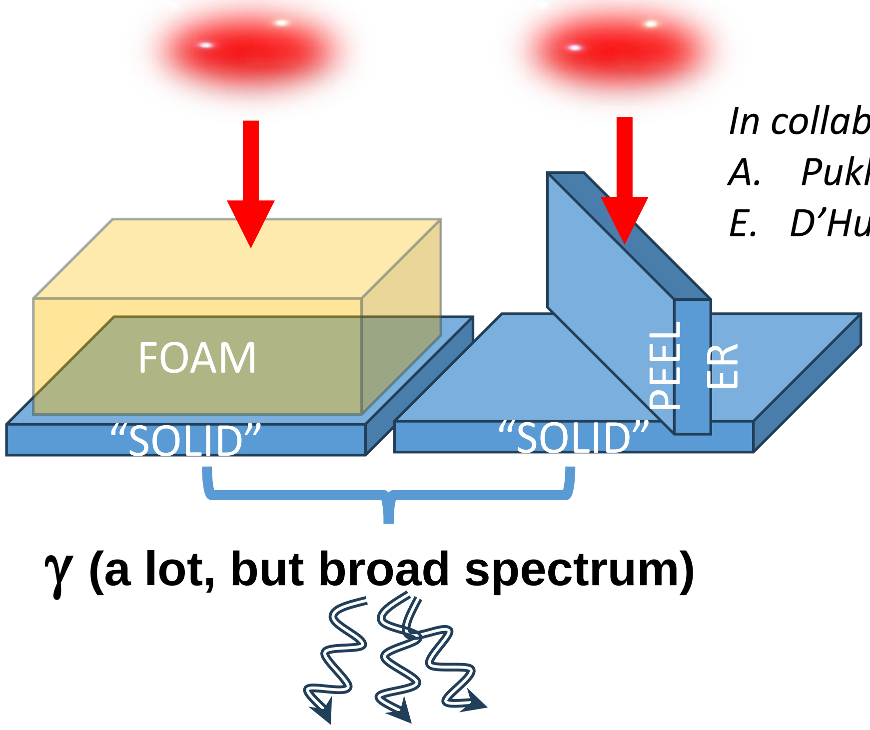


>4nC with E>50 MeV

Electron bunches useful for broadband γ conversion and VHEE

Interaction zoology at ELI-NP: Gamma ray bursts at NP 1/1

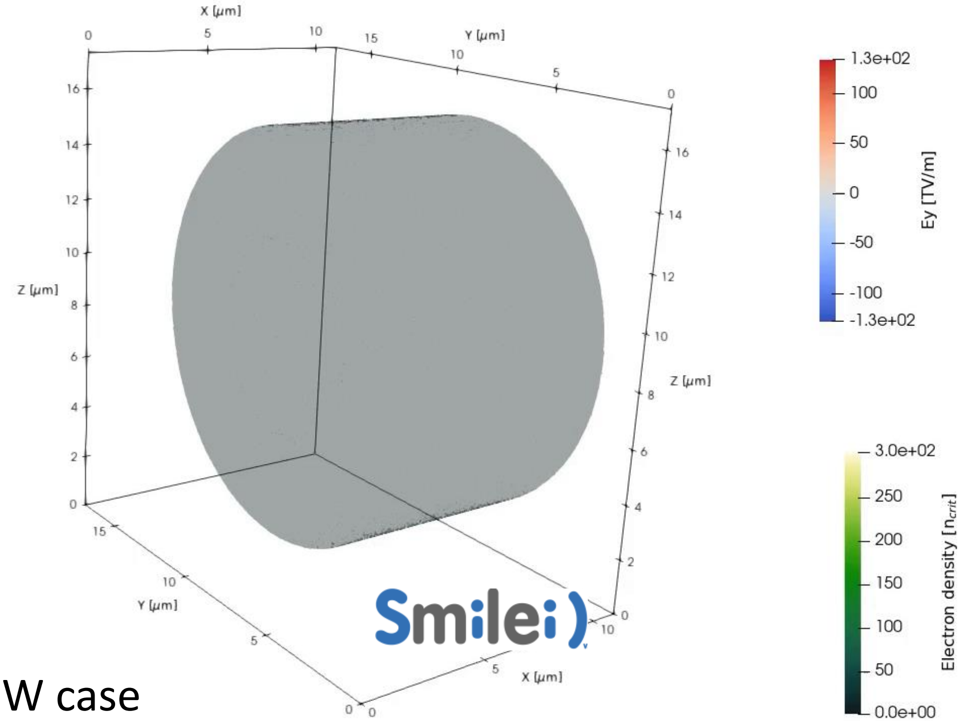
A lot of MeV scale photons can be generated, but at **very low rep rate**

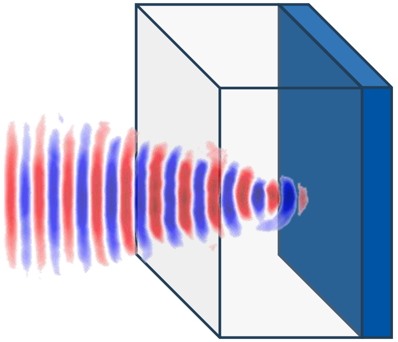


γ (a lot, but broad spectrum)

In collaboration with
A. Pukhov and
E. D'Humieres

Dragana Dreghici
Ph. D. student





10PW case

3D sim. By D. Dreghici, V. Horny ELI-NP/LDED

nature COMMUNICATIONS

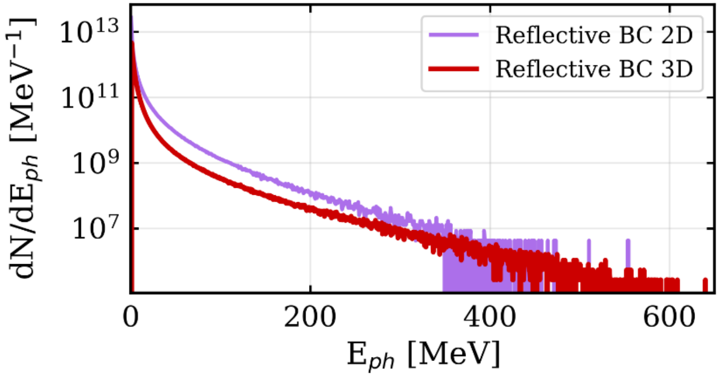
ARTICLE

Check for updates

https://doi.org/10.1038/s41467-021-27694-7 OPEN

Forward-looking insights in laser-generated ultra-intense γ-ray and neutron sources for nuclear application and science

M. M. Günther[1✉], O. N. Rosmej[1,2,3], P. Tavana[2], M. Gyrdymov[2], A. Skobliakov[4], A. Kantsyrev[4], S. Zähter[1,2], N. G. Borisenko[5], A. Pukhov[6] & N. E. Andreev[7,8]

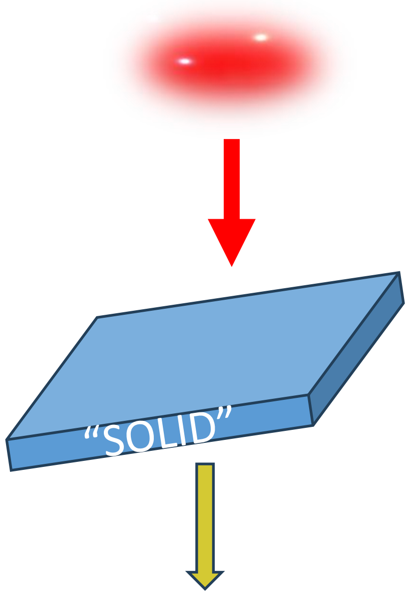


Conversion efficiency:

laser to photons:

12%

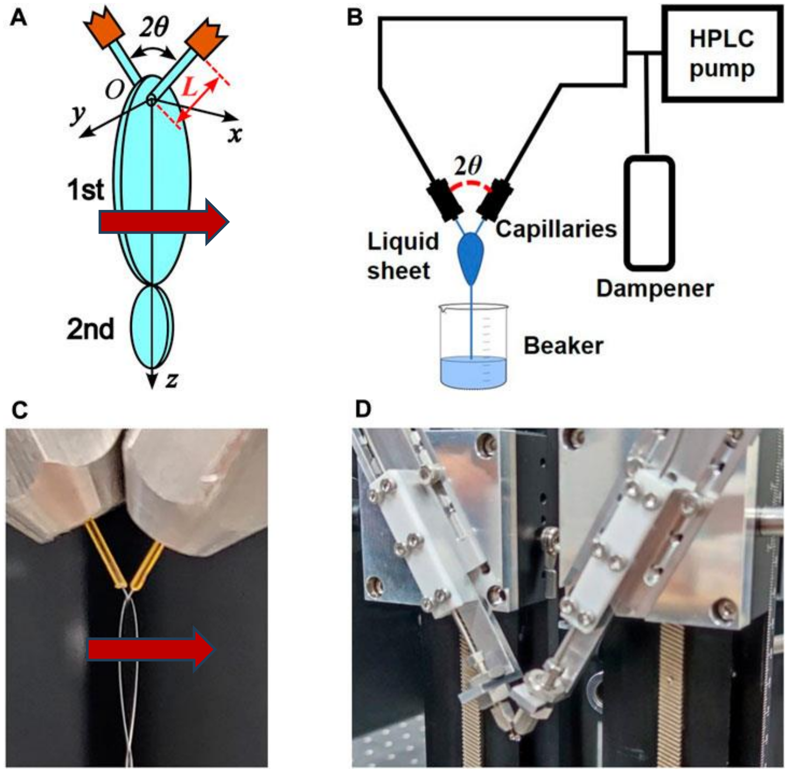
Interaction zoology at ELI-NP: Liquid targets for TNSA proton generation



p (broadband)

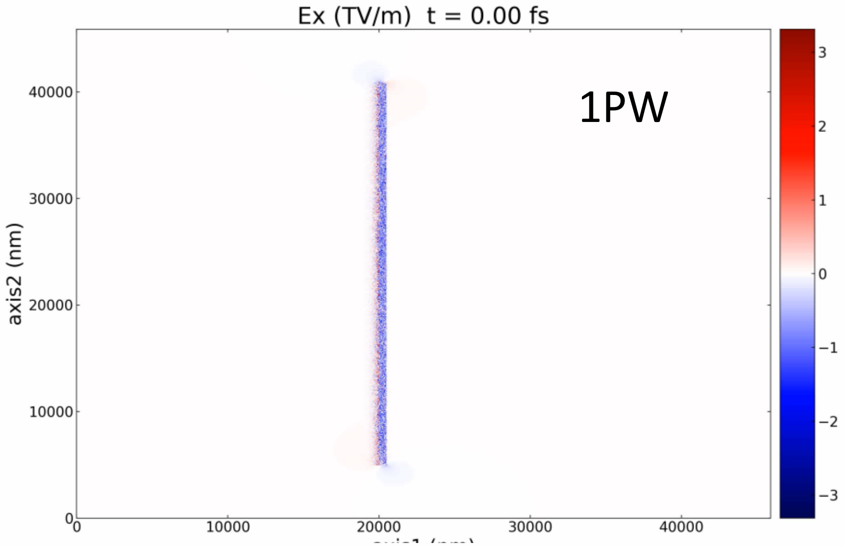
Protons can be used for neutron or fast decaying radionuclides generation

Here the key is a "high" rep-rate. We are optimizing the usage of water target leaf. **Thickness of a few microns.**

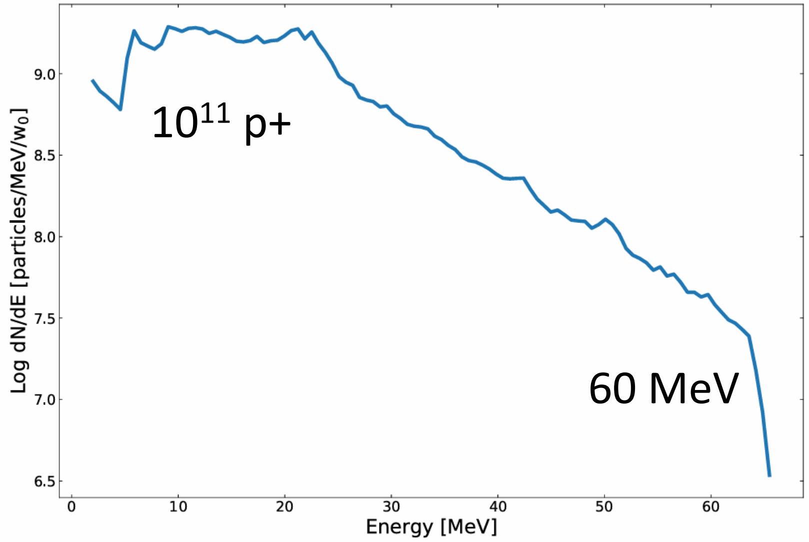


Z. Cao et al., Front. Phys., 2023 Nuclear Physics
Volume 11 - 2023 | https://doi.org/10.3389/fphy.2023.1172075

2D PIC simulation by B. Corobean/ELI-NP



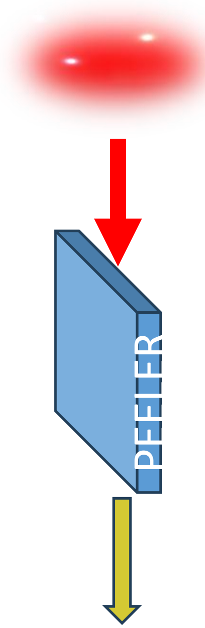
Bogdan Corobean
Ph. D. student



Interaction zoology at ELI-NP: PEELER proton and Carbon generation

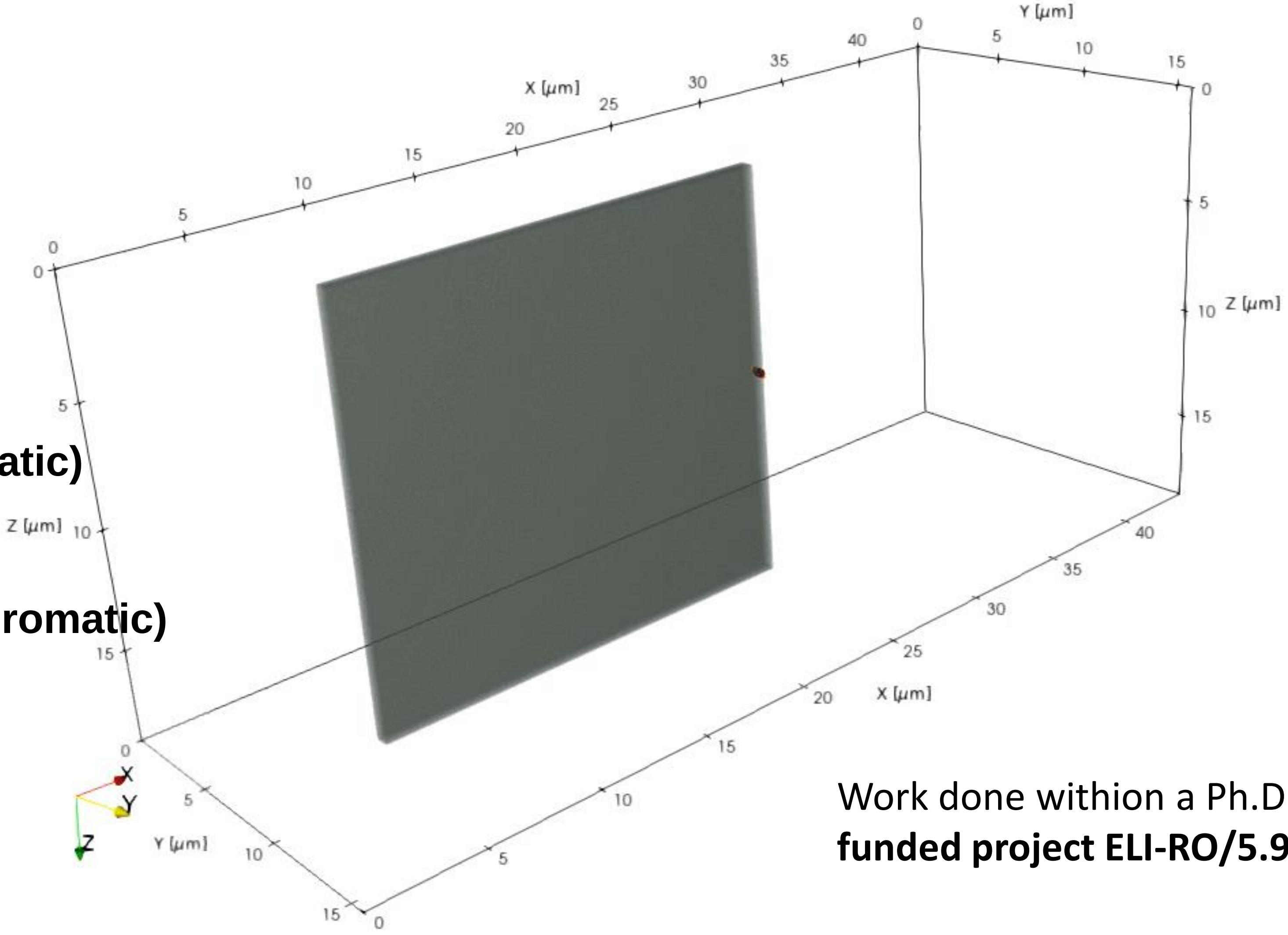
Quasi monochromatic and low divergence Protons and Carbon ions can can be generated with the peeler scheme

3D PIC simulation by B. Corobean/ELI-NP



p (monochromatic)

C (poli-monochromatic)



Bogdan Corobean
Ph. D. student

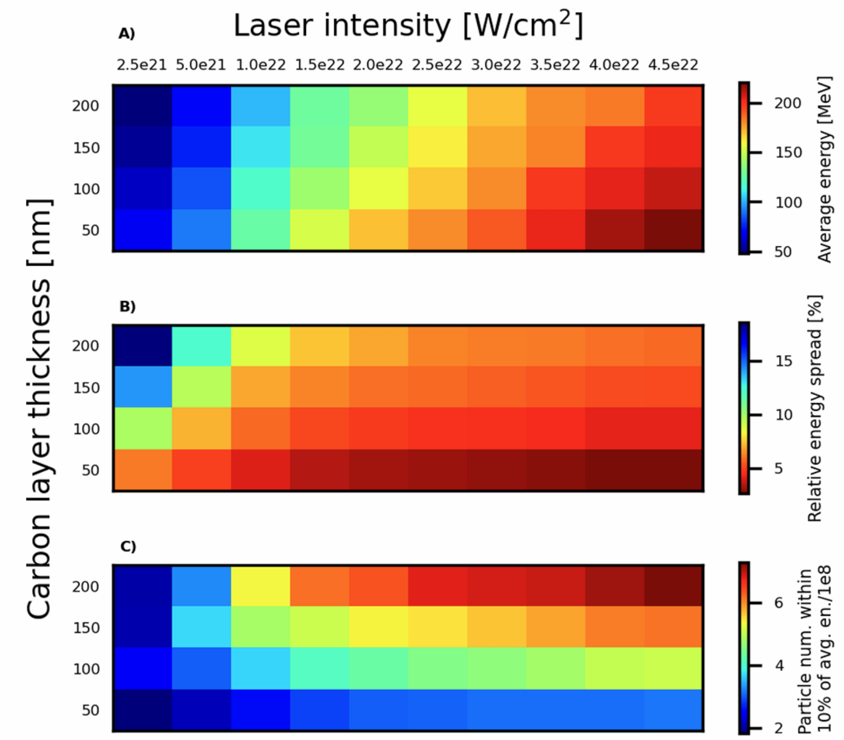
Work done withion a Ph.D. thesis project and and **ELI-RO funded project ELI-RO/5.9/14 2924-2027 [P. Tomassini]**

B. Corobean, D. Doria, V. Horny and P. Tomassini, in prep.

Interaction zoology at ELI-NP: PEELER proton and Carbon generation

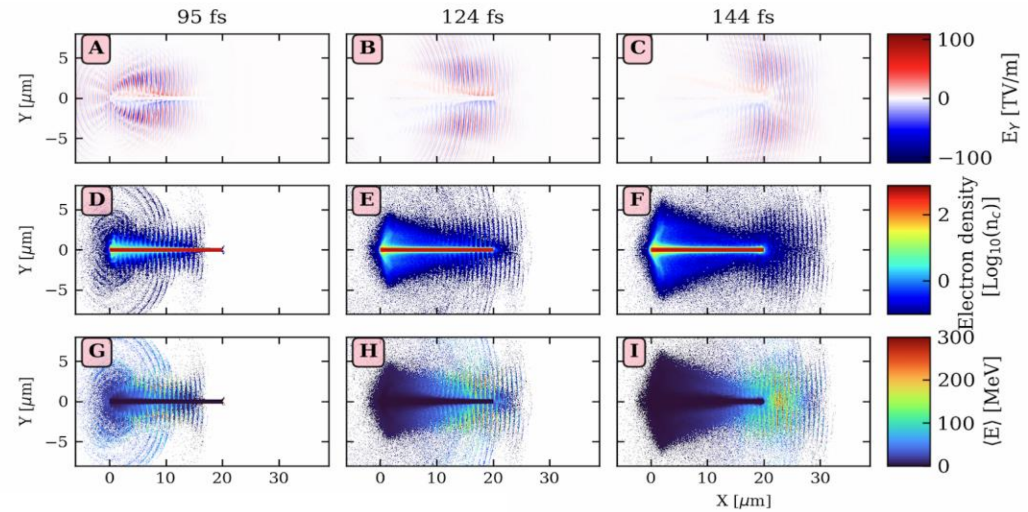
Credits: P. Tomassini and coworkers

2D scan and full 3D PIC simulations were performed, the latter with the **E5 + PM parameters assuming a 75% encircled energy**

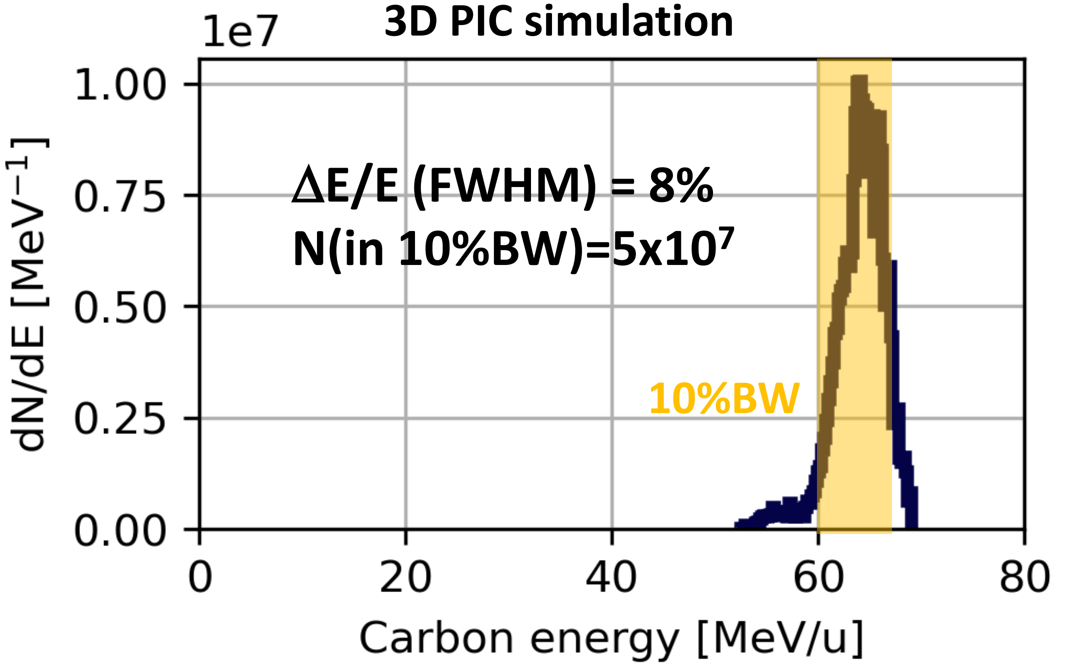


2D PIC scan

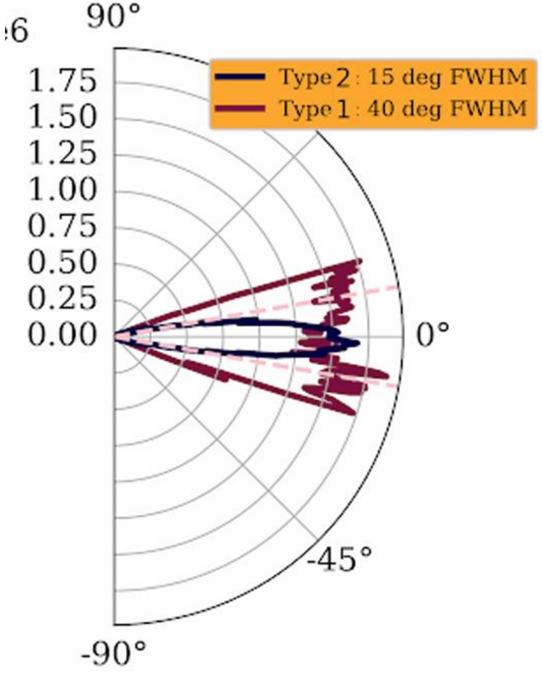
3D PIC simulation



3D PIC simulation



ΔE/E (FWHM) = 8%
N(in 10%BW)=5x10^7



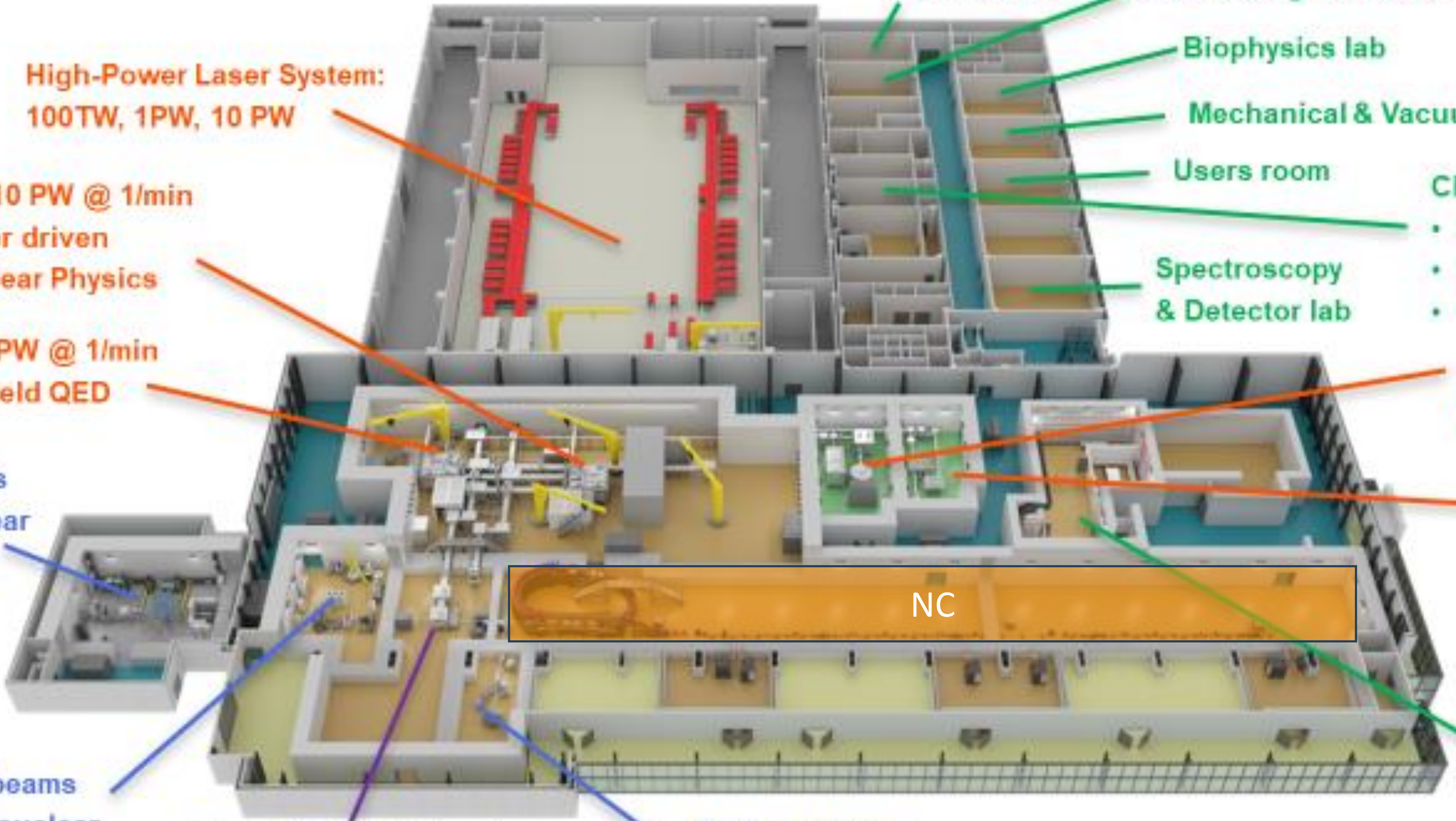
B. Corobean, D. Doria, V. Horny and P. Tomassini, in prep.

Commissioning experiments

ELI-NP

P.I. D. Doria, M. Cernaianu, P. Ghenuche

Experimental building layout



Dosimetry lab

Plasma diagnostics lab

Biophysics lab

Mechanical & Vacuum workshop

Users room

Clean rooms
- Optics lab
- Laser lab
- Target lab

Spectroscopy & Detector lab

High-Power Laser System:
100TW, 1PW, 10 PW

E1: 10 PW @ 1/min
Laser driven
Nuclear Physics

E6: 10 PW @ 1/min
High Field QED

E5: 1 PW @ 1 Hz
Material Studies

E4: 0.1PW@10 Hz
Photon-photon int., LWFA, X-ray imaging

E9: γ beams
Photonuclear
Reactions

E3: X rays
Test/develop instrumentation and technology

E8: γ beams
Photonuclear
Reactions

E7: 10 PW + 1 PW + γ/e^-
High Field QED

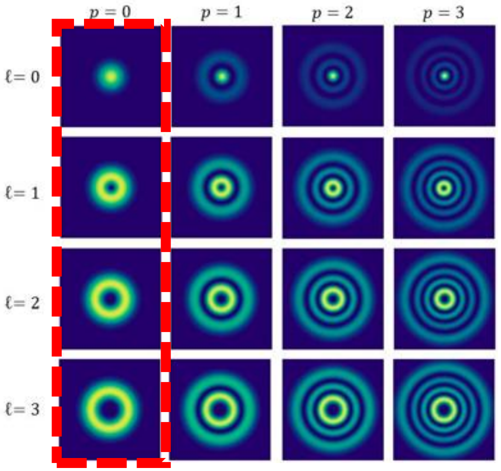
ERA: positrons
Material Studies

1 PW LASER-SOLID commissioning: Helical laser beam

Helical laser beam (Laguerre-Gaussian beam)

$$u(r,\phi,z) = C_{lp}^{LG}\frac{w_0}{w(z)}\left(\frac{r\sqrt{2}}{w(z)}\right)^{|l|}\exp\left(-\frac{r^2}{w^2(z)}\right)L_p^{|l|}\left(\frac{2r^2}{w^2(z)}\right)\exp\left(-ik\frac{r^2}{2R(z)}\right)\exp(-il\phi)\exp(i\psi(z))$$

Laguerre modes

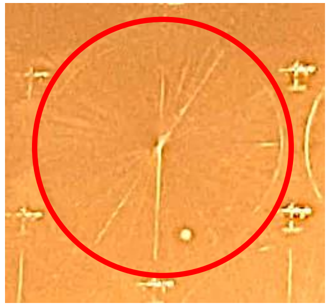


where L_p^l are the generalized Laguerre polynomials

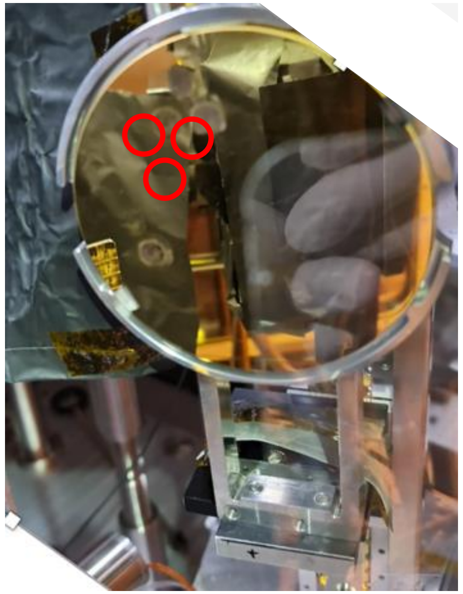
$$C_{lp}^{LG} = \sqrt{\frac{2p!}{\pi(p+|l|)!}} \Rightarrow \int_0^{2\pi} d\phi \int_0^{\infty} rdr|u(r,\phi,z)|^2 = 1$$

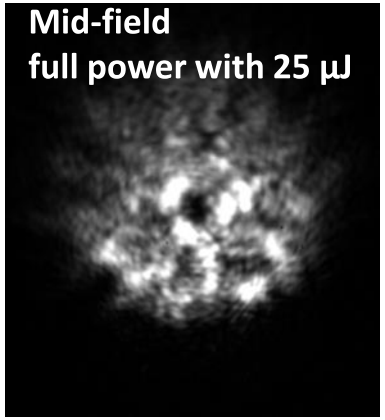
with a twist index *l* and radial index *p*

Helical mirror element

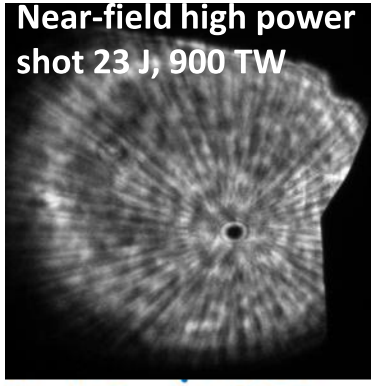


Helical PM





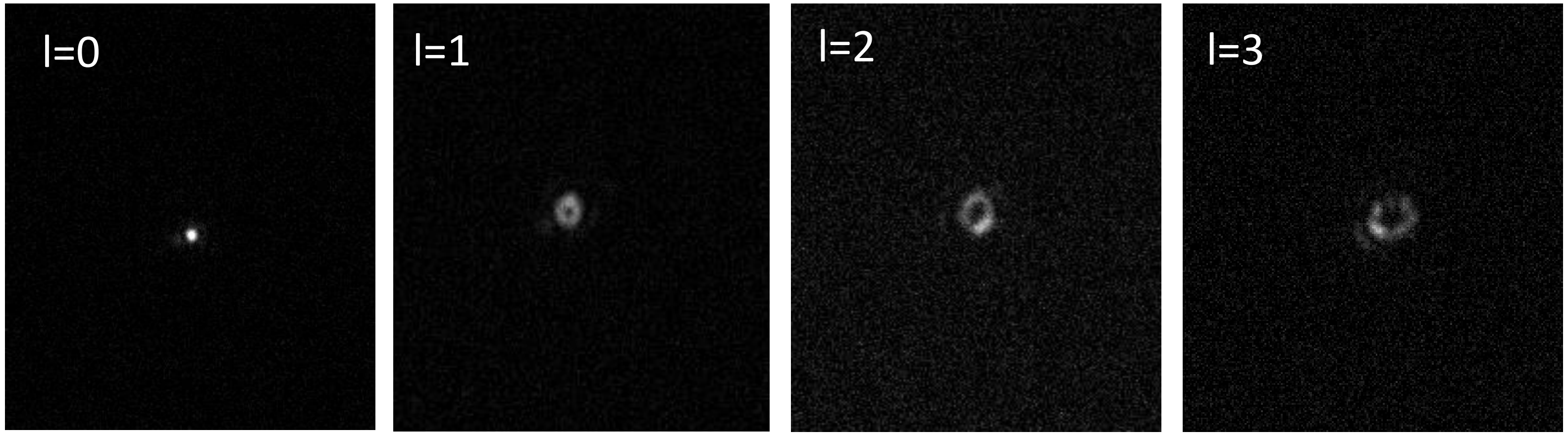
Mid-field full power with 25 µJ



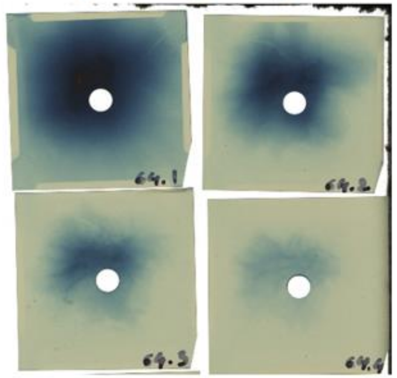
Near-field high power shot 23 J, 900 TW

Experimental results
M. Cernaianu et al., in prep

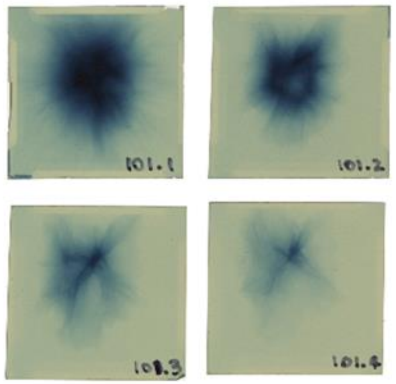
(far-field: focal spot at full power with but 25 µJ)



Some shots



E27, Al 1.5um, Gauss, 7.13J



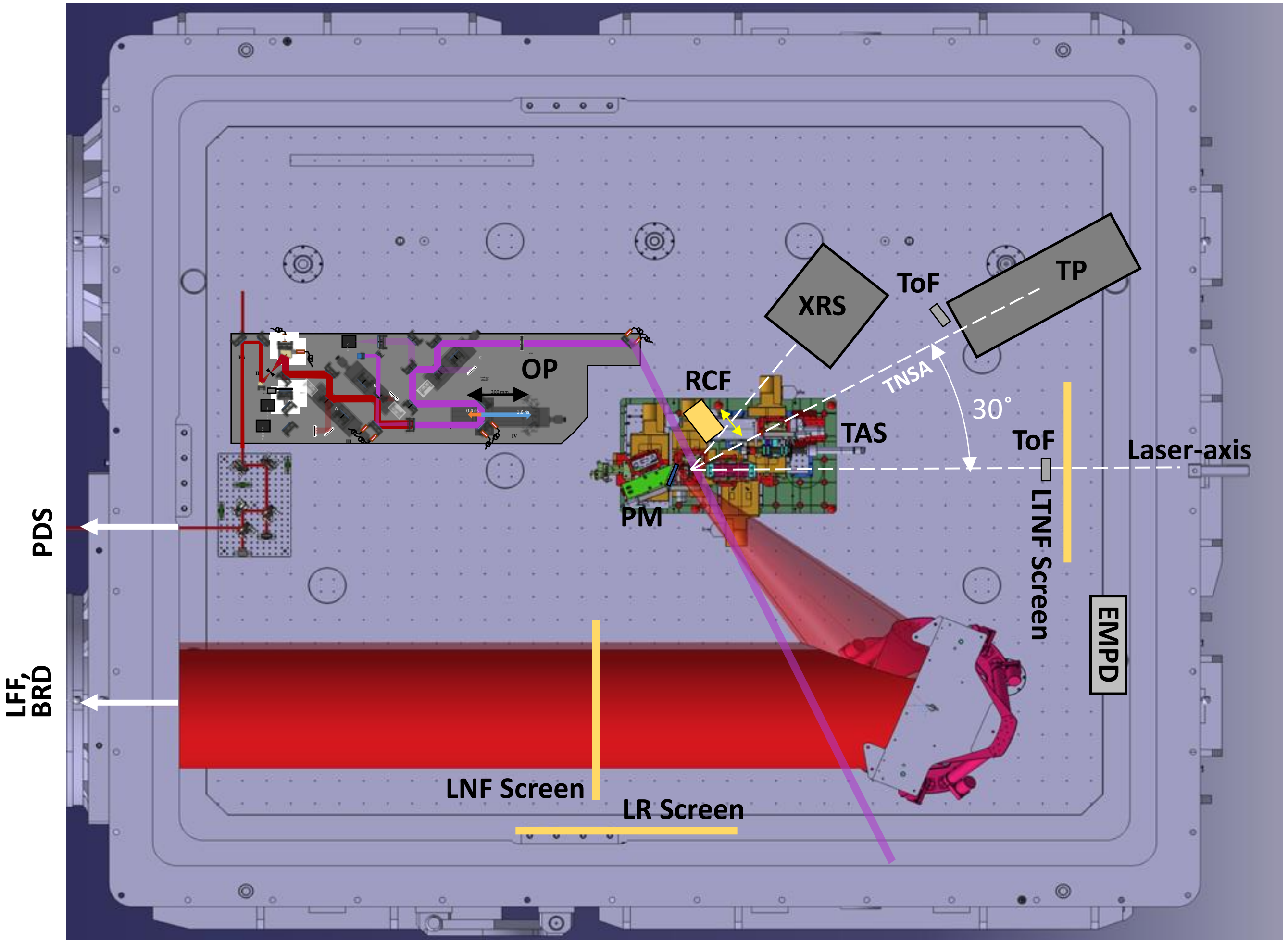
C31, Al 1.5um, CP-L3,7.09J

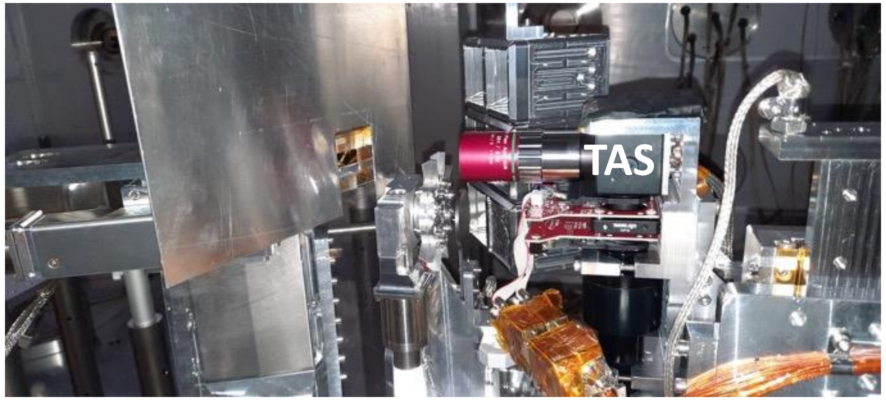
10 PW E1 LASER-SOLID experimental area commissioning

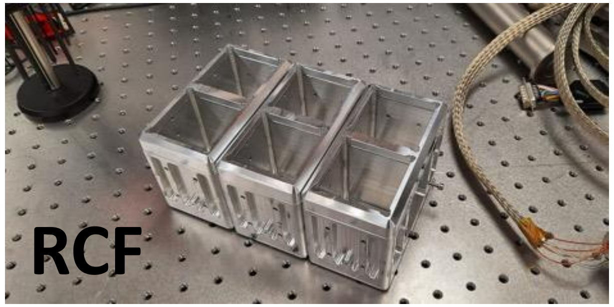
Commissioning goals: TNSA >200 MeV protons

List of diagnostics of E1

- Laser Diagnostics: pulse duration (PDS), laser near-field (LNF), laser far-field (LFF), back-reflection diagnostics (BRD), laser transmission near-field (LTNF),
- Target Alignment System (TAS),
- Radiochromic films & CR39 stack (RCF),
- Thomson Parabola (TP),
- Time-of-flight with diamond (ToF),
- Optical Probe/Pump (OP),
- X-ray spectrometer (XRS),
- e.m.p. diagnostic (EMPD).



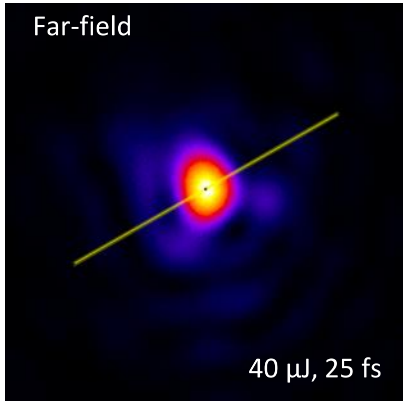


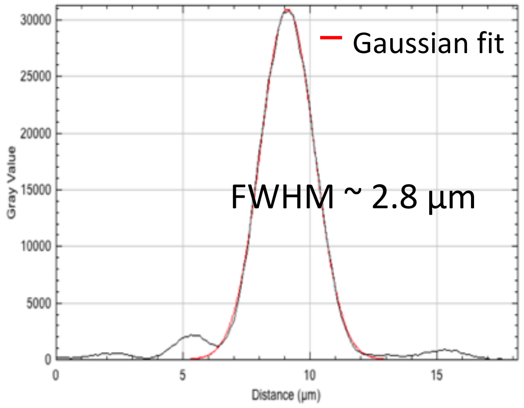


Far-field measurement and optimization

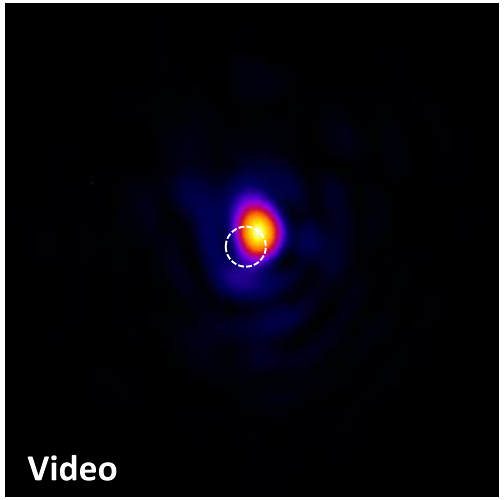
HPLS at low power

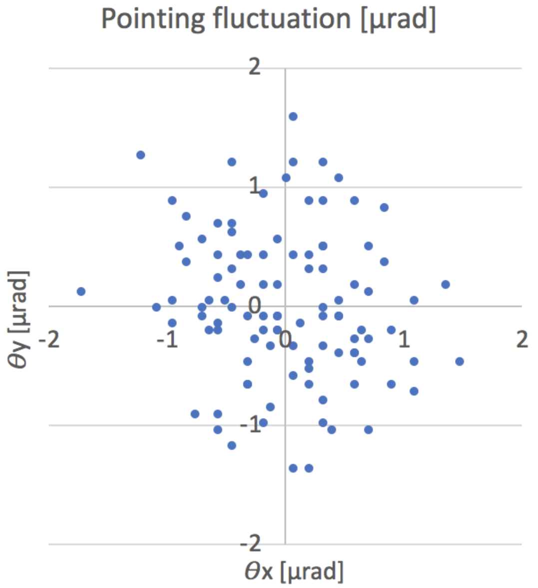
Best focal spot

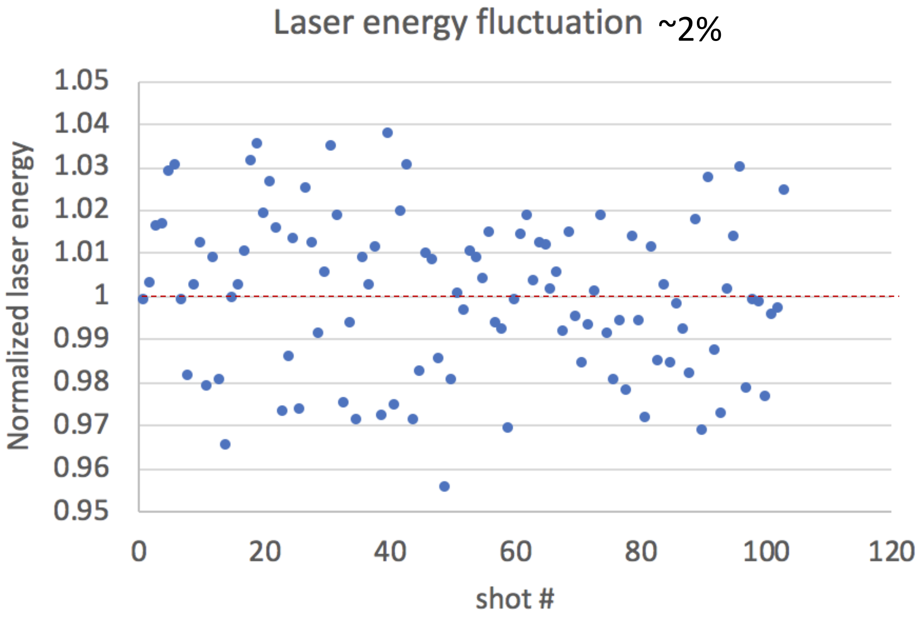




Movie of pointing fluctuation







Laser peak intensity

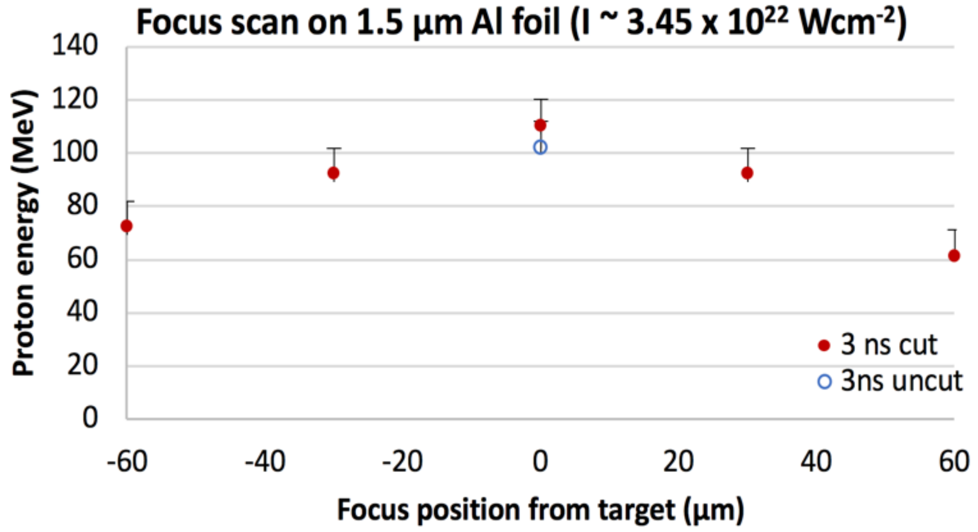
10 PW with 2.8 µm FWHM focal spot -> ~1.0 x 10^{23} Wcm^{-2}

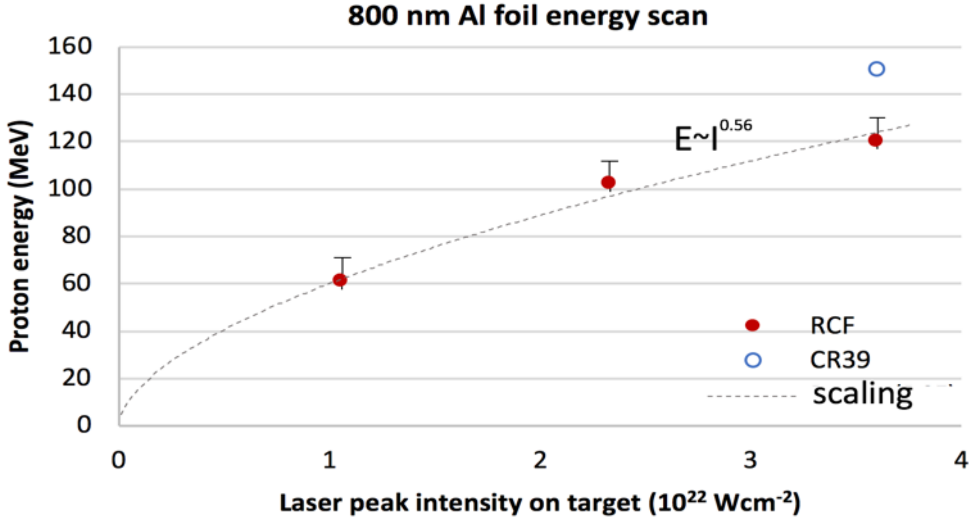
with an encircled energy @ $1/e^2$ of ~ 55% -> ~5.5 x 10^{22} Wcm^{-2}

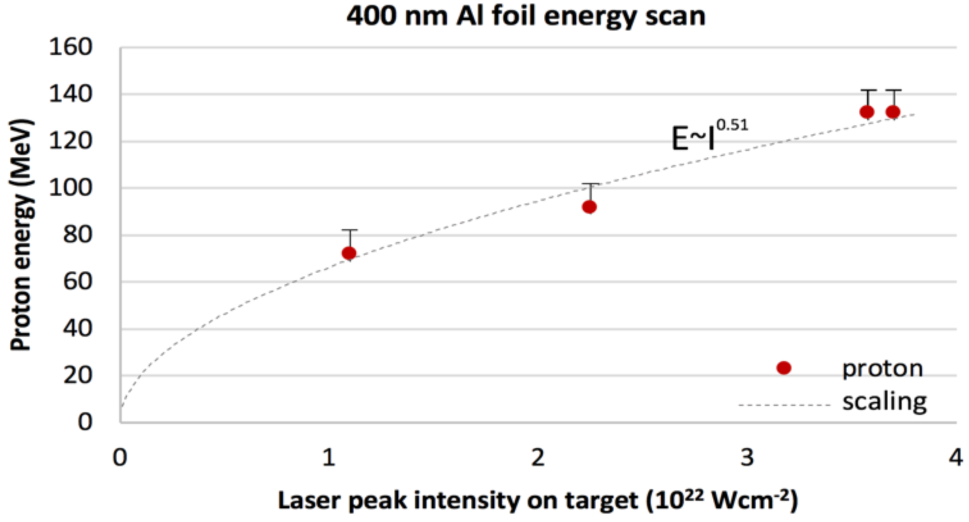
with PM ~ 75% reflectivity -> ~4.1 x 10^{22} Wcm^{-2}

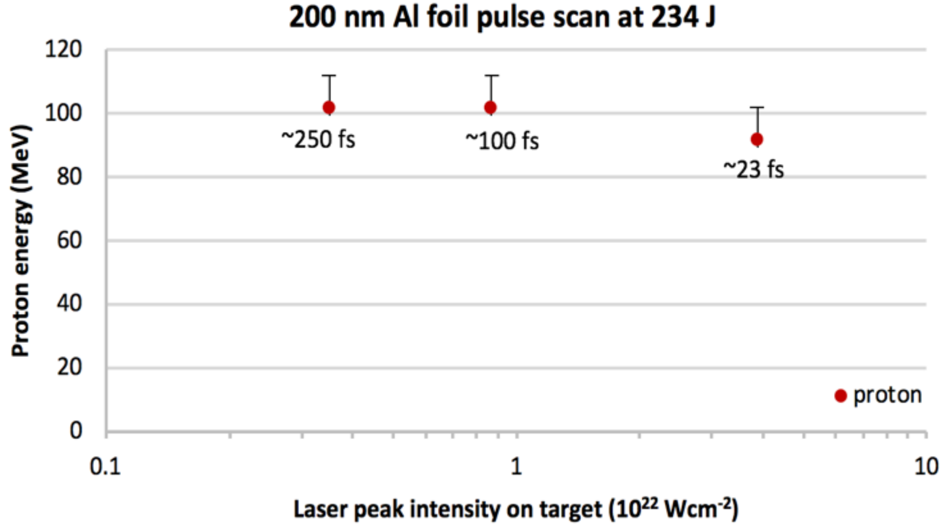
10 PW LASER-SOLID TNSA/RPA laser shots

High-power shots on Al foils - parametric scan









No transmitted light was observed, but during these shots our diagnostic was not sensitive to signals below 10% transmission

PIC simulation with the 10 PW of ELI-NP

10 PW Hydro and PIC simulation with prepulses contribution

Theory@LDED Led by P. Tomassini

Simulations performed with effective laser energy of 240 J * 0.55 * 0.75 = 100J in the TEM00 mode with 22 fs pulse duration and 3 µm FWHM laser spot, and peak intensity of **5×10^{22}W/cm^2** (a_0=150), and with perpendicular incidence

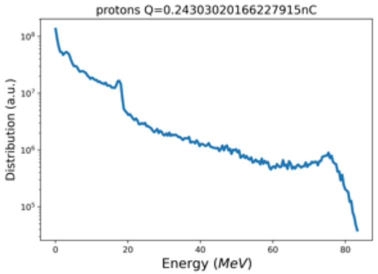
1-D **Hydro simulation** have been done on a **200nm Al** target using 3 different contrasts for a **prepulse at -20ns**

q3D PIC simulations have been performed using FB-PIC with 3 rotational modes.
Resolution of 5nm longitudinal, and 10nm radial, with 48ppc

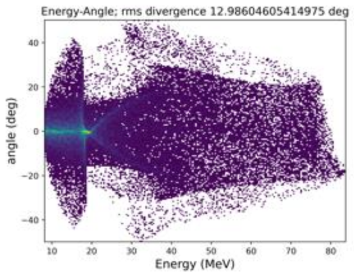
Using a **single PM** the prepulses on target can have a contrast of: ____

10^{-9} -> ~ 5×10^{13} W/cm^2

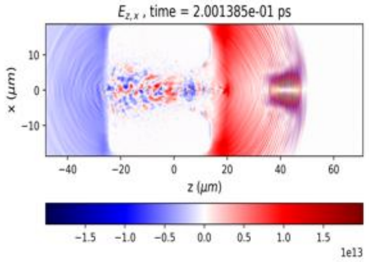
Proton spectrum



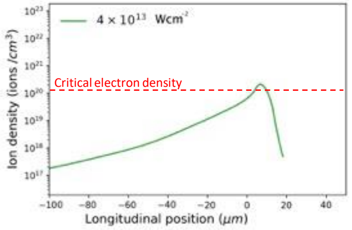
Angular distribution



Electric field z, x

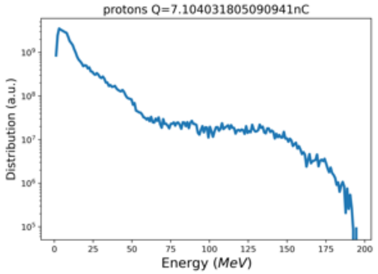


Input target density

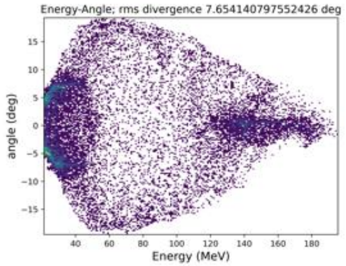


10^{-10} -> ~ 5×10^{12} W/cm^2

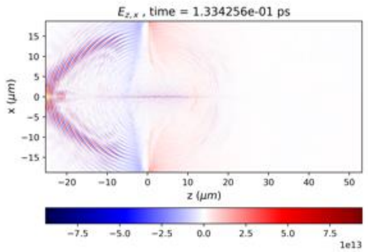
Proton spectrum



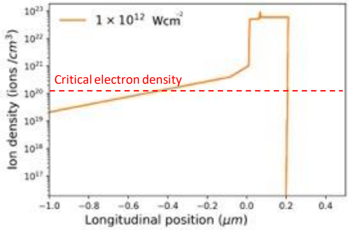
Angular distribution



Electric field z, x

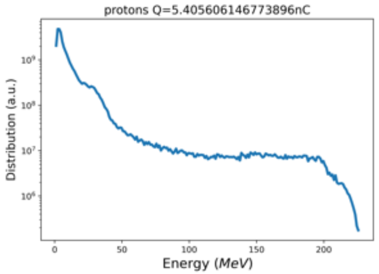


Input target density

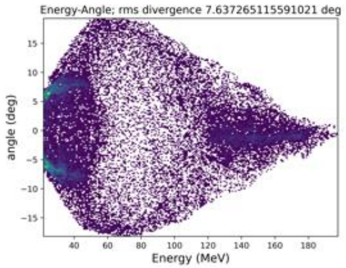


10^{-11} -> ~ 5×10^{11} W/cm^2

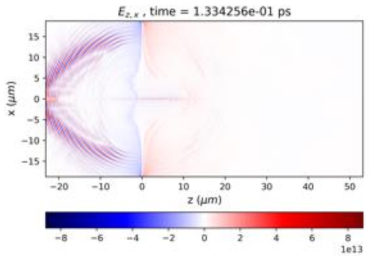
Proton spectrum



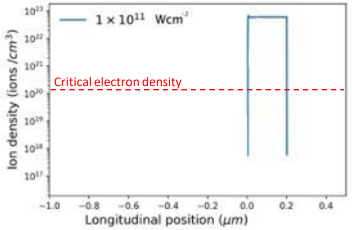
Angular distribution



Electric field z, x



Input target density



10 PW commissioning with gas targets (LWFA investigation)

Latest performance of the ELI-NP 10 PW on laser-driven electron acceleration

Laser characteristics with the shot focal mirror

Parabolic mirror: 30 mt focal length (F# ~28)

Spot size diameter: ~ 60.0 ± 2 µm at FWHM

Laser max. energy: 243±1 J on target

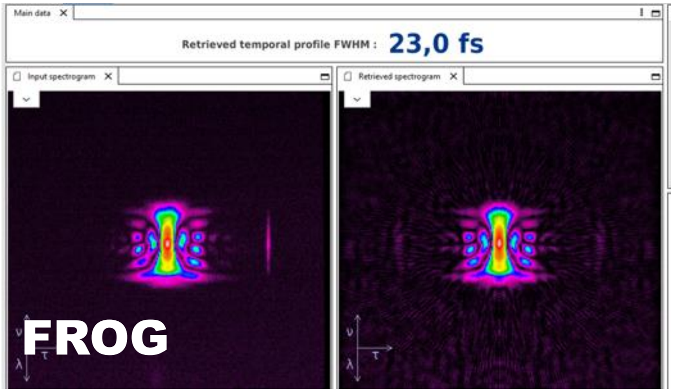
Encircled energy: ~ 50% @ 1/e^2 (ideal Gaussian beam is 86%)

Pulse duration : 23±1 fs on target

Laser energy stability at full power: ±2%

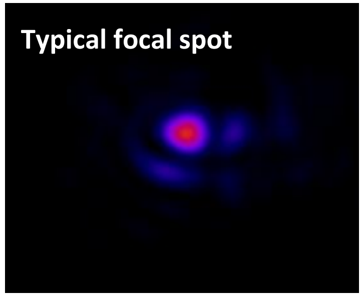
Laser pointing stability on target: < 2 µrad

Pulse duration measurement

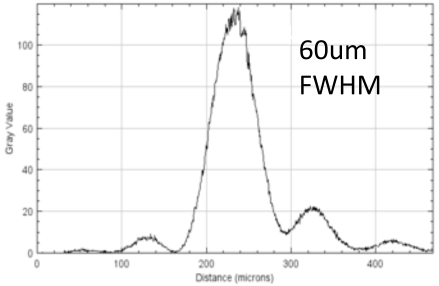


Retrieved temporal profile FWHM : 23,0 fs

Laser energy up to 185 J in E6, Nominal 8PW

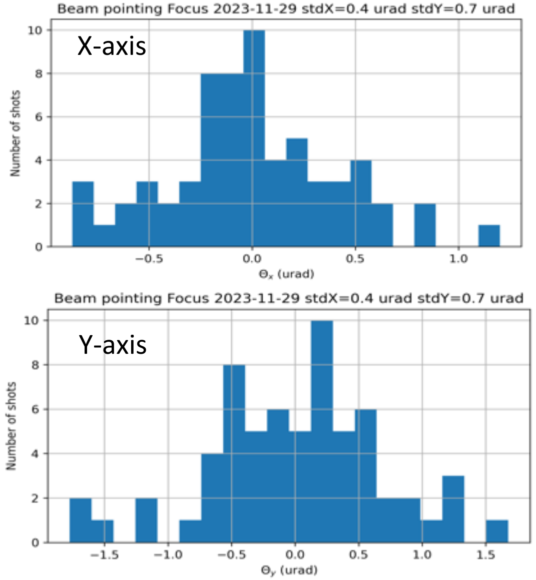


Laser best focal spot profile

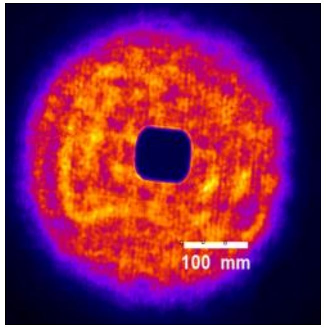


Pointing fluctuation

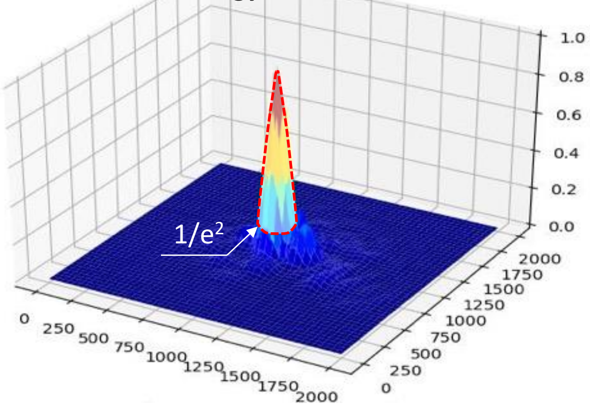
Less than 1 urad FWHM focus pointing
(0.5 - 1 focal spot)



Near-filed



Estimated encircled energy ~40%

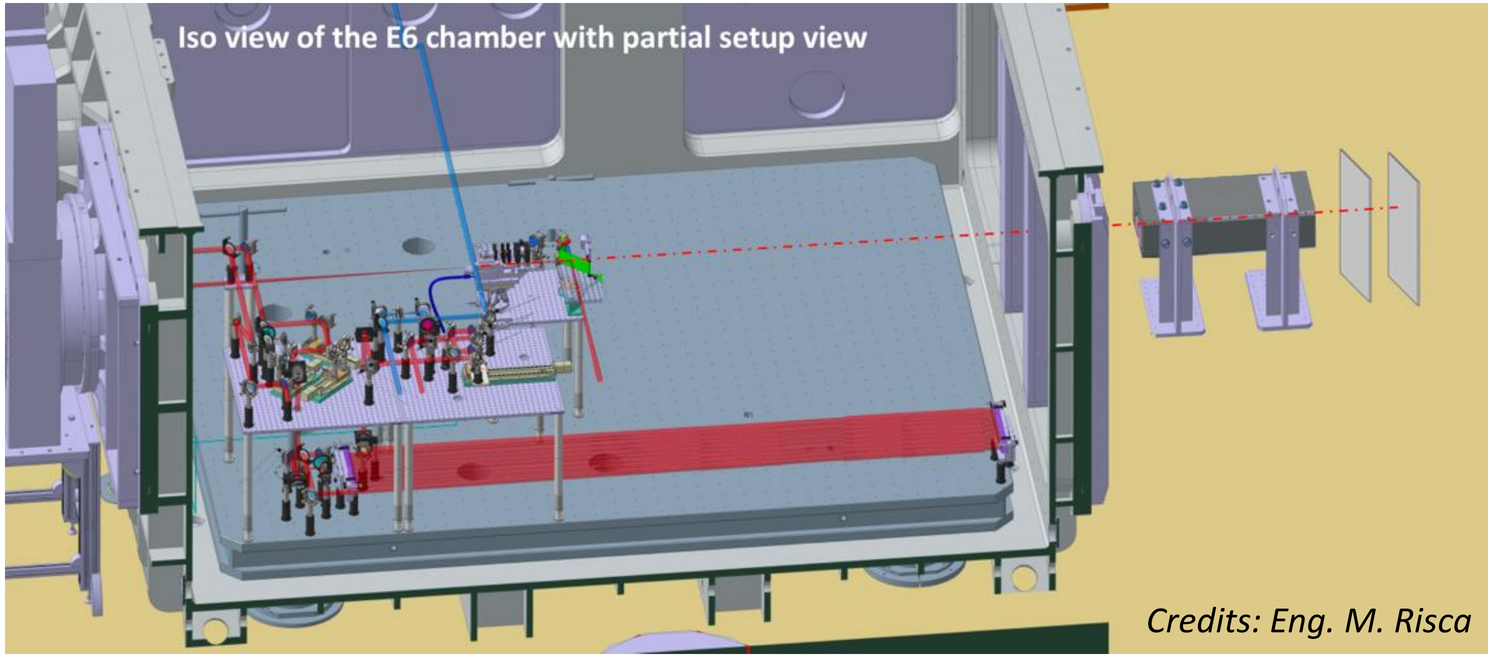


10 PW E6 experimental area commissioning experiments

10 PW multi-GeV electron acceleration commissioning run Nov2023

PI: P Ghenuche

Collaboration: LDED, LGED, GDED, LSD, Weizmann Institute (Israel), QUB (UK)

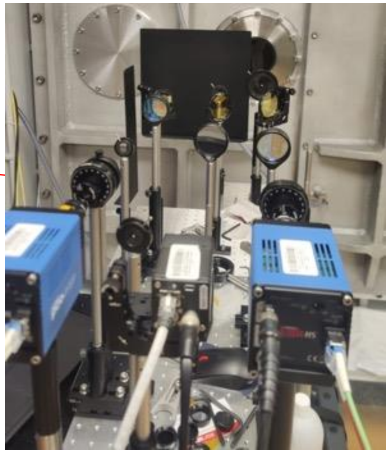


Iso view of the E6 chamber with partial setup view

Credits: Eng. M. Risca

E6 interaction chamber setup

Electron Spectrometer



Plasma Diagnostics

E6 Commissioning goals and long-term goals:

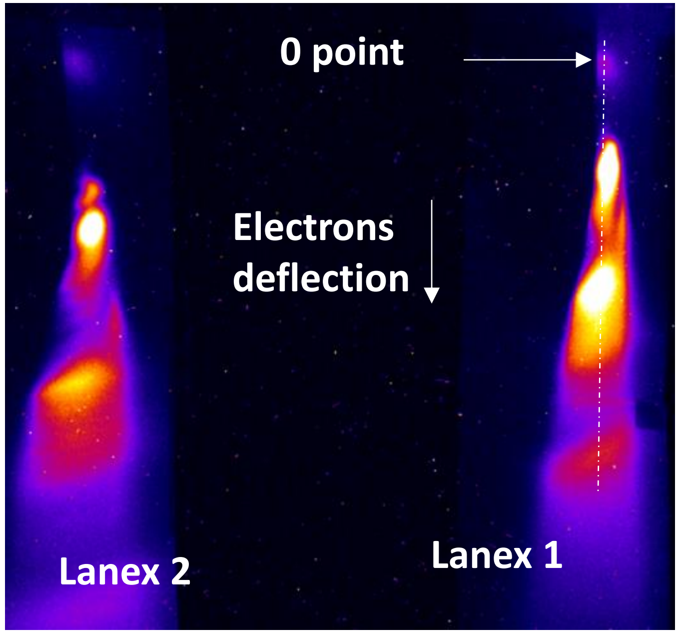
- Commissioning experiment: stable multi-GeV electron acceleration at multi-PW
- 2x10PW laser exp.: Collision of multi-GeV electron beam with $I>10^{22}$ W/cm^2 laser QED effects: radiation reaction, BW pairs, Inverse non-linear Thomson/Compton scattering with 2x10 PW laser beams
- Generation of muon/anti-muon beams

First run done in 2+5 weeks, but only 5 days of high power shots; second rum coming in Nov 2024

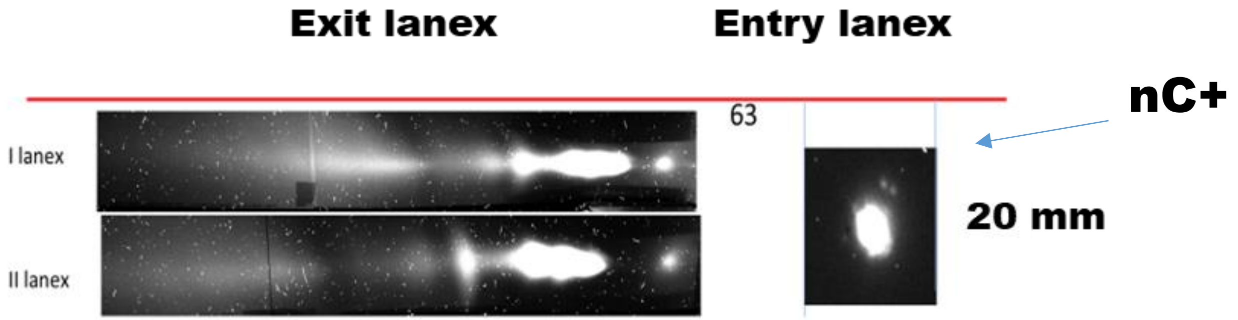
10 PW E6 experimental area commissioning experiments

First Multi-GeV beams at E6

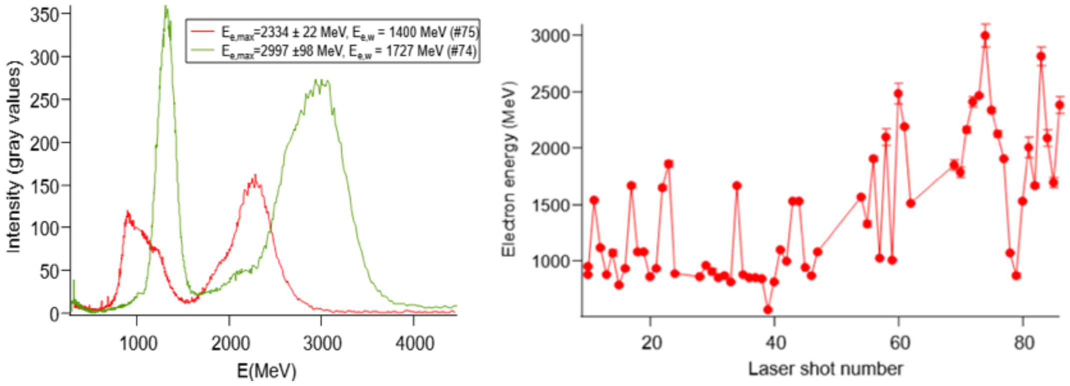
800mm Electron Spectrometer



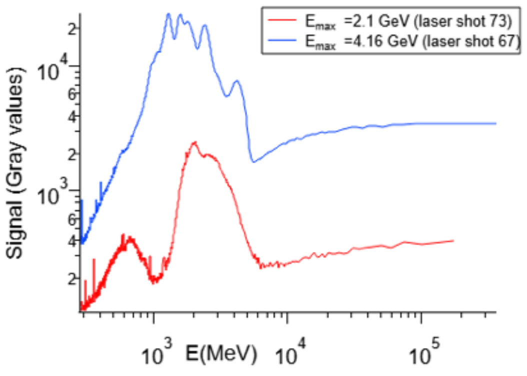
B.Diaconescu, C. Ticos, F. D'Souza, L.Tudor, S.Ter-Avetisian, V. Nastasa, S. Balascuta



15 mm gas length



40 mm gas length

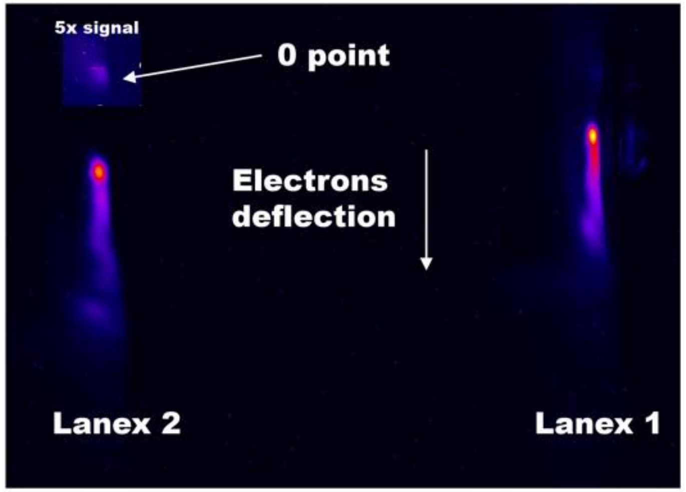


Preliminary data analysis S. Balascuta, S.Ter-Avetisian, R. Iovanescu
Lanex calibration Prof. V. Malka's group

Results of the first run

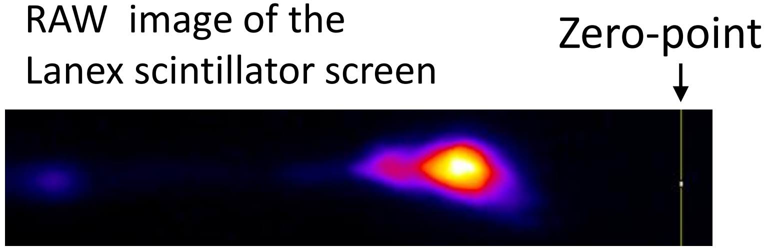
- Good Charge and Divergence, up to 4 GeV at nominal max 8 PW, as predicted by simulations (Dr. P. Tomassini)
- Longer target and guiding will increase considerably the accelerated electron energy

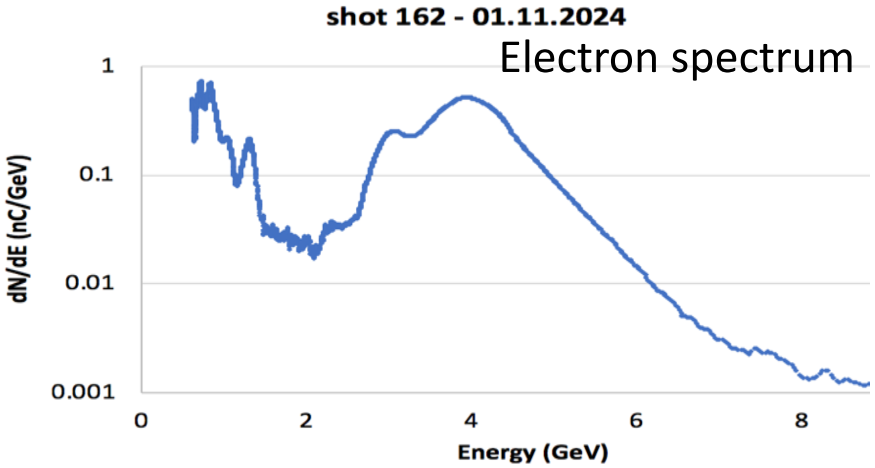
LWFA of electron via 10 PW laser beam



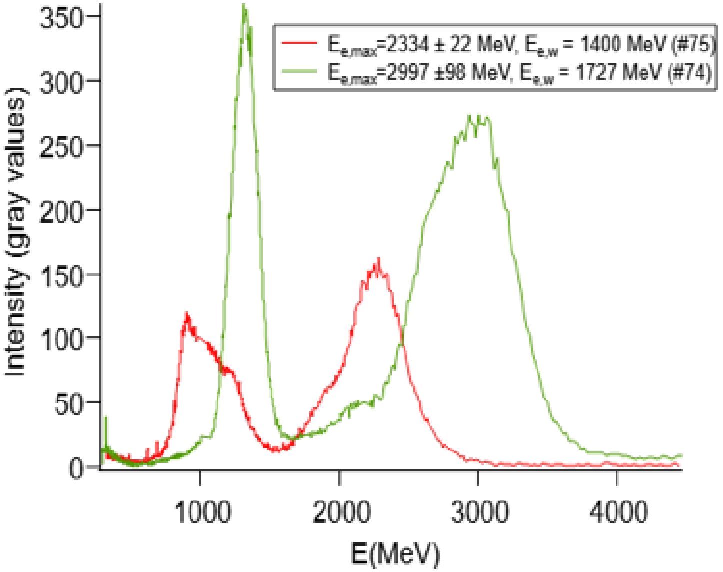
Using 60 mm gas length , He+N2 2% gas

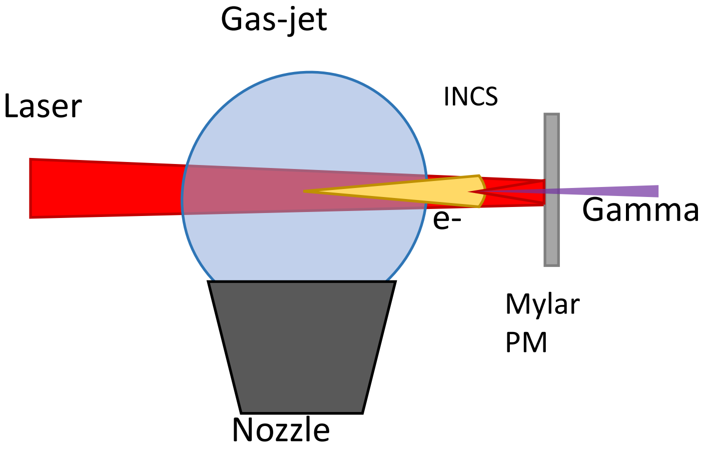
RAW image of the
Lanex scintillator screen





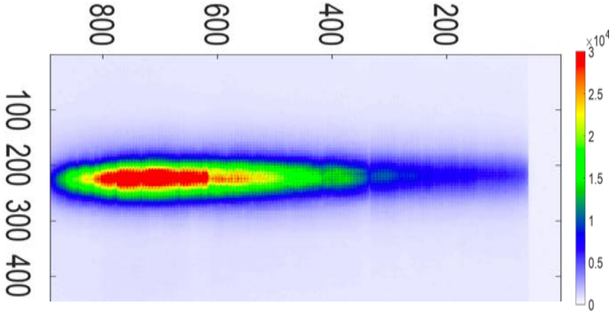
15 mm gas length, He+N2 2% gas





Sketch of the NICS setup

Gamma from Inverse Compton
Scattering – LYSO matrix detector



Muon experiment on Dec 2024

ELI-NP

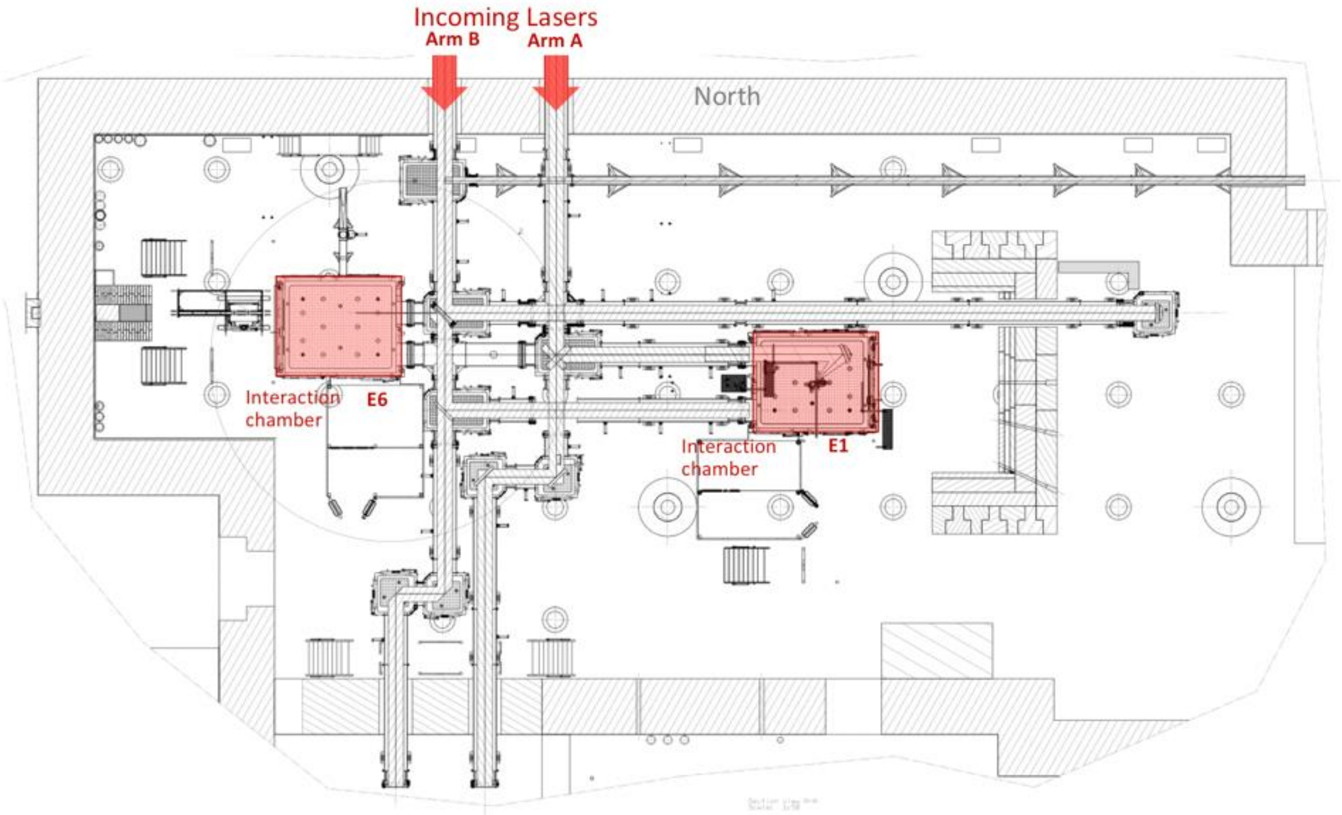
P.I. D. Doria
Co-P.I. P. Ghenuche

The 10 PW experimental area

The muon generation experiment will be performed in the E6 area.

Recently there is an interest in muons generation via laser-driven and very few experiments with no clear results have been performed with ~ 1 GeV electron beam.

Recently, in March 2024, an experiment on laser generated muon via LWFA electrons and Bethe-Heitler pair production was conducted at the Colorado State University's L-ALEPH in the framework of the "Intense and Compact Muon Sources for Science and Security (ICMuS2)" project —Led by Lawrence Livermore National Laboratory (LLNL) with ELI-Beamlines as partner. The have achieved ~5 GeV electron and produced muons' pairs. Similar parameters will be achieved at E6 but with much more muons production.



E6: 10 PW experimental area

HPLS: 1 arm of 240 J, 23 fs, 1/60 Hz

LDED department
(Head of LDED: Domenico Doria)

Contact Person: Petru Ghenuche
Email: petru.ghenuche@eli-np.ro

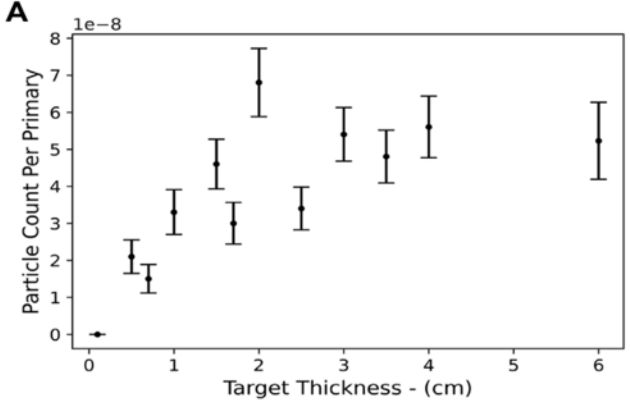
10 PW E6 experimental area commissioning experiments

Muon generation via bremsstrahlung

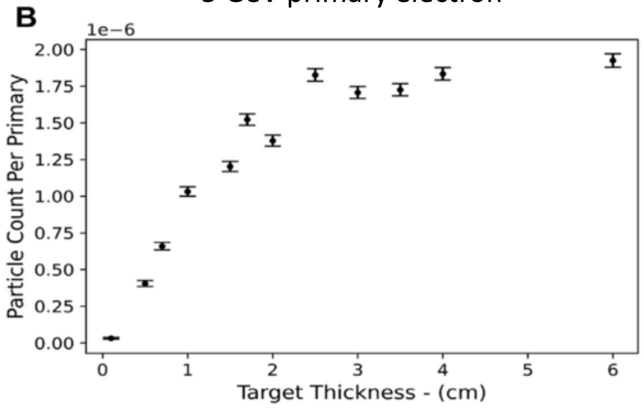
L. Calvin et al., Front. Phys., 19 June 202311| https://doi.org/10.3389/fphy.2023.1177486

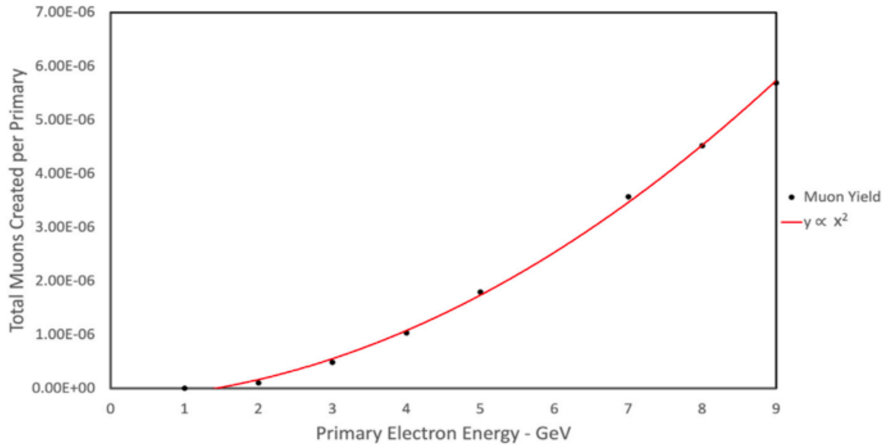
Conversion efficiency scaling with lead length

2 GeV primary electron



5 GeV primary electron

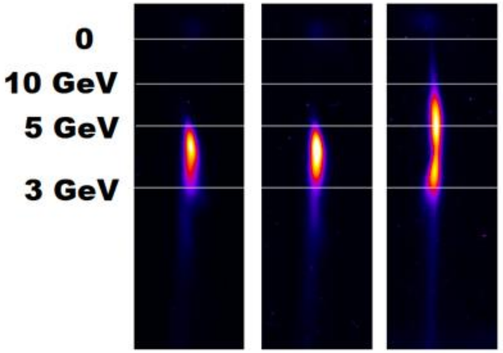




Conversion efficiency scaling for 2 cm lead

LWFA Electron RAW image obtained at E6 recently

- ☐ **Series of high power shots @ 8 PW nominal**
- ☐ **40 mm target**



We have already proven to be able to generate about up to 5 GeV electron with a charge of about 2 nC using 8 PW laser beam.

Conversion efficiency for an electron energy of

2 GeV -> (7 ± 1) × 10^{-8} muons per electron

5 GeV -> (1.85 ± 0.10) × 10^{-6} muons per electron

Example:

- **2 cm** lead converter
- assuming a **1 nC** electron charge

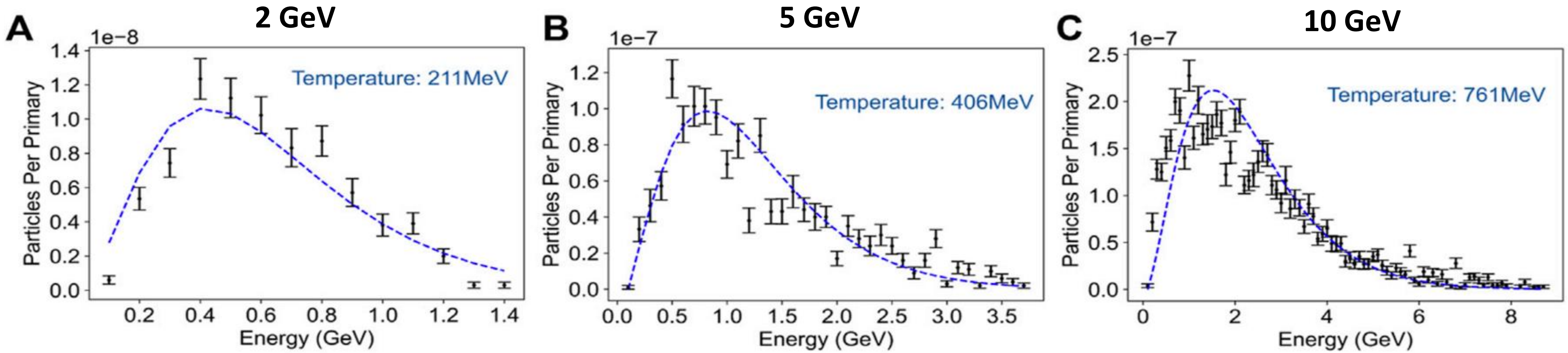
We obtain a total of **400 ± 60 muons for a 2 GeV electron** beam and **(1.16 ± 0.06) × 10^4 muons for a 5 GeV** electron beam

10 PW E6 experimental area commissioning experiments

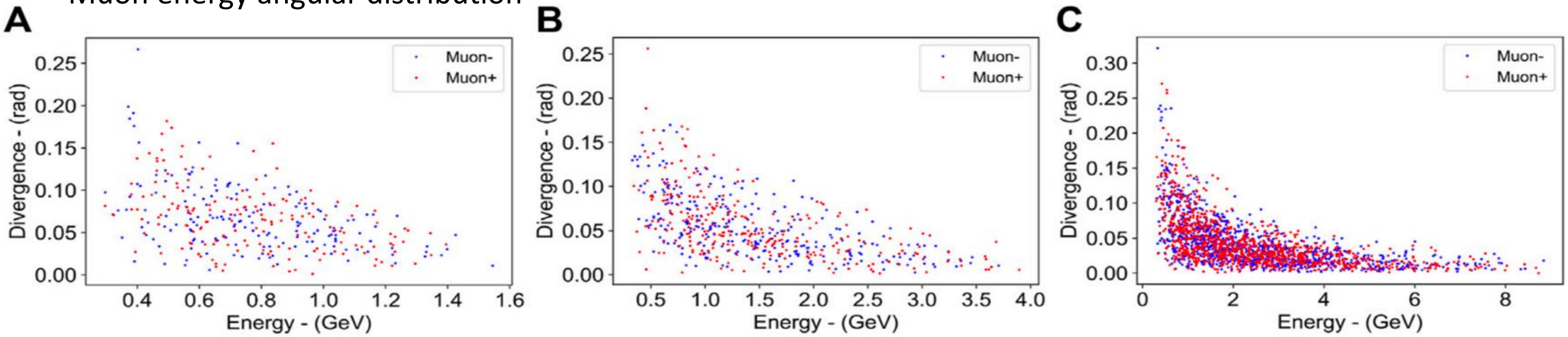
Muon generation

L. Calvin et al., Front. Phys., 19 June 202311|
https://doi.org/10.3389/fphy.2023.1177486

Muon total spectral emission



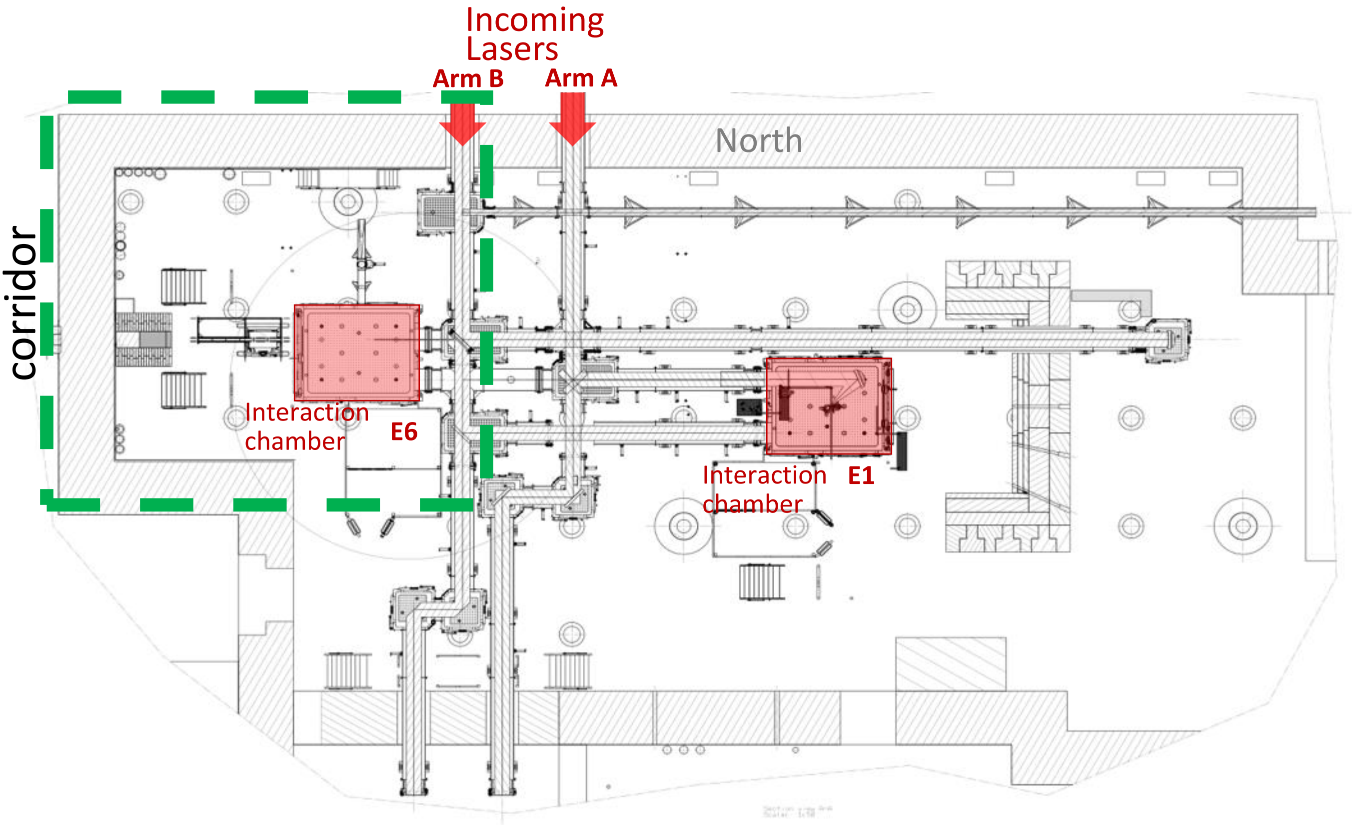
Muon energy angular distribution

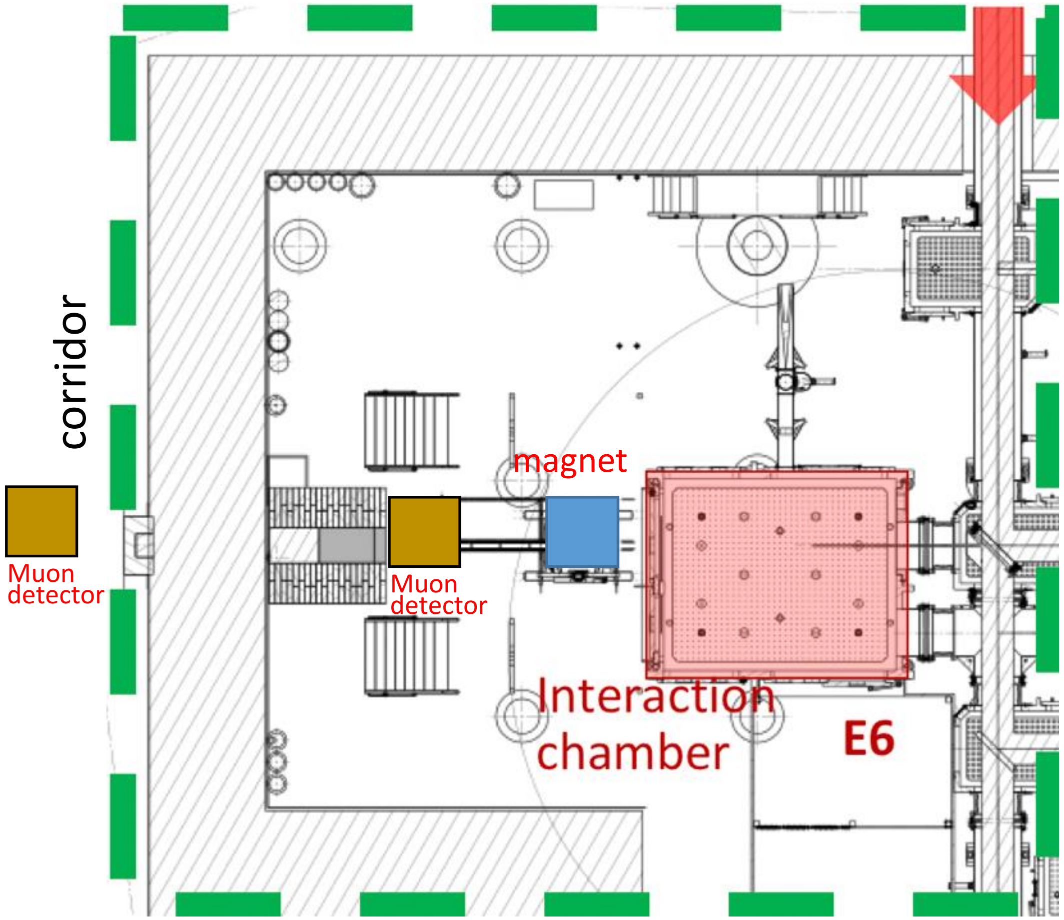


Muons’ energy spectra distribution for 2 cm lead converter

The 10 PW experimental areas

Muon detectors will be placed inside and outside the experimental area





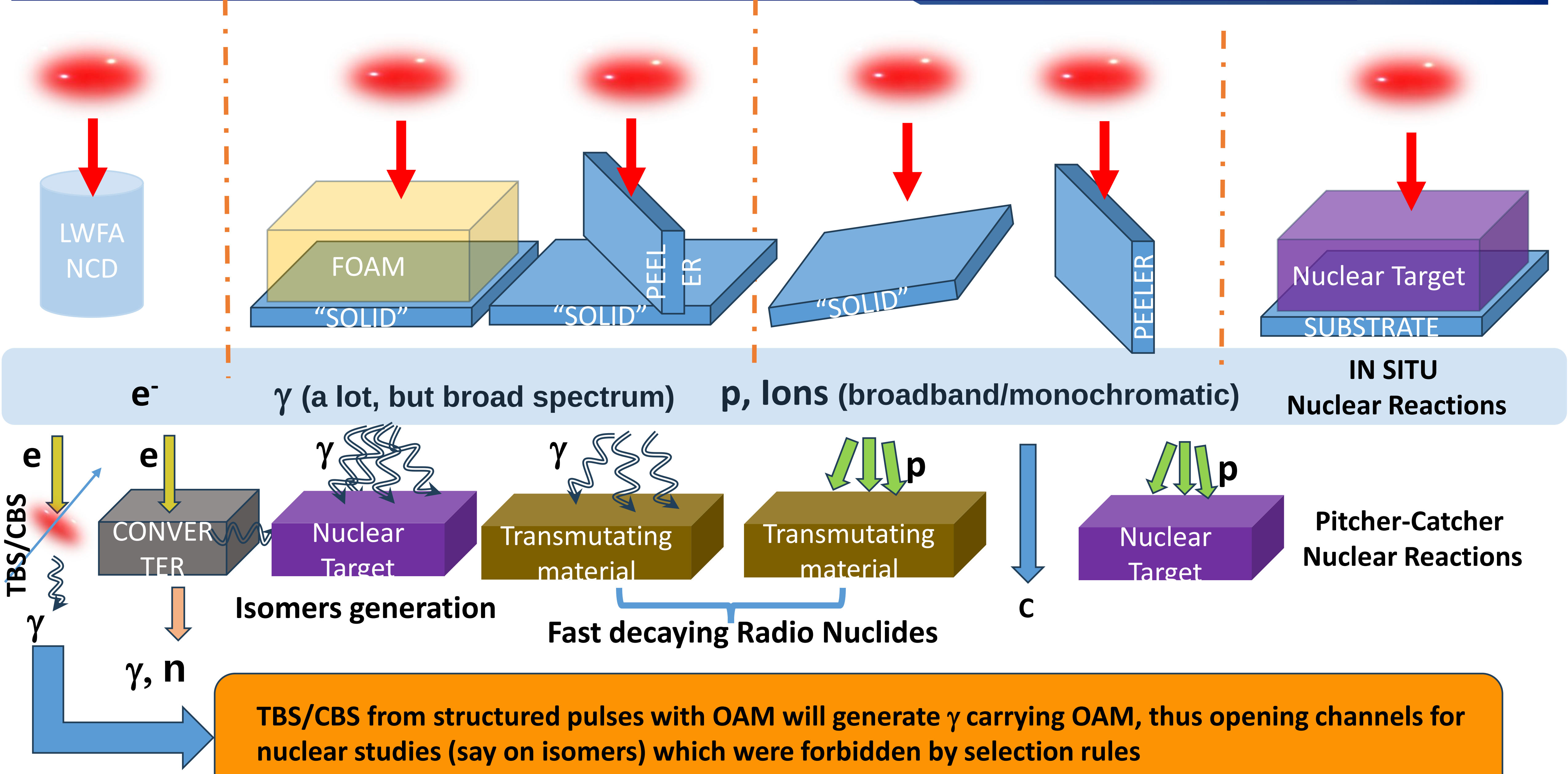
We can use the ~ 10 m long corridor to install detectors

The structure of the talk

Sections:

1. A survey on laser-matter interaction
2. What’s going on at ELI-NP
3. **Some NP applications of laser-matter interactions**

Interaction zoology (useful for NP studies) at ELI-NP



e⁻

γ (a lot, but broad spectrum)

p, Ions (broadband/monochromatic)

IN SITU Nuclear Reactions

Isomers generation

Fast decaying Radio Nuclides

Pitcher-Catcher Nuclear Reactions

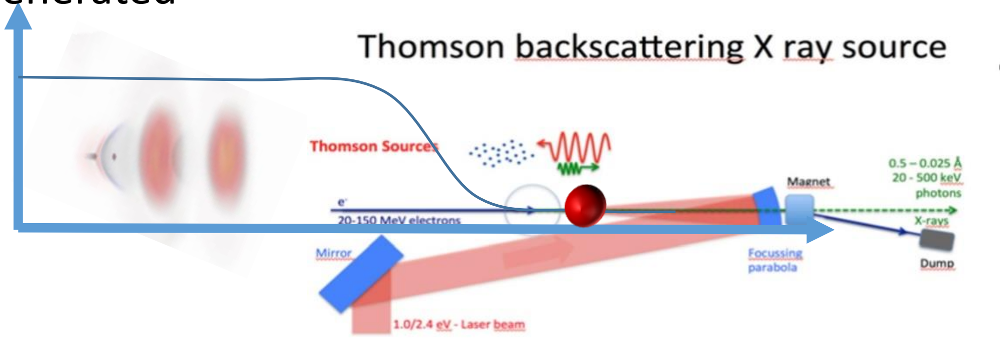
TBS/CBS from structured pulses with OAM will generate γ carrying OAM, thus opening channels for nuclear studies (say on isomers) which were forbidden by selection rules

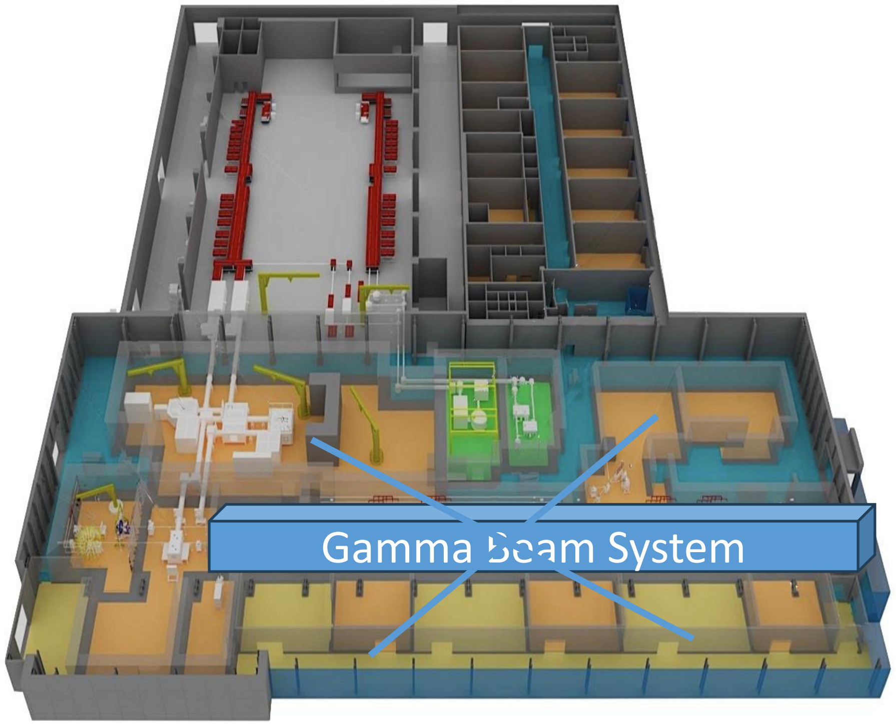
Nuclear Physics with Compton/Thomson BS gamma beams

The missing EUROGAMMAS gamma beam (now being substituted) TBS with high-brightness beams

<u>While waiting for a gamma beam system</u>, studies with Compton/Thomson backscattered radiation can be done

We cannot expect the same spectral density/flux/energy spread of the gamma beam system, but at least quasi-monochromatic beams must be generated





The **minimum attainable** energy spread of the gamma beam is
[P. Tomassini et al., Appl. Phys. B 80 (2005)]

$$(\delta\omega/\omega)_{min} \simeq \sigma(u_\perp)^2 + 2\frac{\delta\gamma}{\gamma} + a_0^2/2$$

(Ψ=0, negligible pulse BW)

Very useful definition of the normalized acceptance

$$\Psi \equiv \gamma \cdot \theta_c$$

$$\text{if } \Psi \ll 1 \Rightarrow N_{Acc}(\Psi) \simeq \delta\omega/\omega \simeq \Psi^2$$

Therefore, a **high brightness** LWFA 100’s MeV/GeV **must be employed** so as to get monochromatic and low transverse momentum electron beam.

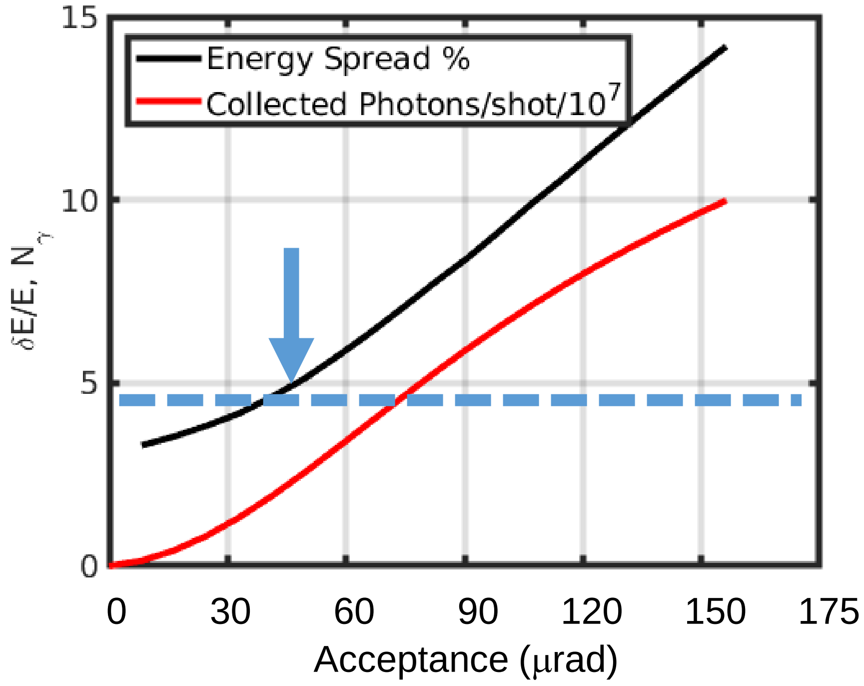
Quasi monochromatic and brilliant gamma beam with ReMPI+TBS

Projected beam quality (ReMPI/2pulses)

σ(E)/E	Q	σ(u perp.)	σ(x perp.)	σ(z long.)
0.7%	20pC	0.12	1 μm	0.2μm

Counterpropagating pulse Yb:YAG (1.053 μm)

Energy	Duration	w0	a0
1J	2ps	12.5 μm	0.2



Expected minimum energy spread

$$(\delta\omega/\omega)_{min} \approx 3\%$$

The **peak** brilliance is very large

$$B = \frac{N_{ph}\text{‰}bw}{\delta t_\gamma(s)S(mm^2)\theta^2_{max}(mrad^2)} = \mathbf{2\cdot 10^{28}}\, ph/(s\cdot mm^2\cdot mrad^2\cdot \text{‰}bw)$$

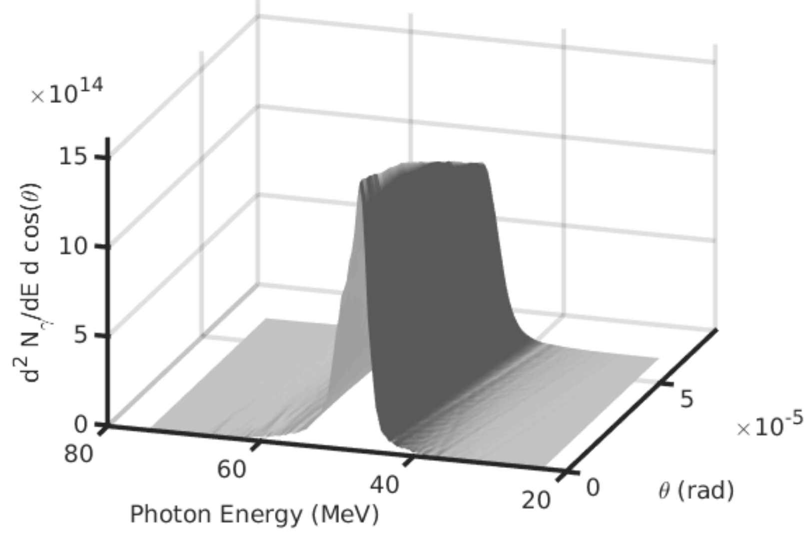
But the (average) spectral density and photon number are low (we don't have any recirculation)

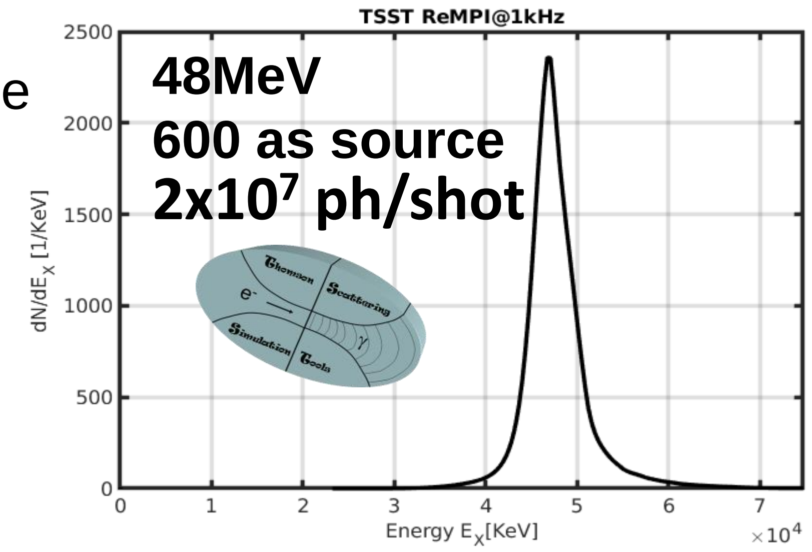
S = 50 γ/eV/s (10 Hz)

Vortex (LG with OAM) gamma beams can also be generated

ReINTS

P. Tomassini, 2022

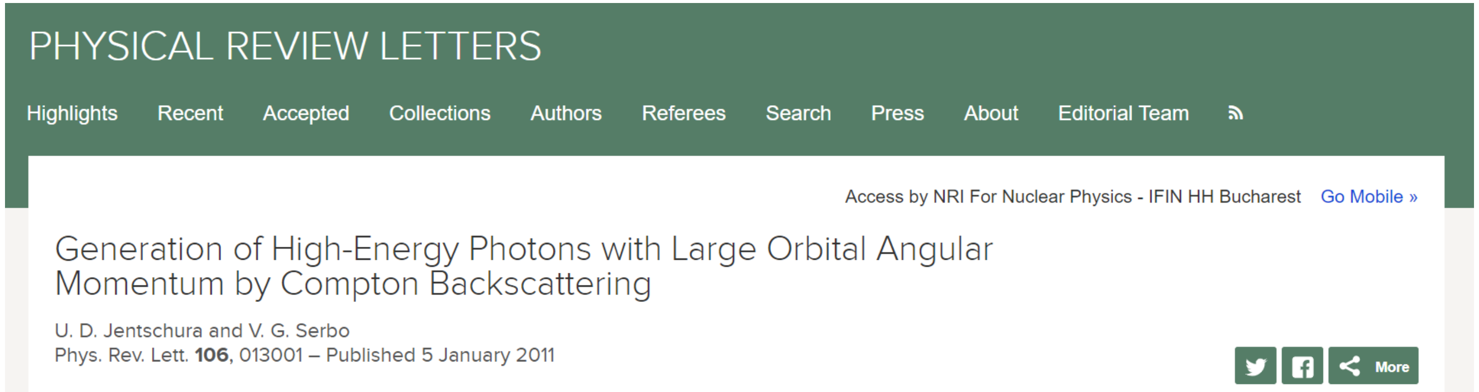




48MeV
600 as source
$2\text{x}10^7$ ph/shot

Quasi monochromatic and brilliant OAM gamma beam with TBS

Beside the standard gamma beams with flat/quasi-flat phase fronts and quasi TEM00 spatial distribution, **backscattering with structured beams carrying Orbital Angular Momentum (OAM) can be made**, thus generating γ **beams with OAM**



PHYSICAL REVIEW LETTERS

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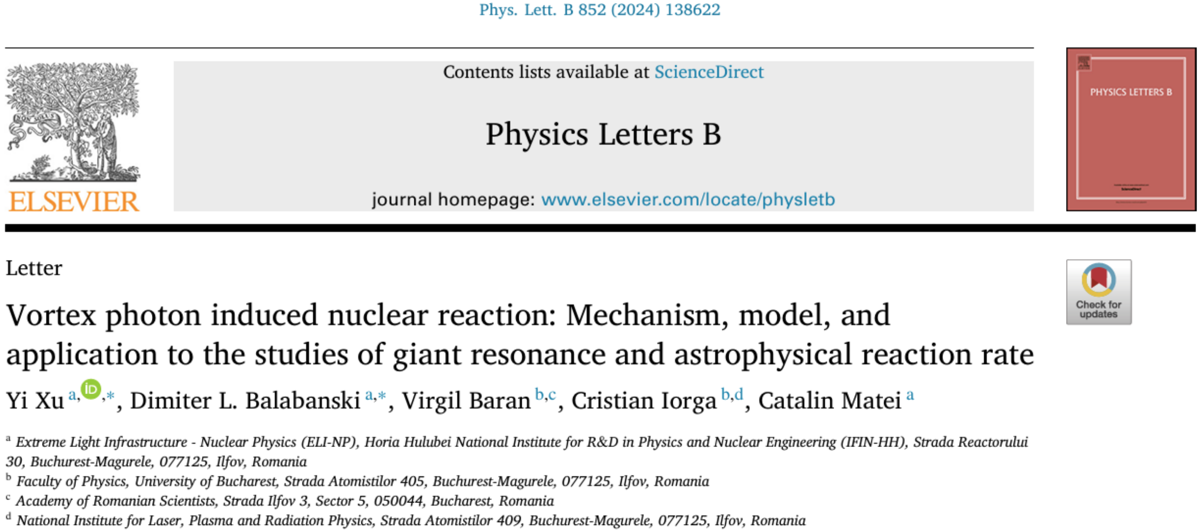
Generation of High-Energy Photons with Large Orbital Angular Momentum by Compton Backscattering

U. D. Jentschura and V. G. Serbo

Phys. Rev. Lett. **106**, 013001 – Published 5 January 2011



Phys. Lett. B 852 (2024) 138622

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Letter

Vortex photon induced nuclear reaction: Mechanism, model, and application to the studies of giant resonance and astrophysical reaction rate

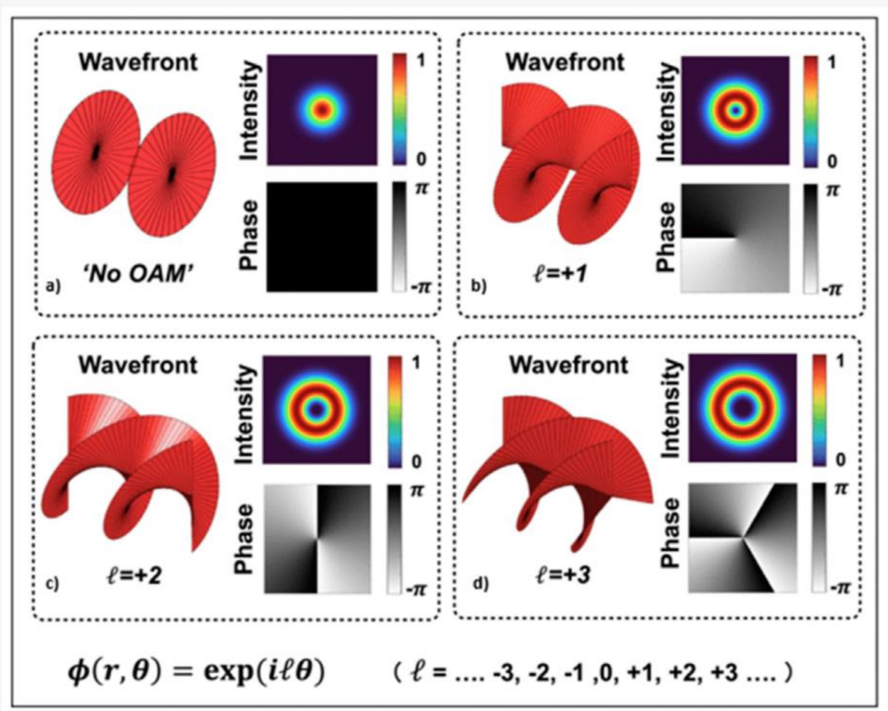
Yi Xu [a,*], Dimiter L. Balabanski [a,*], Virgil Baran [b,c], Cristian Iorga [b,d], Catalin Matei [a]

[a] *Extreme Light Infrastructure - Nuclear Physics (ELI-NP), Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Strada Reactorului 30, Bucharest-Magurele, 077125, Ilfov, Romania*

[b] *Faculty of Physics, University of Bucharest, Strada Atomistilor 405, Bucharest-Magurele, 077125, Ilfov, Romania*

[c] *Academy of Romanian Scientists, Strada Ilfov 3, Sector 5, 050044, Bucharest, Romania*

[d] *National Institute for Laser, Plasma and Radiation Physics, Strada Atomistilor 409, Bucharest-Magurele, 077125, Ilfov, Romania*



$\phi(r,\theta) = \exp(i\ell\theta)$ (ℓ = ... -3, -2, -1 ,0, +1, +2, +3 ....)

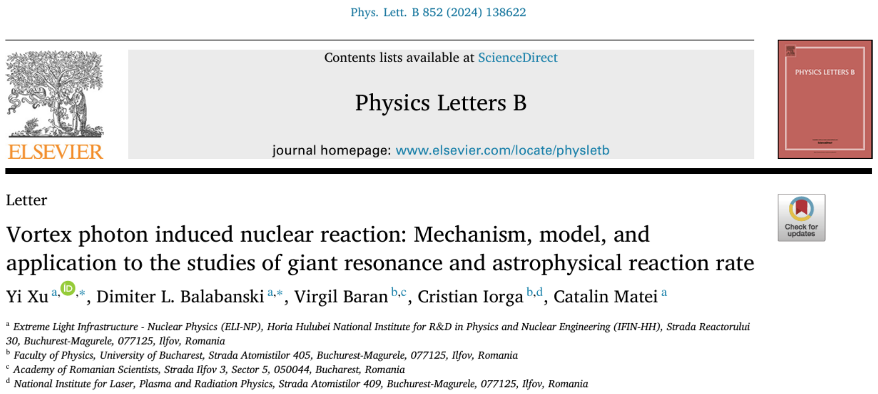
T. M Olaye et al., 10.3390/photonics10060664

Vortex (LG with OAM) gamma beams can also be simulated

ReINTS

P. Tomassini,2022

Quasi monochromatic and brilliant OAM gamma beam with TBS: Application to NP



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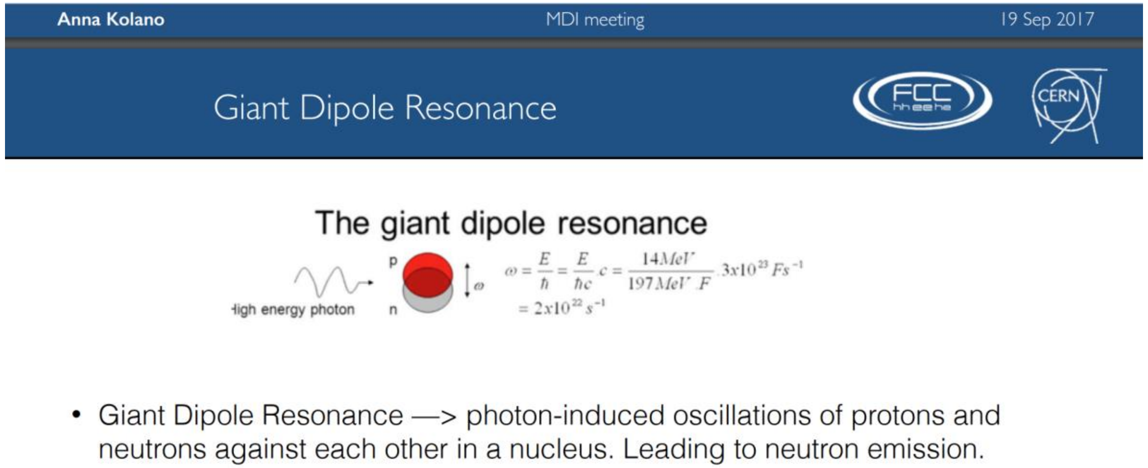
[a] Extreme Light Infrastructure - Nuclear Physics (ELI-NP), Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Strada Reactorului 30, Bucharest-Magurele, 077125, Ilfov, Romania
[b] Faculty of Physics, University of Bucharest, Strada Atomistilor 405, Bucharest-Magurele, 077125, Ilfov, Romania
[c] Academy of Romanian Scientists, Strada Ilfov 3, Sector 5, 050044, Bucharest, Romania
[d] National Institute for Laser, Plasma and Radiation Physics, Strada Atomistilor 409, Bucharest-Magurele, 077125, Ilfov, Romania

Study of the influence of OAM on the Giant Dipole Resonance of some nuclei



Anna Kolano MDI meeting 19 Sep 2017

Giant Dipole Resonance

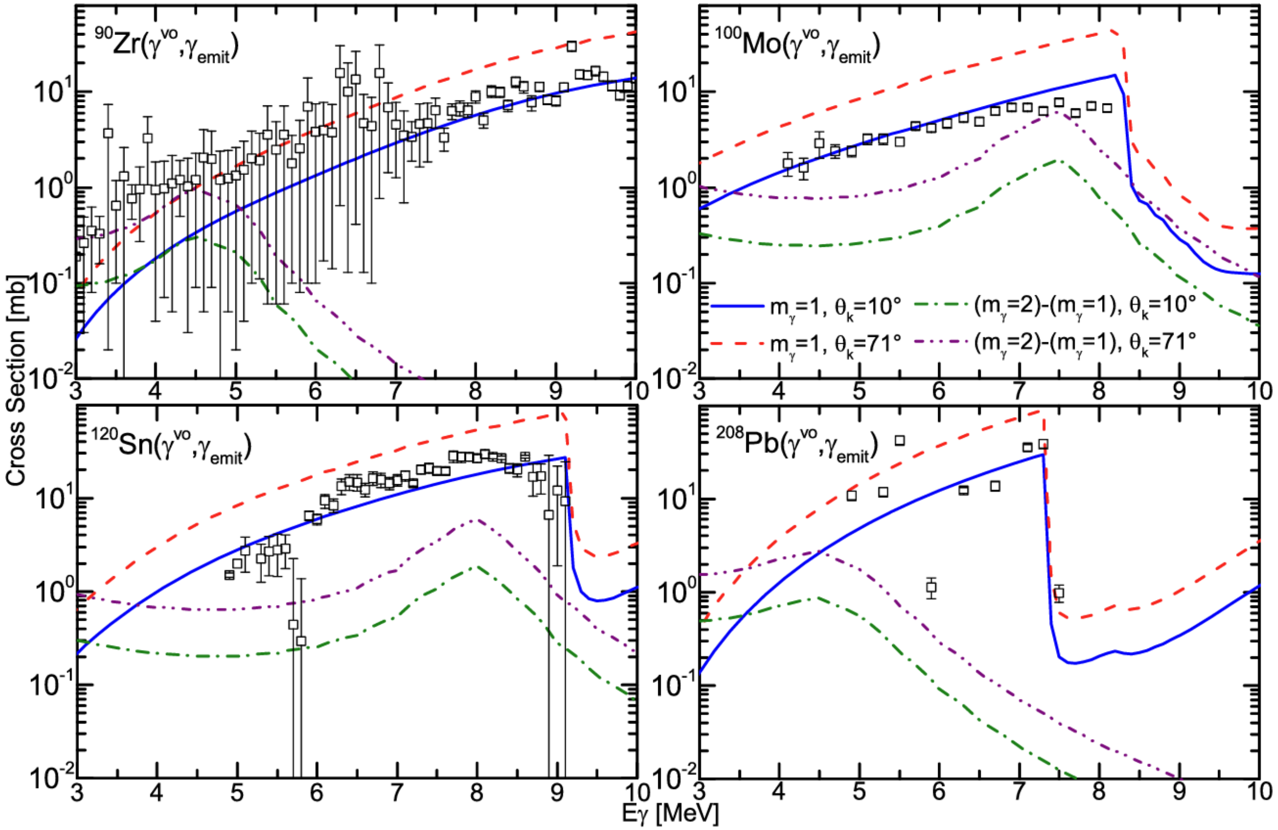
The giant dipole resonance

$$\omega = \frac{E}{\hbar} = \frac{E}{\hbar c}c = \frac{14MeV}{197MeV\ F}3x10^{23}Fs^{-1} = 2x10^{22}s^{-1}$$

- Giant Dipole Resonance —> photon-induced oscillations of protons and neutrons against each other in a nucleus. Leading to neutron emission.

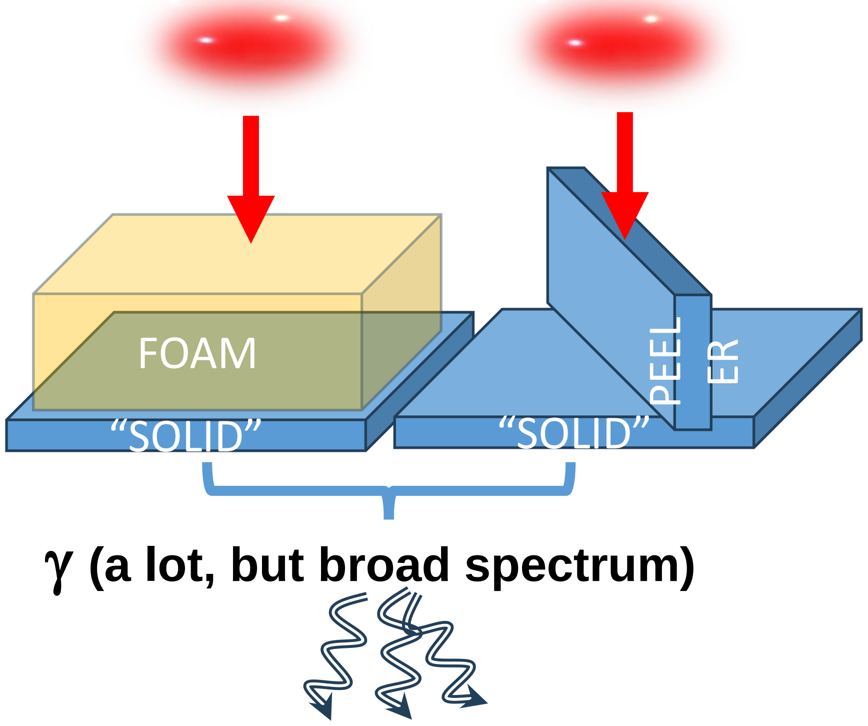
https://indico.cern.ch/event/666960/contributions/2726609/attachments/1526494/2387021/19SEP17MDI.pdf

Y. Xu, D.L. Balabanski, V. Baran et al.



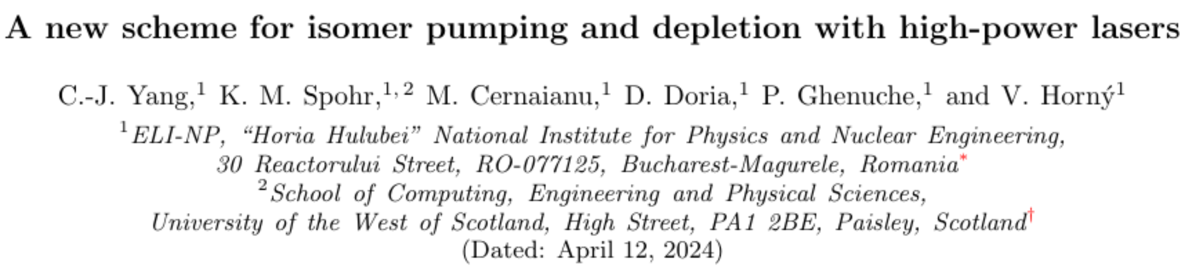
Change by orders of magnitude of the cross sections for the cases w/wo OAM are expected

Isomer pumping via multiphoton γ absorption



γ (a lot, but broad spectrum)

With ultrashort γ bursts multiphoton absorption can be not negligible and excite isomer states



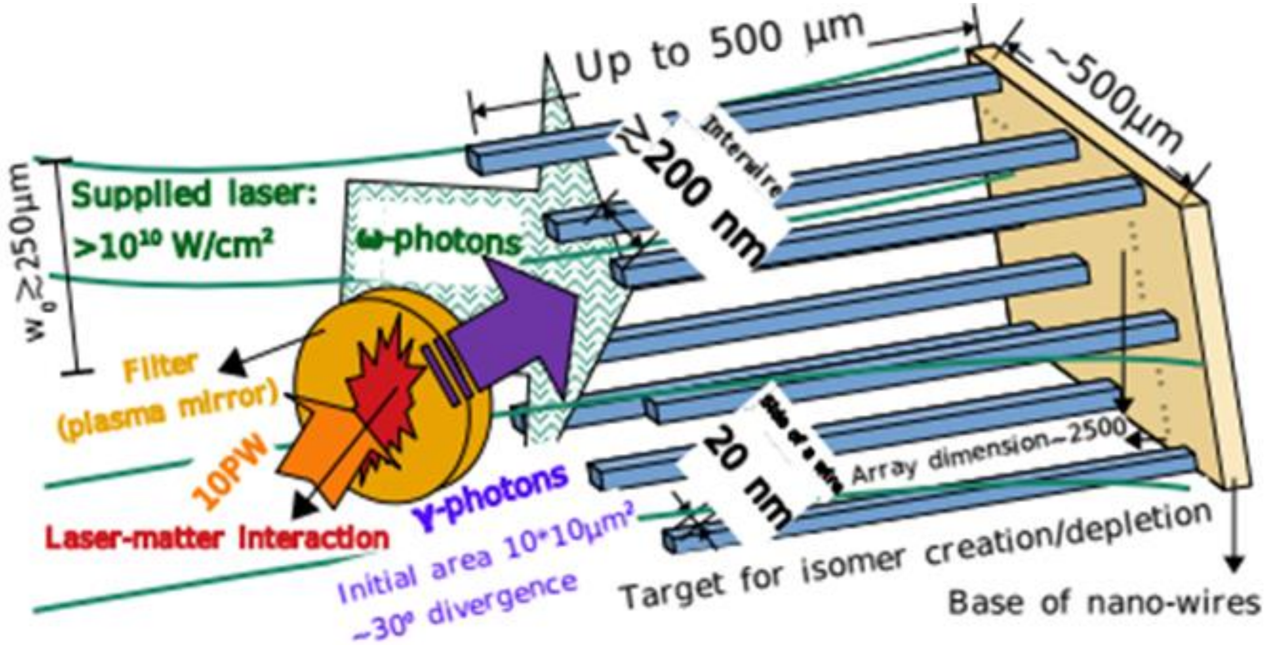
A new scheme for isomer pumping and depletion with high-power lasers

C.-J. Yang,[1] K. M. Spohr,[1,2] M. Cernaianu,[1] D. Doria,[1] P. Ghenuche,[1] and V. Horný[1]
[1] *ELI-NP, "Horia Hulubei" National Institute for Physics and Nuclear Engineering, 30 Reactorului Street, RO-077125, Bucharest-Magurele, Romania**
[2] *School of Computing, Engineering and Physical Sciences, University of the West of Scotland, High Street, PA1 2BE, Paisley, Scotland*†
(Dated: April 12, 2024)

C.-J. Yang, K.M. Spohr, M. Cernaianu, D. Doria, P. Ghenuche, V. Horny, arXiv:2404.07909 [nucl-th] (under review)

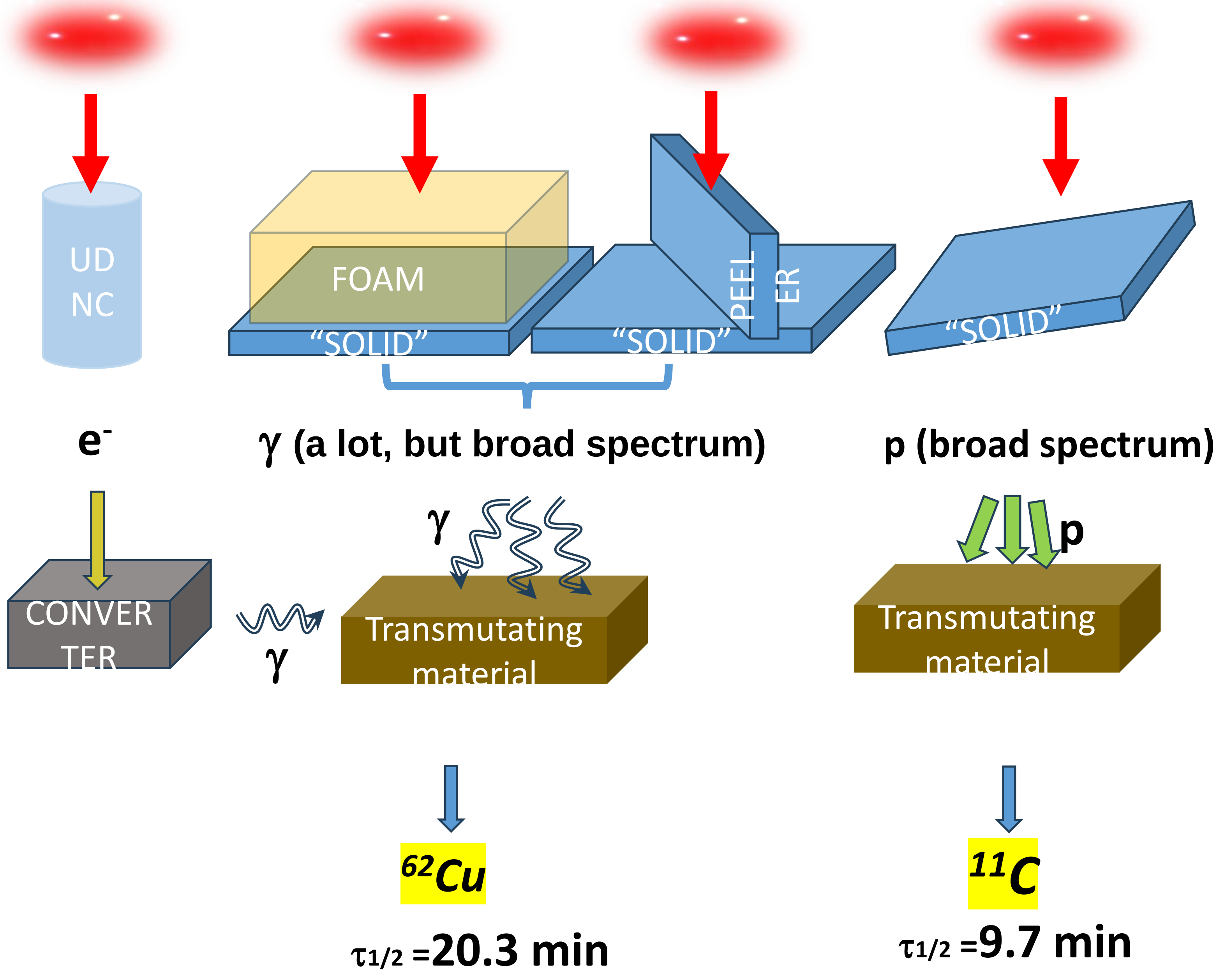
Nuclear Physicist

Chieh-Jen Yang
Young Researcher



Fast Radio Isotopes generation

Paths to use HPLS for fast decaying Medical Radioisotope Production



e^-

γ (a lot, but broad spectrum)

p (broad spectrum)

^{62}Cu

$\tau_{1/2}$ =20.3 min

^{11}C

$\tau_{1/2}$ =9.7 min

PROS	CONS
➢ *Type of beam flexibility with different targets* ➢ *Potential for minimization, possibility of "table-top" systems*	➢ *Presently low repetition rate, Hz level with ≤ PW lasers* ➢ *Radiochemistry needs to be optimised*

Towards Societal Applications: Laser-driven radioisotope production

nuclear physics

Slide by Andi Cocuanes

- ***The full chain of radioisotope production with lasers has never been demonstrated***. *Small laser (hundreds of TW) systems have the greatest potential.*

- *Several studies (review: Z.Sun AIP Adv. 2021) shown isotope production based on single/few shots events, and then extrapolated to hours beamtime.*

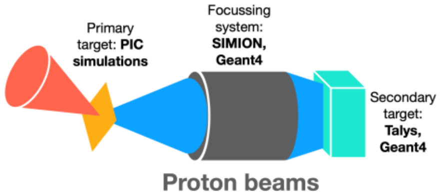
- *2 examples: ^{11}C with **proton** beams via **$^{11}B(p,n)^{11}C$** and ^{62}Cu with **gamma** beams via **$^{63}Cu(\gamma,n)^{62}Cu$** :*

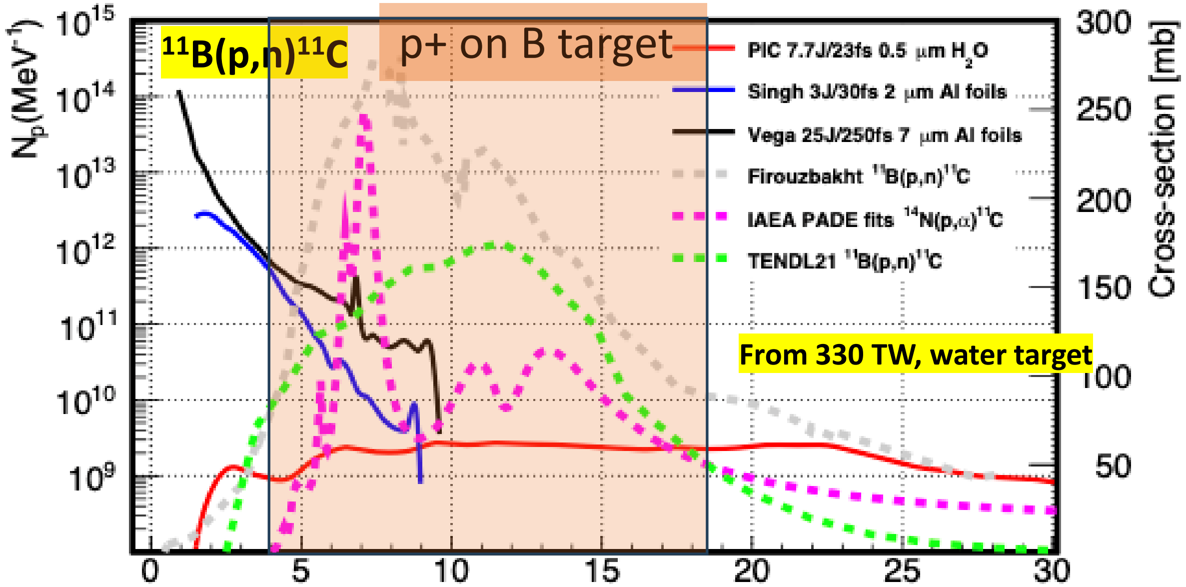
Ref. ^{11}C prod.	E [J]	Pulse T [fs]	Rep. [Hz]	Activ [MBq]	Obs.
Tayyab et al. 2019	2.4	25	1	9	**7-10 shots (2-3 min) meas. Cu,Al, Ni foils**
Singth et al. 2018	3	30	1	7.6	**Spectrum meas. Al foils, analysys in** *Penas et al.*
Penas et al. 2024	25	250	1	21.7	**174 shots at 0.1 Hz meas., Al foils**
ELI-NP estim.	**8**	**23**	**1**	**30**	**PIC + TENDL21 CS, water-leaf tg.**

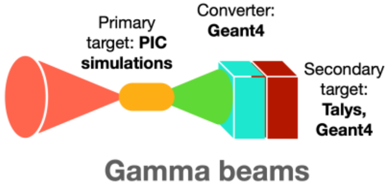
Ref. ^{62}Cu prod.	E [J]	Pulse T [fs]	Rep. [Hz]	Activ [MBq]	Obs.
Ma et al. 2019	11.5	33	1	180	**PIC + Geant4, Varlamov CS**
Lobok et al. 2022	4	30	1	87	**PIC + Geant4**
ELI-NP estim.	**2.3**	**23**	**1**	**35**	**PIC + Geant4, TENDL21 CS.**

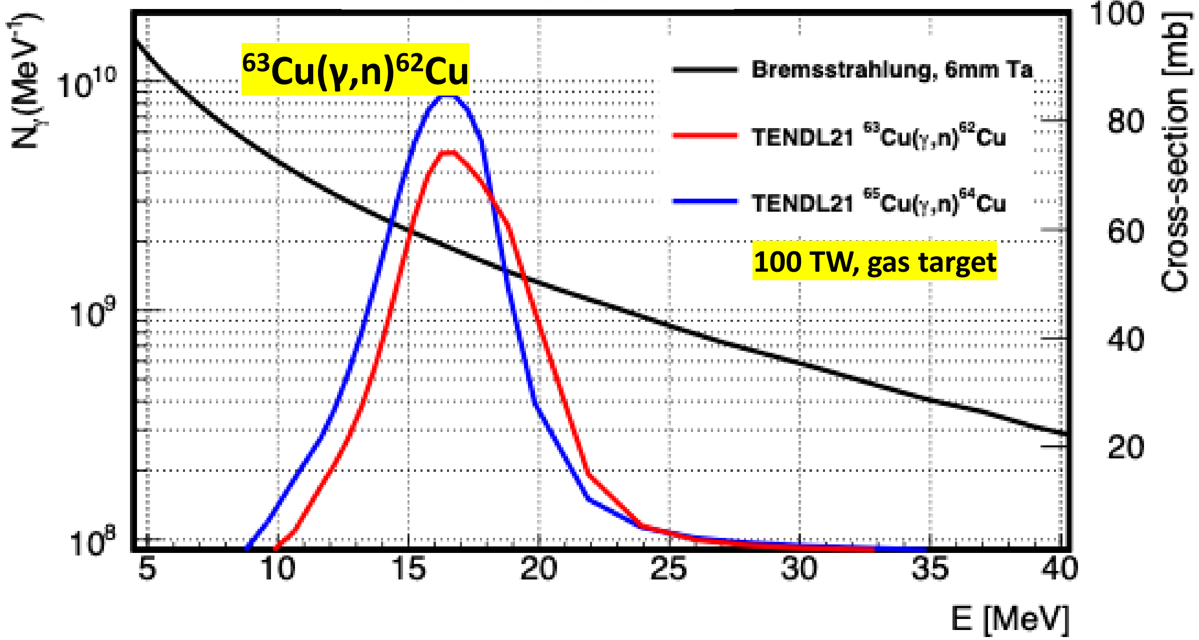
Towards Laser-driven radioisotope production: Challenges

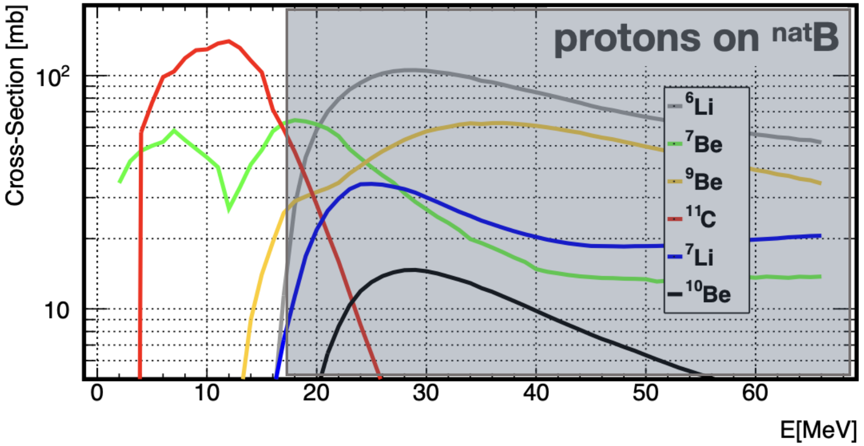
Slide by Andi Cocuanes







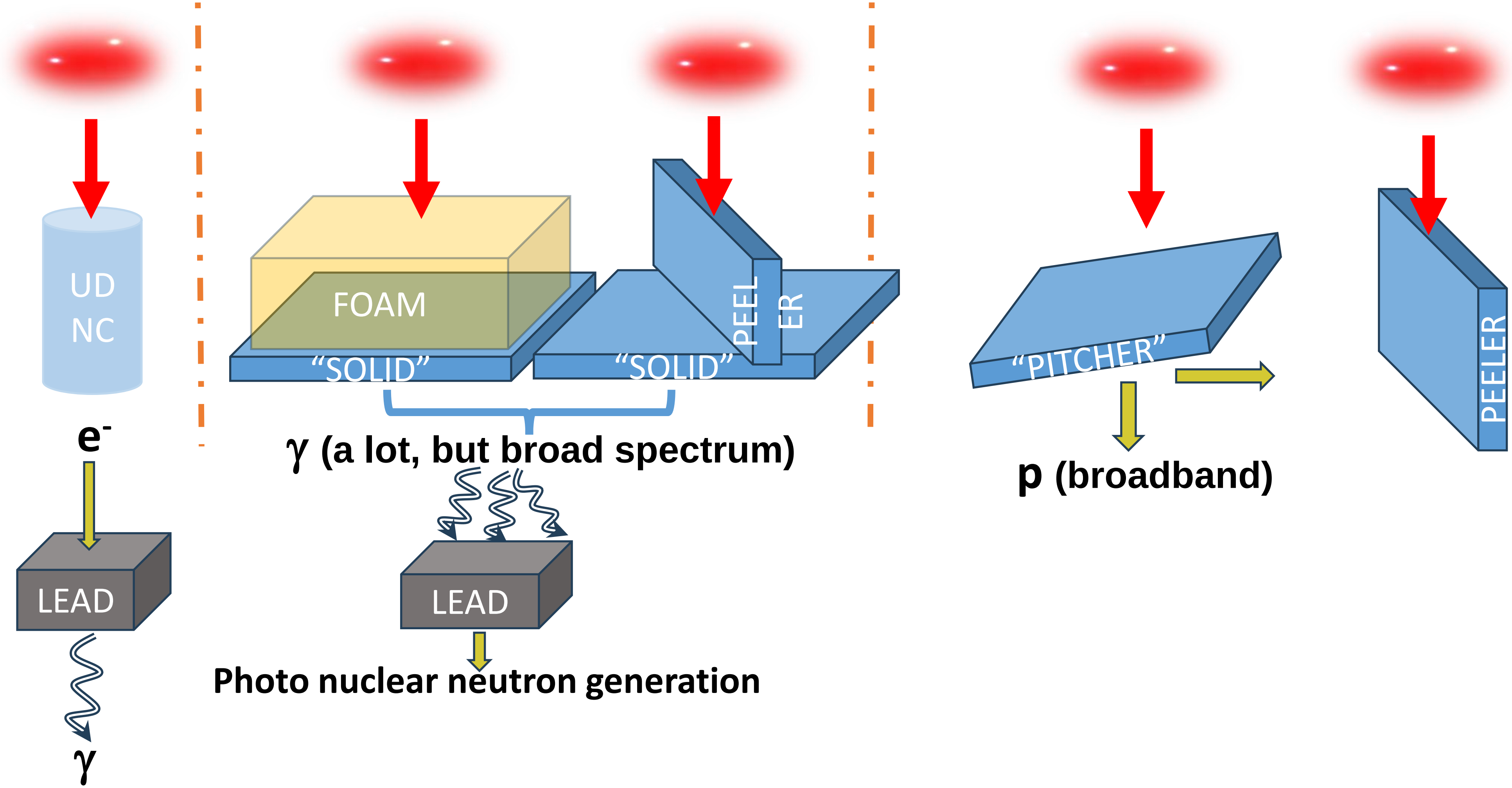




- ➢ *laser-based isotope production channels might be different wrt the cyclotron-based reactions due to the different beam characteristics → **need for fast radiochemistry of "non-traditional" channels.***
- ➢ *Need for isotope producing **targets optimized** for laser-based production and **efficient focusing** system (contaminants, specific activity, radiochemistry).*

Neutron sources

Paths for fast neutron generation at ELI-NP



e^-

γ

γ (a lot, but broad spectrum)

Photo nuclear neutron generation

p (broadband)

Paths for fast neutron generation at ELI-NP

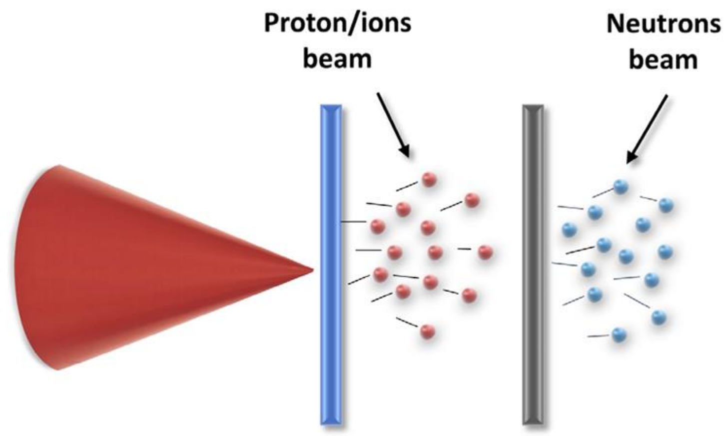


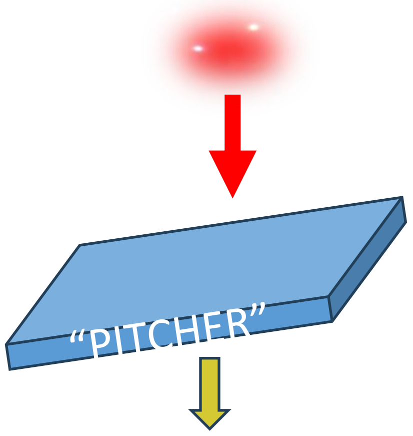
Table 2

Uncollimated thermal neutron fluence rate expected from different fast neutron sources. For Proton and Deuterons we assume 10^{11} particles per shot at 10 Hz, for laser electron 0.5 nC at 10 Hz for the 250 MeV case, while 1.2 nC at 5 Hz for 1 GeV case.

Source	Primary	Energy (MeV)	Y (n/prim)	m (moderation efficiency)	$Y x m$	Neutrons/s/cm^2
RF	Electrons	1000	4.0e−1	2.3e−4	9.3e−5	5.8e5
Laser	Electrons	250	8.0e−2	2.0e−4	1.6e−5	5.0e5
Laser	Electrons	1000	4.0e−1	2.0e−4	8.0e−5	3.0e6
Laser	Protons	5	8.7e−4	2.2e−4	1.9e−7	2.0e5
Deuterons	Protons	7	7.6e−4	1.2e−4	9.4e−8	9.4e4

^{7}Li+p -> ^{7}Be +n

LiF Catcher

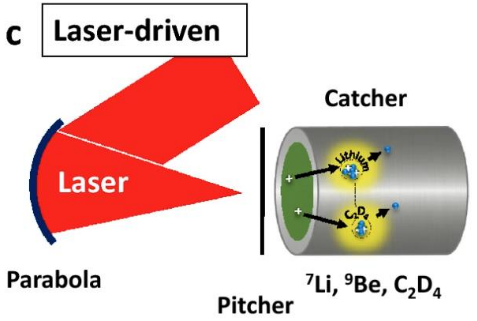


p (broadband)

A complementary compact laser based neutron source

A. Cianchi [a,b,*], C. Andreani [a,b,c,d], R. Bedogni [e], G. Festa [c], O. Sans-Planell [e], R. Senesi [a,b,c,d]

[a] University of Rome Tor Vergata, Department of Physics and INFN-Roma Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy
[b] University of Rome Tor Vergata, Centro NAST, Via della Ricerca Scientifica 1, 00133 Rome, Italy
[c] CNR-IPCF Sezione di Messina, Viale Ferdinando Stagno d' Alcontres, 98158 Messina, Italy
[d] Centro Fermi-Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Piazza del Viminale, 1, 00184 Roma, Italy
[e] INFN-LNF, Via Enrico Fermi 40, 00044 Frascati, Italy



$$ {}^{2}_{1}d(\bar{d},n){}^{3}_{2}He \text{ and } {}^{7}Li(p,n){}^{7}\bar{Be} $$

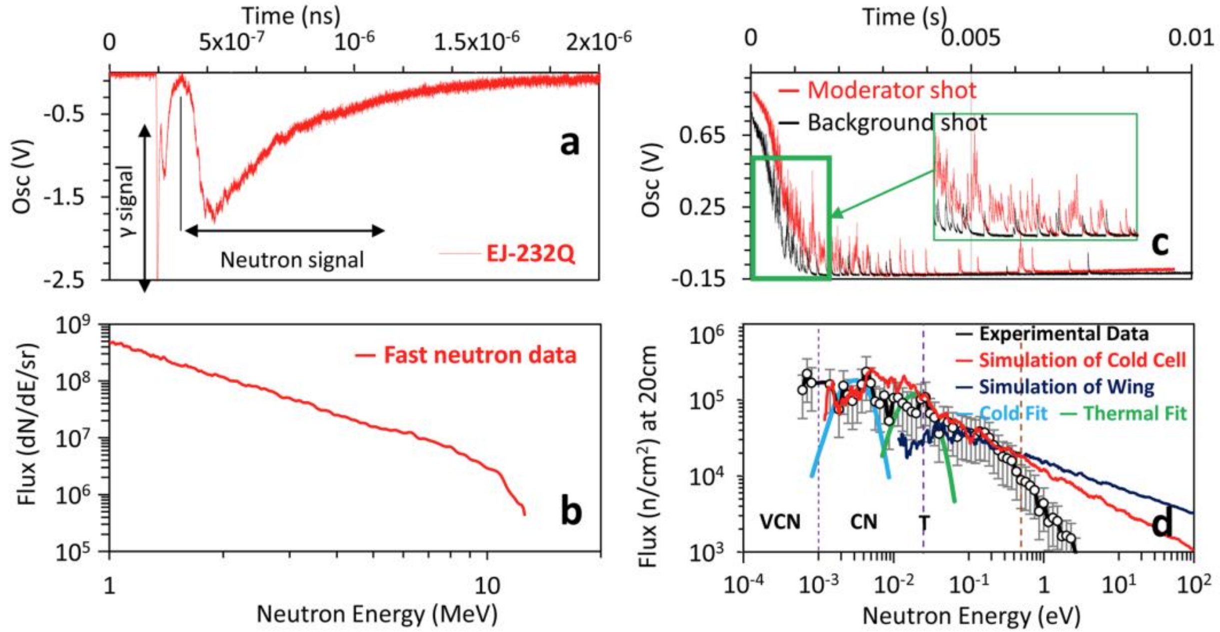
scientific reports

https://doi.org/10.1038/s41598-020-77086-y

OPEN

Proof-of-principle experiment for laser-driven cold neutron source

S. R. Mirfayzi[1,2], A. Yogo[1], Z. Lan[1], T. Ishimoto[1], A. Iwamoto[3], M. Nagata[1], M. Nakai[1], Y. Arikawa[1], Y. Abe[1], D. Golovin[1], Y. Honoki[1], T. Mori[1], K. Okamoto[1], S. Shokita[1], D. Neely[4], S. Fujioka[1], K. Mima[5], H. Nishimura[1,6], S. Kar[4,7] & R. Kodama[1]



The experiment was carried out at the Institute of Laser Engineering (ILE), Osaka using 1.2 ps beams of LFEX[44], delivering total energy of 300 J on the target. A schematic of the experimental setup is shown in Fig. 2. The fast

Paths for fast neutron generation at ELI-NP

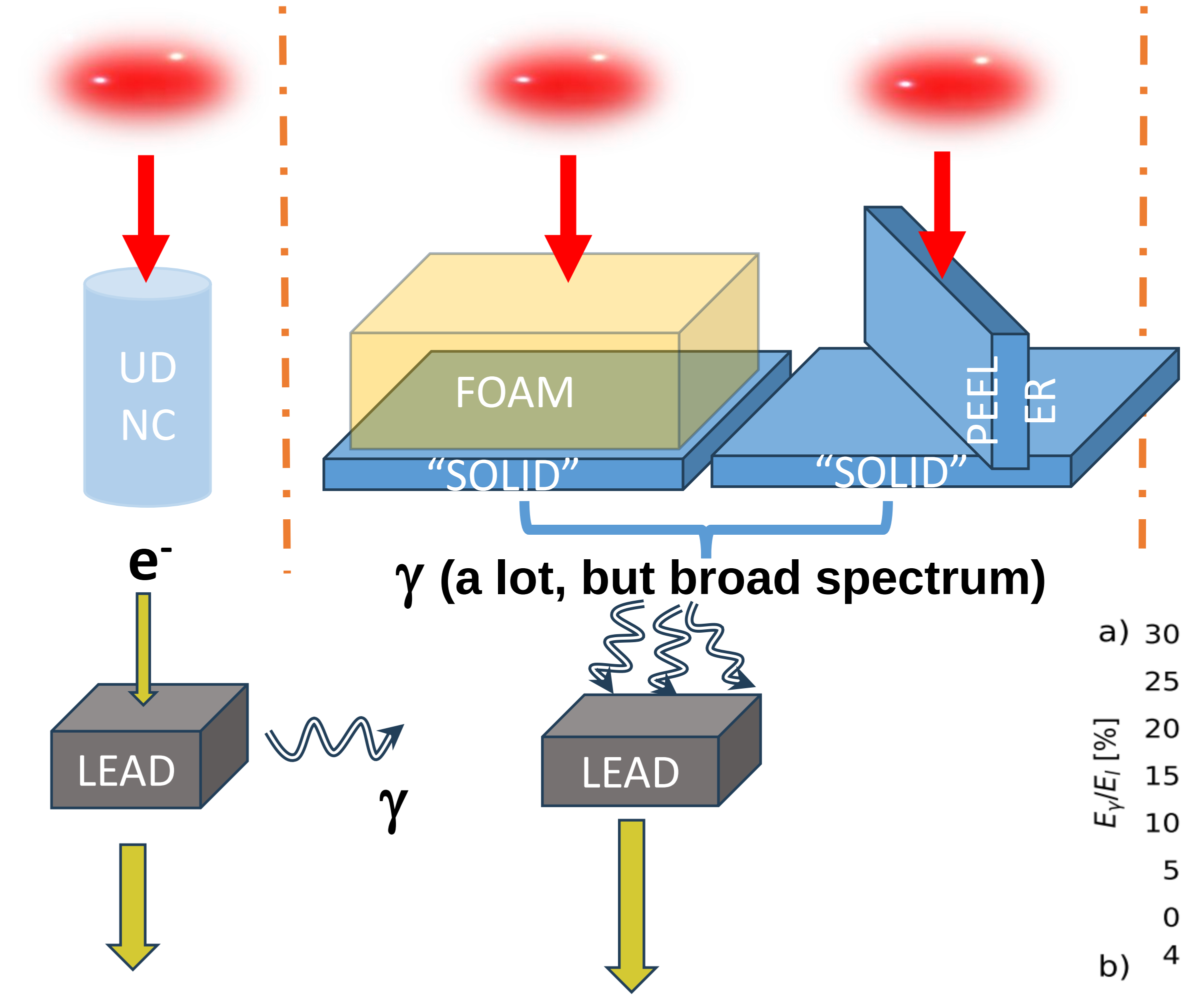


Photo nuclear neutron generation

Few-cycle, 100-TW-class laser pulses as efficier sources of nanocoulomb electron bunches and Bremsstrahlung

Vojtěch Horný[1], Gabriel Bleotu[1], Daniel Ursescu[1], and Paolo Tomassini[1]

[1]Extreme Light Infrastructure - Nuclear Physics, Romania
*vojtech.horny@eli-np.ro

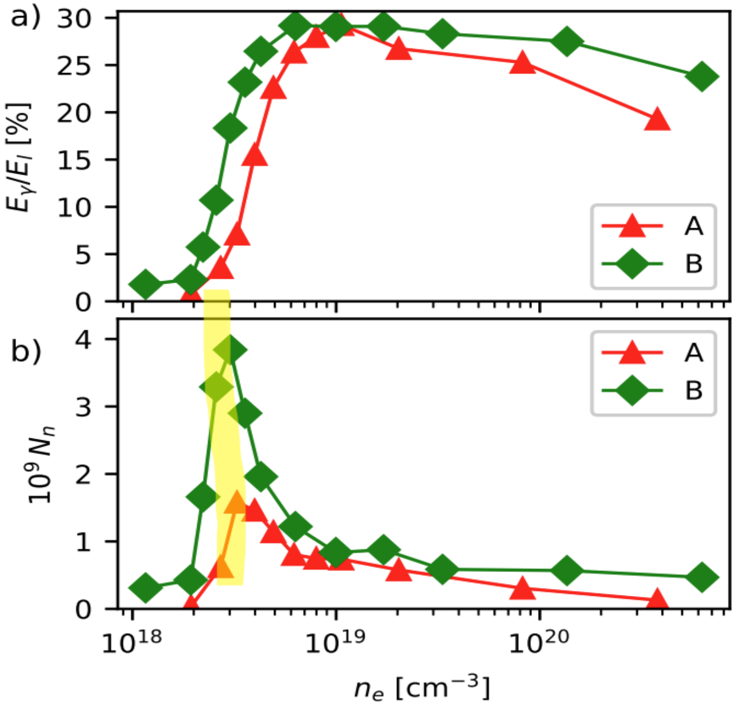
Vojtech Horny
Young Researcher

High efficient regime

$1J\ , 6-11\ fs$

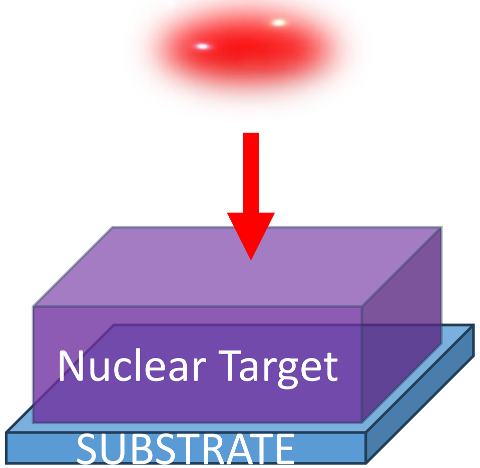
4×10^9photoneutrons/shot

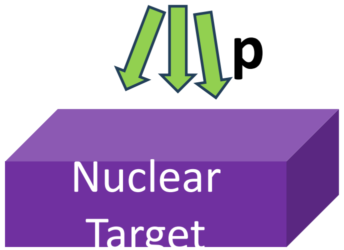
V. Horny et al, DOI: 10.21203/rs.3.rs-3856955/v1



Laser-Driven Nuclear Reactions

Laser-Driven Nuclear Reactions





Pitcher-Catcher Nuclear Reactions

Laser Boron Fusion Reactor

H. Hora *et al.*, "Laser Boron Fusion Reactor With Picosecond Petawatt Block Ignition," in *IEEE Transactions on Plasma Science*, vol. 46, no. 5, pp. 1191-1197, May 2018, doi: 10.1109/TPS.2017.2787670.

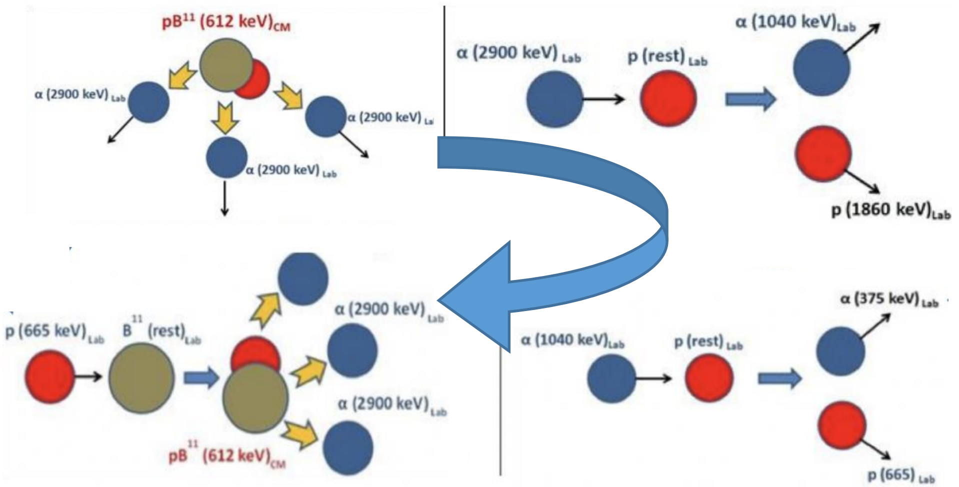
Aneutronic fusion of hydrogen with the boron isotope 11, **H^{11}B**.

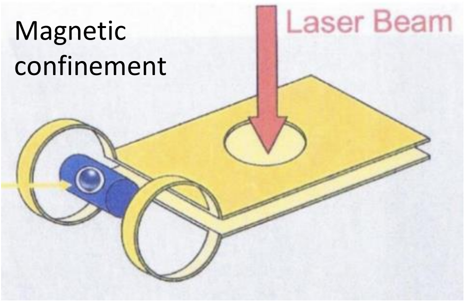
At local thermal equilibrium, is 10^{5} times more difficult than fusion of deuterium and tritium (DT)
But at extreme nonequilibrium plasma conditions the fusion of H^{11}B is comparable to DT fusion

Method

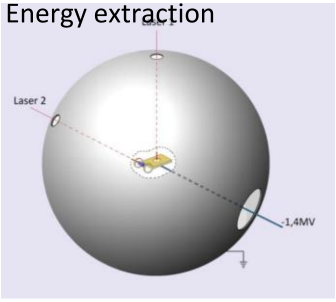
- **H11B rod a cm size**
- **Main laser for driven-ignition:** 30PW laser energy and ps pulse duration
- **A second laser for magnetic field generation of ~10 kT:** 1kJ energy and ns pulse duration

Nuclear reaction schema





Magnetic confinement



Energy extraction

Using a container electrostatically charged to -1.4 MV, it will be possible to generate about **277 kWh** of energy per laser **shot**.

Comments

Super short overview of similarities with EuPRAXIA and ELI-NP lines of research on NP:

NP with electron acceleration (LWFA, NCD) PWFA:

- ✓ Neutron generation with LWFA + bremsstrahlung **[Suitable for the 2nd site+Short parabola]**
- ✓ Fast radioisotopes generation with gamma induced reactions **[Suitable for 2nd site+Long parabola, Marginally suitable for the 1st site]**
- ✓ Gaussian and Laguerre Gaussian gamma beams through CBS and isomers generation/NP studies **[Suitable for both sites+Long parabola]**

NP with laser/"solid" ion acceleration:

- ✓ In Target fusion preparation studies **[Marginally suitable]**
- ✓ Neutron generation from protons **[Suitable for the 2nd site+Short parabola]**
- ✓ Fast radioisotopes generation with protons induced reactions **[Suitable for the 2nd site+Short parabola]**
- ✓ Isomers generation by "nuclear excitation by electron capture" (NEEC) " **[Not shown, Marginally suitable]**

Any collaboration between EuPRAXIA@LNF and ELI-NP is welcome, also for testing some acceleration modules.