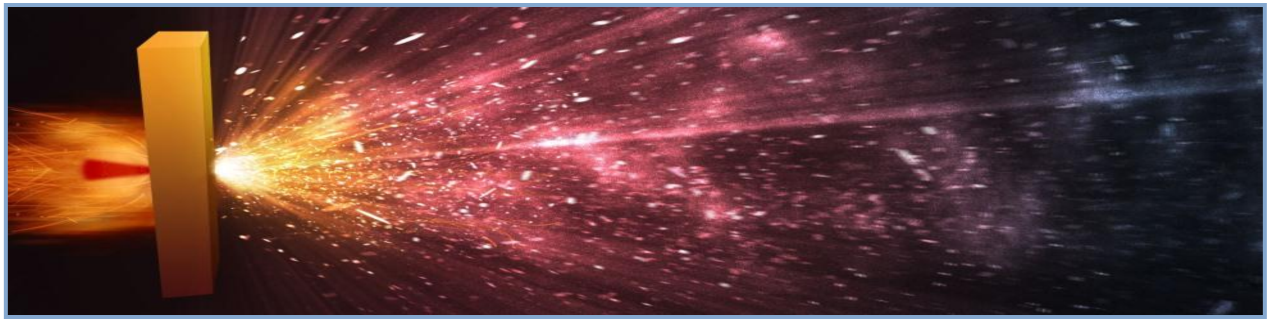

Research on superintense laser-driven ion acceleration at Politecnico di Milano

Matteo Passoni

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3° Topical Workshop on Novel Acceleration Techniques, LA3NET, Dresden, 28-30 April 2014

Outline

- INTRODUCTION
  Nanolab @ Politecnico di Milano

- ACTIVITIES AT NANOLAB-POLIMI ON LASER-DRIVEN ION ACCELERATION
  SULDIS project, main topics, a specific example: foam-based targets

- CONTRIBUTION OF POLIMI TO TRAINING IN LASER-PLASMA INTERACTION
  Master courses, master and PhD theses, future

- CONCLUSIONS & PERSPECTIVES

Micro and Nanostructured Materials Laboratory @ POLIMI

The **Micro and Nanostructured Materials laboratory (Nanolab)** belongs to the **Department of Energy of Politecnico di Milano**

Politecnico di Milano (POLIMI) (www.polimi.it):

It is **the largest University in Italy to train Engineering students**

- About 20 Bachelor - 20 Master Programs in Engineering
- About 15 PhD Programs in Science and Engineering
- QS rank: 1° Italy, top 10 Europe, top 30 World in Engineering

Department of Energy at POLIMI (www.energia.polimi.it) **:**

- Activated in 2008. **More than 100 Professors and Researchers**
- **Research in various topics related to Energy (basic & applied)**
- **Education**: mainly involved in Energy Engineering (Bs & Ms) and Nuclear Engineering (Ms) programs, Contribution to others

Micro and Nanostructured Materials Laboratory @ POLIMI: staff

At present about 20 people:

Permanent staff:

- Carlo E. Bottani (**Head of lab**, Full Prof)
- Marco Beghi, Paolo Ossi (Associate Prof)
- Andrea Li Bassi (Associate Prof)
- Carlo Casari, Matteo Passoni (Assistant Prof)

Technicians:

- Anna Facibeni
- Antonio Mantegazza

Post-Doc/Post-lauream researchers:

- Valeria Russo
- Andrea Sgattoni
- David Dellasega

PhD students:

- Andrea Pezzoli
- Alessandro Maffini
- Andrea Uccello
- Paolo Gondoni
- Lorenzo Cialfi
- Irene Prencipe
- Piero Mazzolini

About 7-8 undergraduate students/year

www.nanolab.polimi.it

Micro and Nanostructured Materials Laboratory @ POLIMI

Vision

Detailed understanding and control of physical phenomena at the **nanoscale** can lead to:

- knowledge of materials behavior in unconventional/extreme conditions
- development of new materials to control the related physics/technology

Experimental research activities

- Development of new nanostructured materials (thin films/surfaces) with tailored structure and properties for:

- energy applications (photovoltaic & nuclear fusion)
- more “basic” science (e.g. **laser-driven ion acceleration**!)

Experimental facilities

- Synthesis: Pulsed Laser Deposition (thermal evaporation, sputtering-ion gun)
- Characterization: SEM, EDS, AFM, STM/STS, Raman, Brillouin

Theoretical/numerical support to the research

- theoretical support to material characterization (group theory; STM theory)
- theoretical & numerical (PIC) activities on laser-plasma interaction

Micro and Nanostructured Materials Laboratory @ POLIMI

NanoLab

NEMAS – Center for NanoEngineered MAterials and Surfaces
Center of Excellence accredited and funded by Ministry of Research, on the basis of review by a panel of international referees.

Starting from 2010, the lab is formally **involved in the research activities on laser-driven ion acceleration** (resp. M. Passoni):

SULDIS
Superintense Ultrashort Laser-Driven Ion Sources

- FUNDING PROGRAM: Futuro in Ricerca (MIUR Italian Ministry of Research)
  - A program started in 2009 and specifically devoted to “young scientists”
  - ERC IDEAS-like approach: new and unique in the Italian scenario
  - about 3800 applicants (2009 call) with 100 final selections (success rate < 3%)
- DURATION: 4 years (started in 2011 – end this year!)
- OVERALL FUNDING: € 350.000
  - ...half of which to hire young researchers (PhD, Post-Docs)

Specific aims of the SULDIS project: Main Goals

- Systematic THEORETICAL AND NUMERICAL STUDY OF THE DIFFERENT ION ACCELERATION REGIMES induced by super intense pulses ($I > 10^{21}$ W/cm^2)

  - *TNSA*: dependence on laser/target properties, scaling laws, predictions at super-high intensities
  - *RPA*: "thick" vs "thin" targets, feasibility and robustness of the concept, non-ideal effects, scaling laws
  - *Other regimes*: foam-based; grating surfaces; shock-driven

- Theoretical DESIGN & experimental PRODUCTION OF INNOVATIVE TARGETS:

  - control down to the nanoscale, optimized for the investigated regimes.

- DESIGN AND REALIZATION OF EXPERIMENTAL CAMPAIGNS aimed to the study of the regimes identified, to be conducted on world class laser facilities.

Scientific approaches & methods in SULDIS

THEORETICAL

Analytical descriptions, to gain insight into the relevant physics of the systems.

NUMERICAL

Particle-In-Cell (PIC) codes will be specifically developed to tackle the multiscale character of the physical regimes & simulate "realistic" experimental conditions

EXPERIMENTAL

Advanced experimental methods of surface science/nanotechnology will be exploited for target manufacturing.

COLLABORATIVE

Experimental campaigns will be designed with top-level internationally recognized partners.

The SULDIS Team - 1

POLIMI group (Dipartimento di Energia, Politecnico di Milano)

Group Leader: Matteo Passoni – Principal Investigator

and: D. Dellasega, A. Sgattoni (PostDocs), PhDs (A. Zani, I. Prencipe, C. Perego)

Specific Role:

- theoretical-numerical investigation of TNSA;
- target manufacturing at the Micro and Nanostructured Materials lab;
- support for experiments on international laser facilities

POLITECNICO
DI MILANO

CNR-PI group (Istituto Nazionale di Ottica, CNR)

Group Leader: Andrea Macchi

and: PhDs (M. Tamburini, L. Fedeli)

Specific Role:

- theoretical and numerical investigation of RPA;
- radiation friction modeling and effects;
- established collaboration with experimental groups

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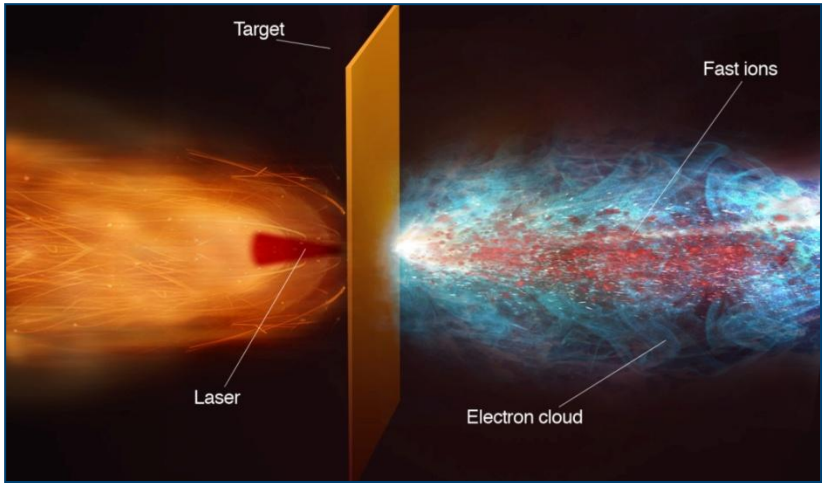
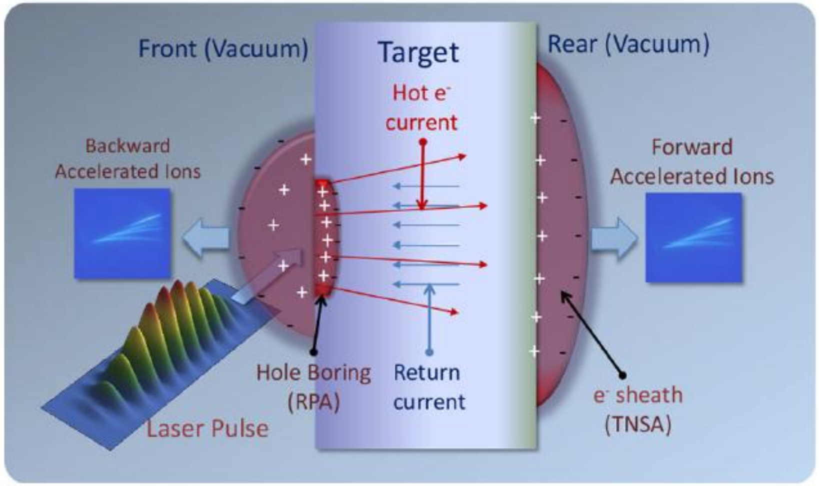
Expertise of the SULDIS team





Expertise of the team on laser-ion acceleration:

-TNSA modeling & interpretation

M. Passoni et al, *Phys. Rev. E* **69**, 026411 (2004); M. Passoni et al, *Phys. Rev. Lett.* **101**, 115001 (2008); ... ...

- RPA modeling & interpretation

A. Macchi et al, *Phys. Rev. Lett.* **94**, 165003 (2005); A. Macchi er al, *Phys. Rev. Lett.* **103**, 085003 (2009); ... ...

…leading also to the preparation of an extensive Review on the subject:

A. Macchi, M. Borghesi, M. Passoni
Ion acceleration by superintense laser-plasma interaction
Reviews of Modern Physics, **85**, 751 (2013)

Main publications in 2010-2014 on laser-ion acceleration @ Polimi

Theoretical-numerical: TNSA theory and novel concepts:

- M. Passoni, C. Perego, A. Sgattoni, D. Batani, **Physics of Plasmas (Letters), 20 , 060701 (2013)**
- A. Sgattoni, P. Londrillo, A. Macchi, M. Passoni, **Physical Review E 85 , 036405 (2012)**
- C. Perego, D. Batani, A. Zani, M. Passoni, **Review of Scientific Instruments, 83 02B502 (2012)**
- A. Zani, A. Sgattoni, M. Passoni, **Nuclear Instruments and Methods A 653 , 89-93 (2011)**
- C. Perego, A. Zani, D. Batani, M. Passoni, **Nuclear Instruments and Methods A 653 , 94-97 (2011)**
- M. Passoni, L. Bertagna, A. Zani, **Nuclear Instruments and Methods A 620 (1), 46-50 (2010)**
- M. Passoni, L. Bertagna and A. Zani, **New Journal of Physics 12, 045012 (2010)**

Experimental: target development & laser-ion acceleration experiments:

- M. Passoni, A. Zani, A. Sgattoni et al, **Plasma Physics and Controlled Fusion**, **56, 045001 (2014)**
- T. Ceccotti, V. Floquet, A. Sgattoni et al, **Physical Review Letters, 111, 185001 (2013)**
- A. Zani, D. Dellasega, V. Russo, M. Passoni, **Carbon 56, 358-365 (2013)**

Reviews/Editorial preparation of special issues on laser-driven ion acceleration

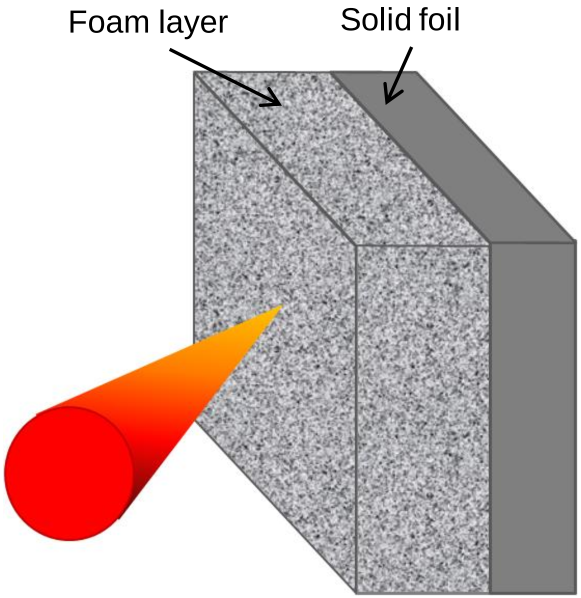
- A. Macchi, M. Borghesi, M. Passoni, **Reviews of Modern Physics, 85, 751 (2013)**
- A. Macchi, A. Sgattoni, S. Sinigardi, M. Borghesi, M. Passoni, **Plasma Physics and Controlled Fusion, 55, 124020 (2013)**
- D. Batani, M. Passoni, **Nuclear Instruments and Methods A, 653, 1 (2011)**

An example: enhancing TNSA with multi-layered targets

Interest in "intermediate", near critical densities: $n_e \sim n_c$

Scalings predics more efficient absorption and fast electron generation

[L.Willingale et al. *Phys. Rev. Lett* **96**, 245002 (2006)]
[L.Willingale et al. *Phys. Rev. Lett* **102**, 125002 (2009)]
[S.S.Bulanov et al. *Phys. Plasmas* **17**, 044105 (2010)]
[T. Nakamura et al. *Phys. Plasmas* **17**, 113107(2010)]



Possibility to achieve an "advanced" TNSA regime: multilayered targets: thin solid foil + low-density layer

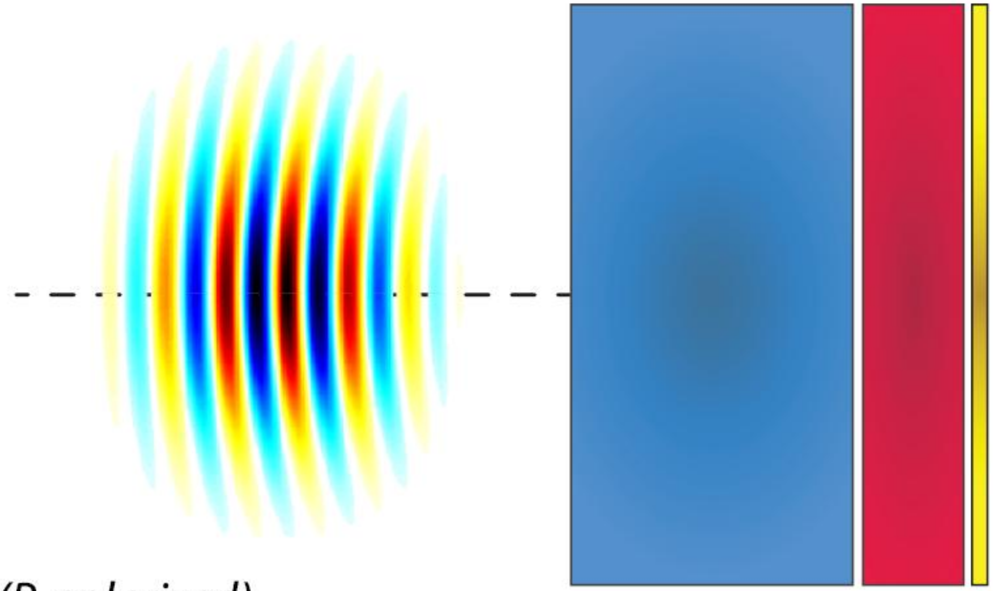
Open problems:

- Theoretical investigation of the ion acceleration dependence on system parameters (foam thickness, density, laser properties)
- Multilayered target manufacturing (not easy controlling density, adhesion to solid..)

TNSA in multi-layers: numerical investigation

Use of the Particle In Cell (PIC) method

(to numerically solve the plasma kinetic equations)



Laser *(P-polarized)*

τ=25 fs

w = 3μm

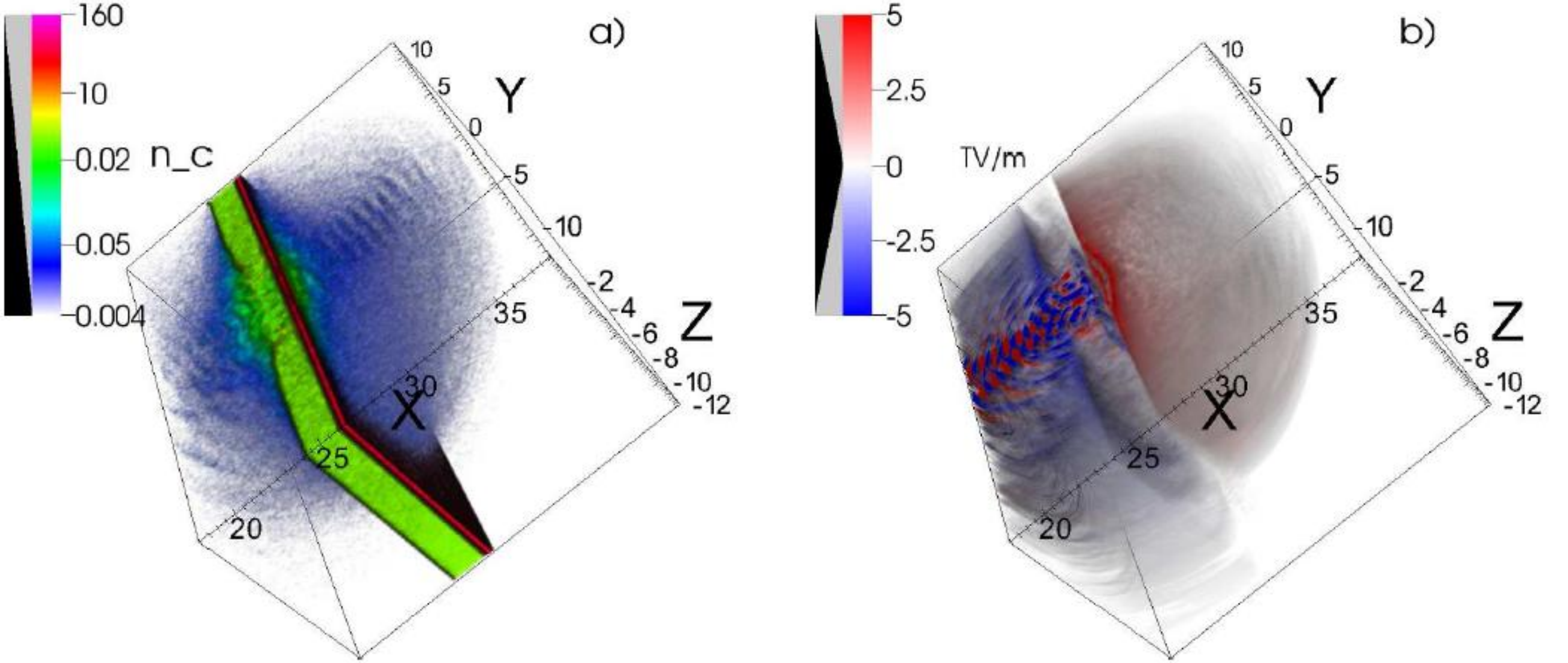
λ=0.8 μm

P=3-120 TW a=3-20

θ_{inc}=0°-30°-45°-60°

Foam	**Metal**	**Impurities**
C^{6+}	**Al^{9+}**	**H^{+}**
1-12 μm	0,5 μm	50 nm
1-8n_c	80 n_c	9 n_c

TNSA in multi-layers: example of results of 3D PIC simulations



- the laser penetrates through the foam layer (relativistic transparency)
- electrons from the foam are accelerated and expands on the rear side
- longitudinal electric field exceeds $5 TV/m$

TNSA in foam-based multi-layers: summary of the 2D-3D PIC analysis

Targets with near critical density layer

- enhanced “TNSA”, the maximum proton energy 3 times higher than bare solid foils
- short, low energy, pulses have been tested ($U < 4$J)

⇒ higher proton energies are expected for longer pulses

- optimal foam thickness depends on laser intensity and foam density
- high energy absorption by the target
- electrons from the foam play key role
- electron acceleration increases with thickness
- volume interaction
- oblique incidence gives no clear advantages

Sgattoni et al, *Phys. Rev. E* **85**, 036405 (2012)

Production of low-density C foams by Pulsed Laser Deposition (PLD)

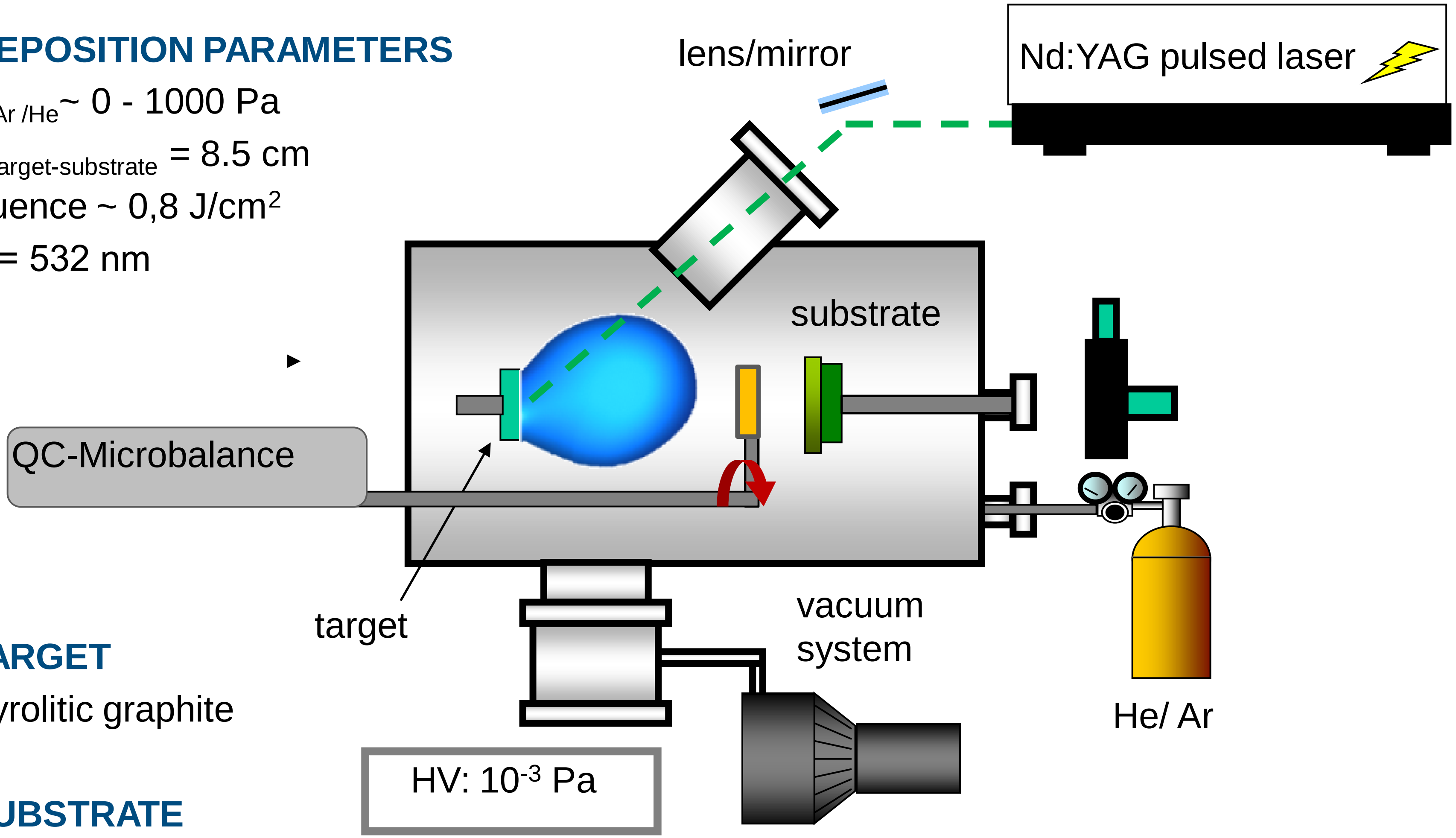
DEPOSITION PARAMETERS

$P_{Ar\ /He}$~ 0 - 1000 Pa

$d_{target\text{-}substrate}$ = 8.5 cm

fluence ~ 0,8 J/cm^2

λ = 532 nm



TARGET

Pyrolitic graphite

SUBSTRATE

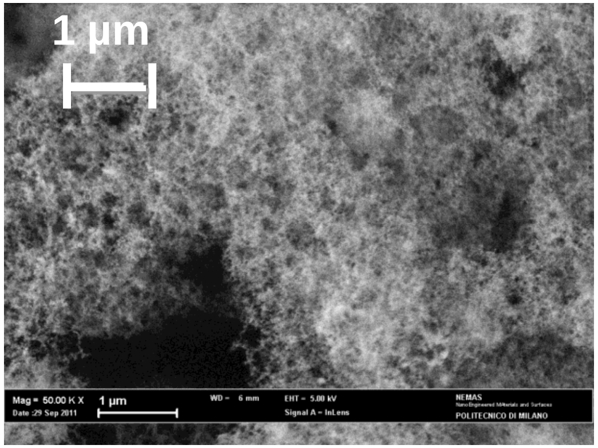
Si <100> for characterization

Al (0.7-10 µm)

A. Zani *et al*., Carbon, **56**, 358 (2013)

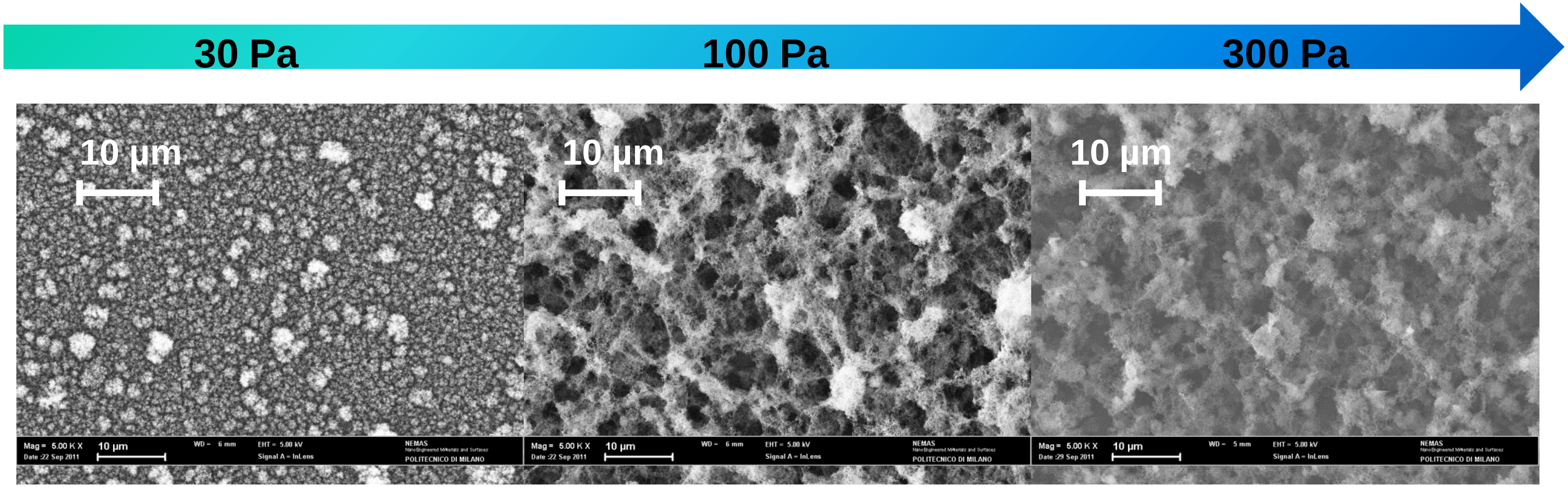
Low-density C foams by PLD

Carbon foam morphology: SEM analysis



Structure at high magnification is very open and porous

On a mesoscale these structures can arrange in different ways by simply varying one process parameter: **Ambient gas pressure (Ar)**



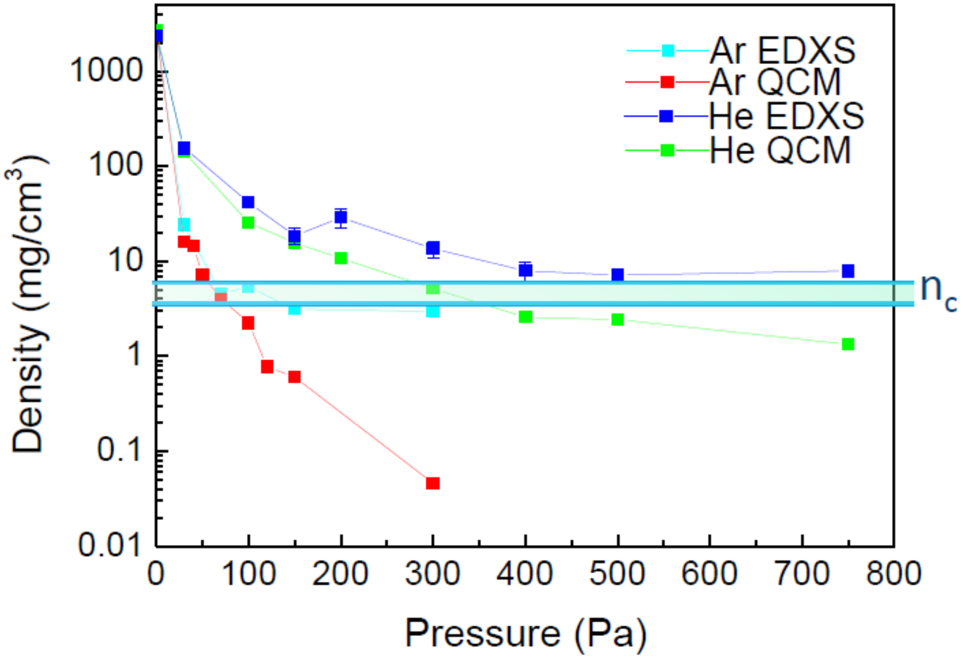
Carbon foam density characterization & foreseen experiments

- Assuming:

  - fully ionized carbon
  - λ=0.8 μm incident laser

  $\rho_{cr}(C) \approx 3.2$ mg/cm^3

- microbalance/EDXS analysis
- Cross-section SEM analysis



- Potential in producing:

  - foam materials having controlled density-composition in the near critical regime
  - foam layers directly grown on solid surfaces (solving adhesion problems)
  - materials with controlled density profile (functionally gradient materials)

- Main challenge:

  - achievement of desired parameters with satisfactory film homogeneity and uniformity

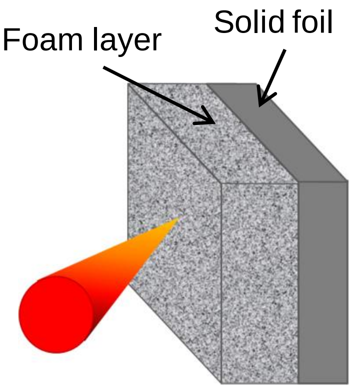
- Experimental tests: LIDyL-CEA/Saclay group, under Laserlab (others foreseen!)

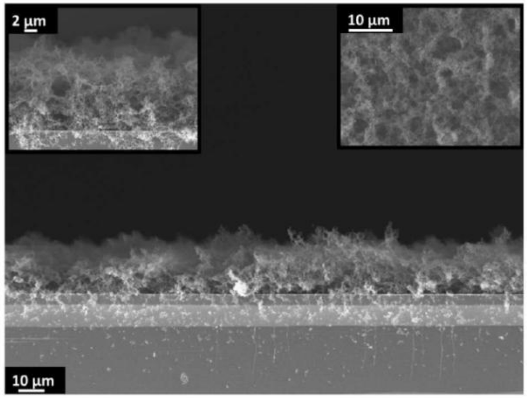
Improved TNSA-like schemes: first experimental tests

Targets: thin solid foil (Al) + foam (~n_c) C layer

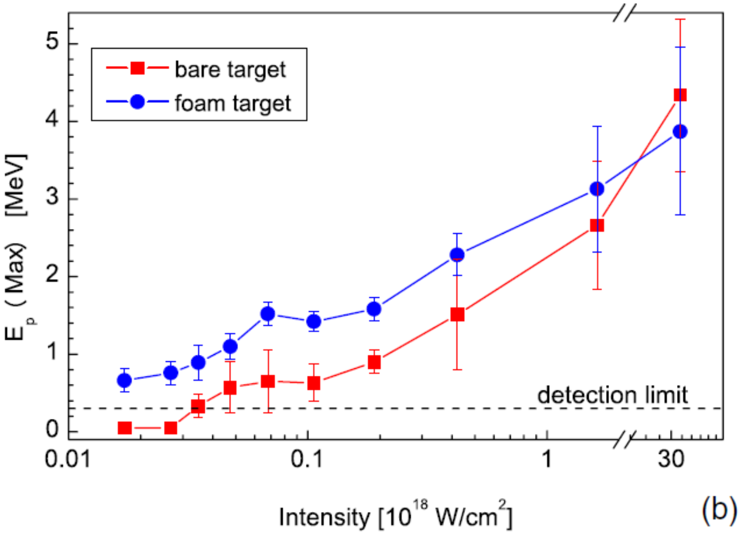
Al foil 1.5 (HC) – 10 (LC) μm

C foam 5 - 6 mg/cm^3 ;12 (HC) – 23 (LC) μm

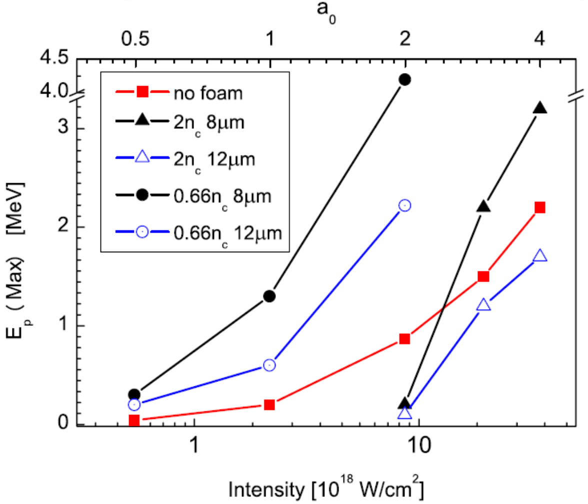




Experimental results:
representative example (HC case)



Interpretation (PIC analysis)



When $I_L < 10^{18}$ W/cm^2:

- partial foam ionization ($C^{2/4+}$) -> sub-critical plasma (~0.5 n_c)
- Laser penetration and e^-_{hot} from volume interactions
- higher proton energy with foam-attached targets

These results suggest enhancement of E_{max} at ultrahigh intensities with proper foam optimization

M. Passoni *et al*., Plasma Phys, Contr. Fusion, **56**, 045001 (2014)

Training of young students on laser-plasma: role of POLIMI

Educational activities at Polimi of relevance for laser-ion acceleration

- Master program in Nuclear Engineering (about 35-40 students/year)
- Master course in Plasma Physics I+II (about 100 h, 20-25 students/year, from Nuclear Engineering, Physical Engineering, Mathematical Engineering)
- Other master courses (Radiation detection and measurements, physics of nuclear materials, laser physics & technology, radioprotection…)
- Phd Program in “Energy and Nuclear Science and Technology” (STEN)
- Polytechnic School…a lot of interdisciplinary topics available

Role of Nanolab in laser-ion acceleration:

- Teaching of the course Plasma Physics I+II (M. Passoni) (+ more…)
- Direct role in: master program Nuclear Engineering, PhD in STEN
- Supervision of master thesis students (about 1-2 each year)
- Supervision of post-lauream, PhD students & Post-Docs (presently: 4)

That’s all
Aknowledgements

CO-WORKERS

D. Batani[1], T. Ceccotti[2], V. Floquet[2], D. Dellasega[3], A. Macchi[4,5], P. Martin[2], C. Perego[6], I. Prencipe[3], V. Russo[3], A. Sgattoni[3,4], A. Zani[3]

1 Universitè Bordeaux, CNRS, CEA, CELIA
2 CEA/DSM/IRAMIS/LIDyL, Gif sur Yvette, France
3 Dipartimento di Energia, Politecnico di Milano, Milan, Italy
4 CNR/INO, Pisa, Italy
5 Dipartimento di Fisica “Enrico Fermi”, Università di Pisa, Pisa, Italy
6 Dipartimento di Fisica, Universita di Milano-Bicocca, Milan, Italy

Work sponsored by:

- **FIRB-MIUR, Italy** (SULDIS – “Superintense Ultrashort Laser-Driven Ion Sources”)
- **Laserlab, EU** (grant n. 228334, Seventh Framework Programme, proposal n.SLIC001689)
- **Use of supercomputing facilities at CINECA (Italy) via grant awards**:

(IBM-SP6, **ISCRA** award: project TOFUSEX – “TOwards FUll-Scale simulations of laser-plasma EXperiments” N.HP10A25JKT-2010)
(FERMI BlueGene/QTM, **PRACE** award: LSAIL –“Large Scale Acceleration of Ions by Lasers”)

THE END

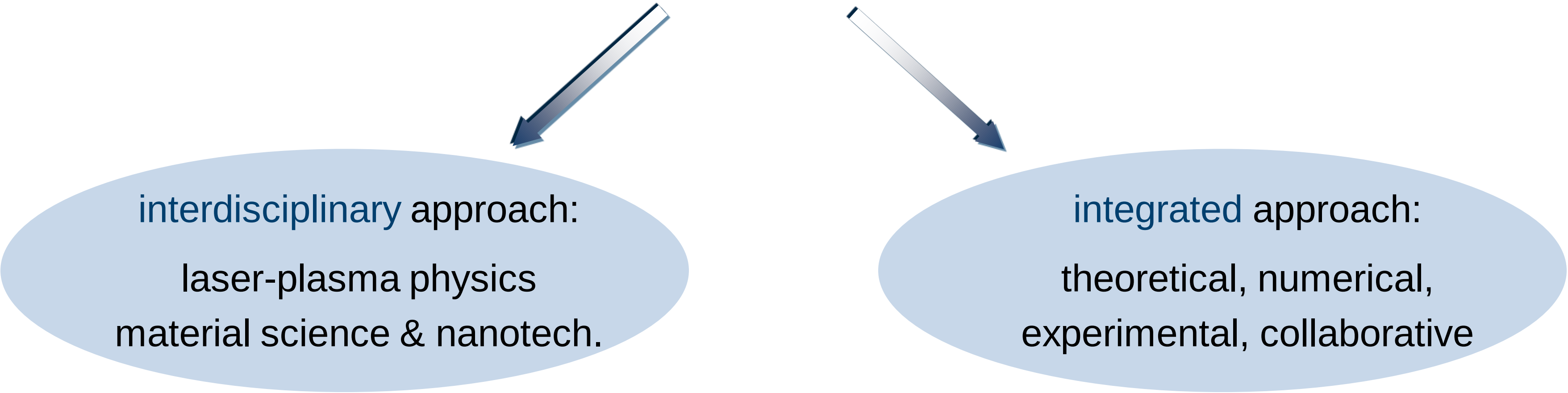
THANK YOU!

EXTRA SLIDES

The SULDIS Team - 2

Overall, THE TEAM INCLUDE:

- the MAIN ITALIAN EXPERTISES about the theoretical study of ION ACCELERATION DRIVEN BY UU LASER pulses
- the MAIN ITALIAN EXPERTISES about the development and the exploitation of PIC SIMULATION codes and their implementation on supercomputers
- the EXPERIMENTAL EXPERTISE of a nanoscience & nanotechnology lab
- collaboration with RESEARCH GROUPS OF RECOGNIZED INTERNATIONAL EXPERTISE in the field of laser-ion acceleration experiments



interdisciplinary approach:

laser-plasma physics
material science & nanotech.

integrated approach:

theoretical, numerical,
experimental, collaborative

PIC simulations for ion acceleration: expertise & numerical resources

- Expertise by the team in development and use of PIC codes

- Team members have been involved in previous projects for numerical investigation of both electron and ion laser-plasma acceleration

  - Quinn et al, PRL 102, 194801 (2009) - Romagnani et al, PRL 105, 175002 (2010) – Macchi et al, New J. Phys. 12, 045013 (2010) - Tamburini et al PRE 85, 016407 (2012)
  - Benedetti et. al. NIMA 608 (2009) - Benedetti et al NIMA 606 (2009) – Londrillo et. al. MIMA 620, 28 (2010) - Sgattoni et al PRE 85, 036405 (2012)

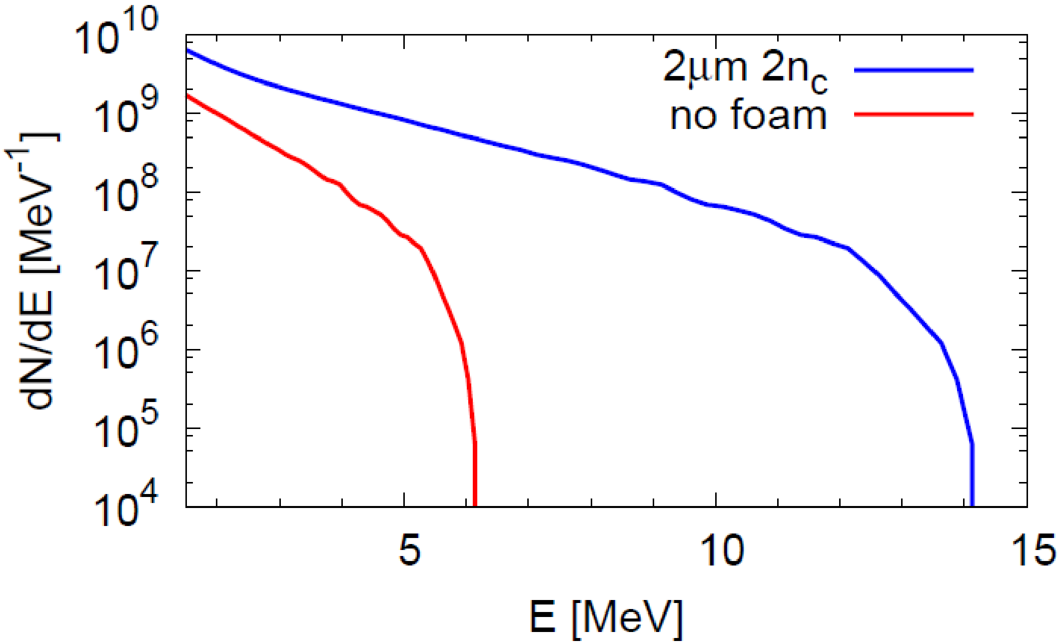
- Various 3D PIC codes available: UMKA[a] , **`ALaDyn`**[b] **`, Piccante`**

  - MPI parallelized and tested on 1000s CPU
  - UMKA: radiation reaction effects
  - **`ALaDyn:`** several particle and field solvers 2nd and 4th order, efficient multispecies definition.
  - Piccante: home made, recently developed and open sourced

a) G. I. Dudnikova et al., Comp. Technol. 10, 37 (2005).
b) Benedetti C. et al IEEE Trans. Plasma Science 36, 1790 (2008)

TNSA in multi-layers: example of results of 3D PIC simulations

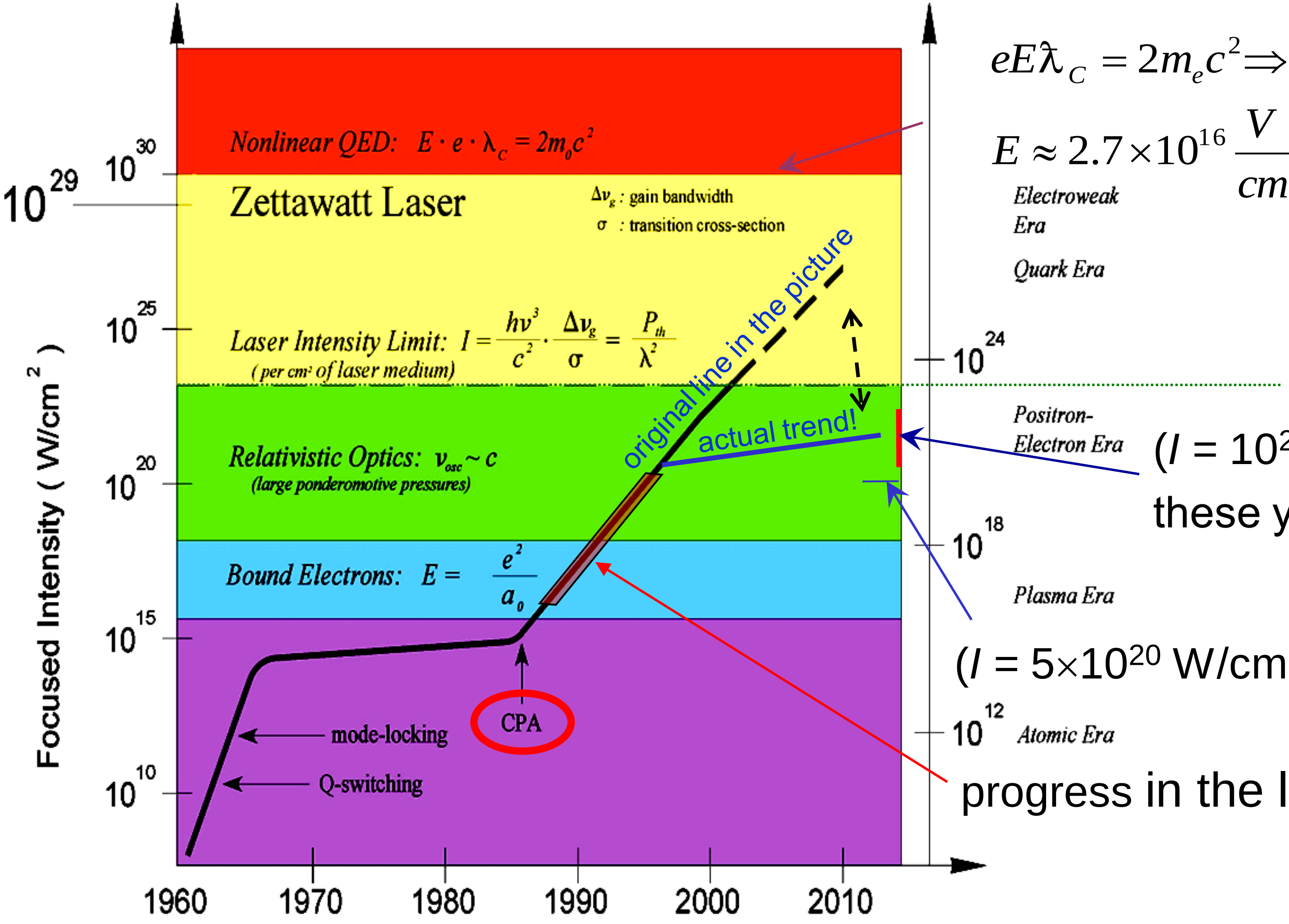
$$P = 32\,TW \;\; \tau = 25\,fs \;\; w_0 = 3\mu m \;\; U = 0.8\mathrm{J} \;\; I = 3.4\,10^{20}\mathrm{W/cm^2} \;\; (a_0 = 10)$$



- exponential with a cut-off (like TNSA)
- thin foam ($l_f = 2\mu m$, $n_f = 2n_c$)
  $\Rightarrow$ cut-off energy increased by a factor ~ 2.5!

→ **Sgattoni** *et al* **PRE 85, 036405 (2012)**

Physical regimes achievable



$$e E \lambdabar_C = 2 m_e c^2 \Rightarrow$$

$$E \approx 2.7 \times 10^{16} \frac{V}{cm} \Rightarrow I \approx 10^{30} \frac{W}{cm^2}$$

(I = 10^{21}-10^{22} W/cm², these years…)

(I = 5×10^{20} W/cm², LLNL,'02)

progress in the last 20 years

[G. Mourou, T. Tajima, S.V. Bulanov, *Rev. Mod. Phys.* **78**, 309 (2006)
M. Marklund, P.K. Shukla, *Rev. Mod. Phys.* **78**, 591 (2006)]

Theoretical description of laser-based ion acceleration: TNSA

How to develop analytical quantitative models of the acceleration process in TNSA?

…generally speaking, two “complementary” approaches are possible:

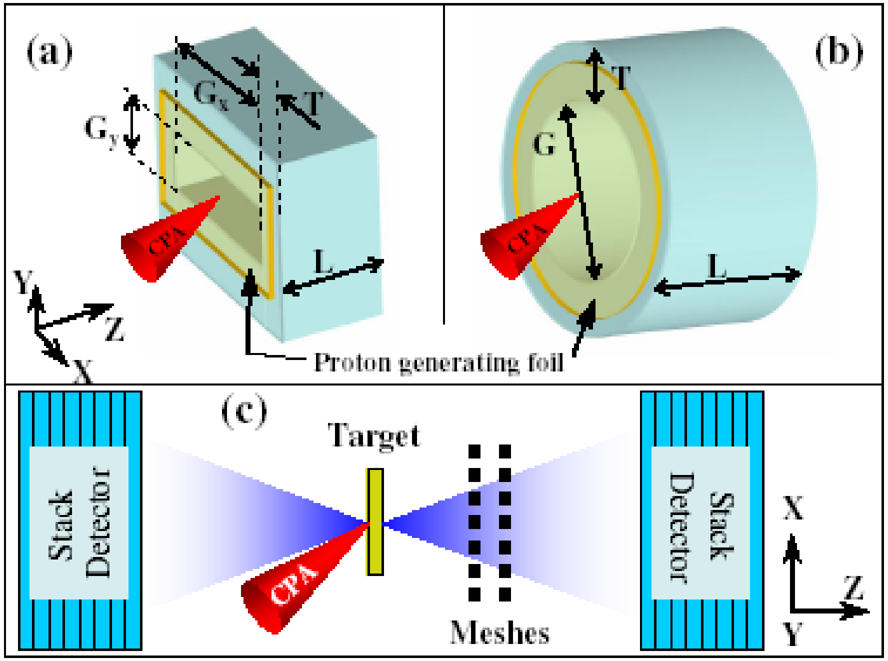
1) **consider ions and hot electrons as an expanding plasma which is described with fluid or kinetic models**
   - accelerated ions are the positive component of a globally neutral plasma
   - focus on the collective time evolution of ion dynamics

2) **describe in detail the accelerating field as a quasi-static sheath electric field set up by the hot electrons**
   - light ions treated as test particles forming a thin low-density layer
   - heavier ions considered almost immobile on the time scales of light ion acceleration
   - focus on the early stages of ion acceleration (energetic ions)

Role of “bound” electrons – 2

Any experimental evidence of “passing” vs “bound” electrons?

“*Dynamic Control of Laser-Produced Proton Beams*”
S. Kar et al., *Phys. Rev*, *Lett.*, **100**, 105004 (2008)



“… **A small fraction of the hot electron population escapes** and rapidly charges the target to a potential of the order of *Up* preventing the bulk of the hot electrons from escaping. …”

“… All targets were **mounted on** 3 mm thick and 2 cm long **plastic stalks in order to provide a highly resistive path to the current flowing from the target to ground**. …”

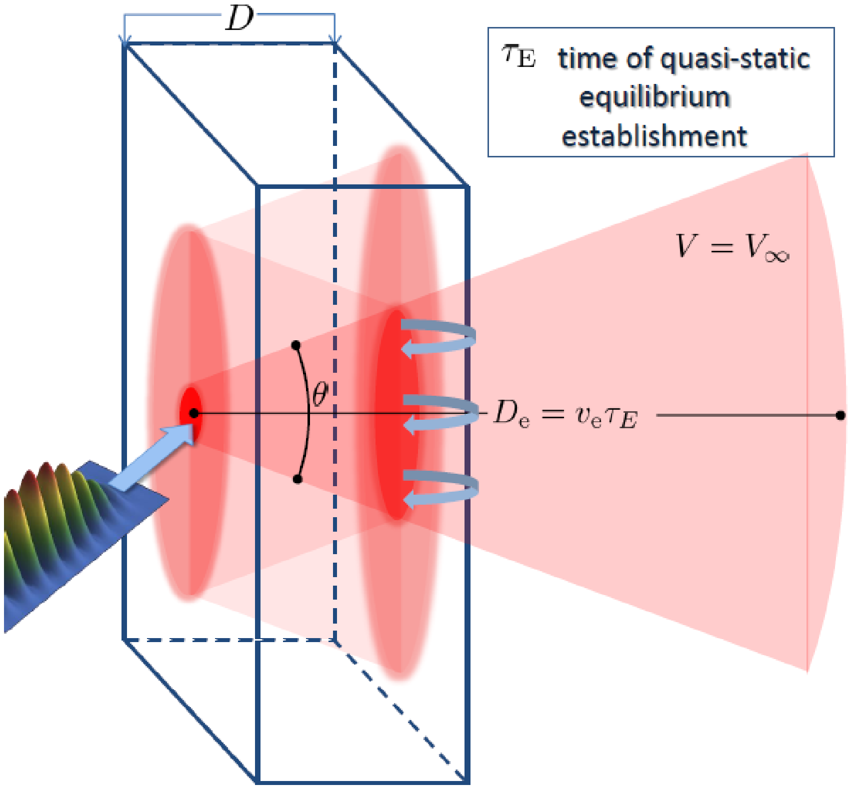
about this issue, see also
K. Quinn et al. *Phys. Rev. Lett.* (2009)

…then, in usual conditions

a globally neutral target with only “bound” electrons develops

TNSA theory: Extension of the description

Thickness Dependence



✓Hot Electron generation: $N_{\mathrm{h}} = \eta E_{\mathrm{L}} / \langle K \rangle$

✓Collision-less Ballistic Transport, with divergence angle θ

$$v_{\mathrm{e}} \lesssim c \qquad \tau_{\mathrm{E}} \sim 50\,\mathrm{fs} \qquad V \to V_{\infty}$$

✓Uniform Density $n_{\infty} = N_{\mathrm{h}} / V_{\infty}$

✓Electron Recirculation, longitudinal confinement

$$n_{\mathrm{h}0} = \frac{D_{\mathrm{e}}}{D} n_{\infty}$$

The hot electron density estimate is used as a boundary condition in Passoni-Lontano theory:

$$\varphi^{*} + \log\left[\frac{I\left(\varphi^{*}, T_{\mathrm{h}}\right)}{\zeta K_{1}(\zeta)}\right] = \log\left(\frac{n_{h0}}{\tilde{n}}\right)$$

Pulse energy – intensity plane: TNSA beyond 10^{21} W/cm^2: ?

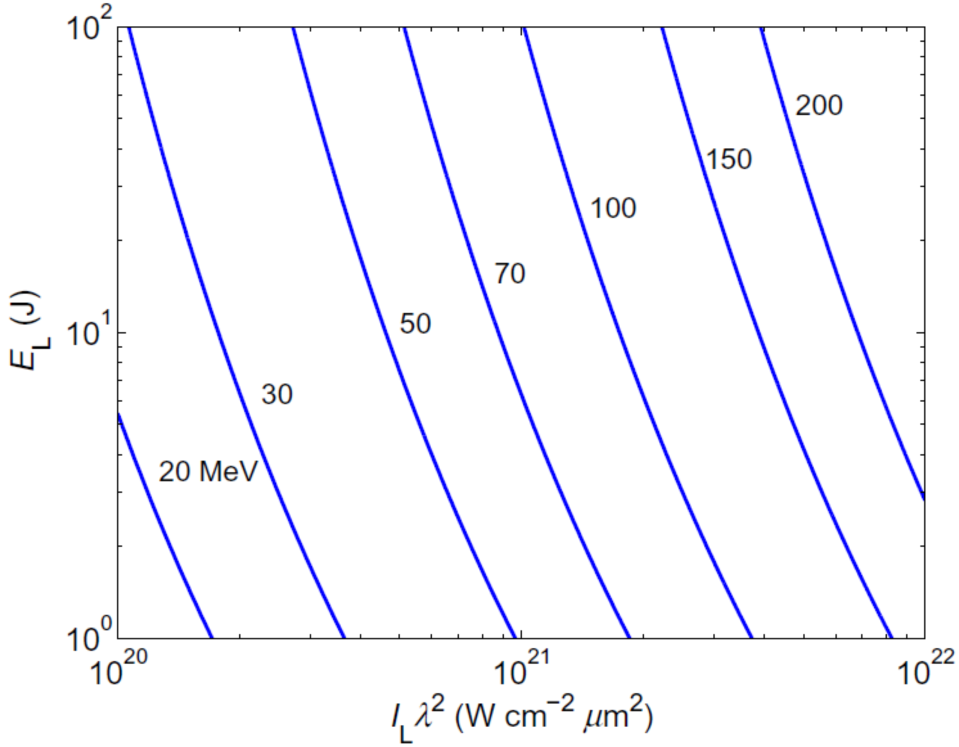


Figure 4. The curves at constant $\varepsilon_{i,\max}$ (in MeV) are plotted in the $(I_L\lambda^2; E_L)$ plane, in units (W cm^{-2} μm^2; J). Ranges relevant for future laser facilities are considered.

Example :

100 MeV protons with

Ti:Sa (λ=800 nm);

I **= 4x10^{21} W/cm^2;**

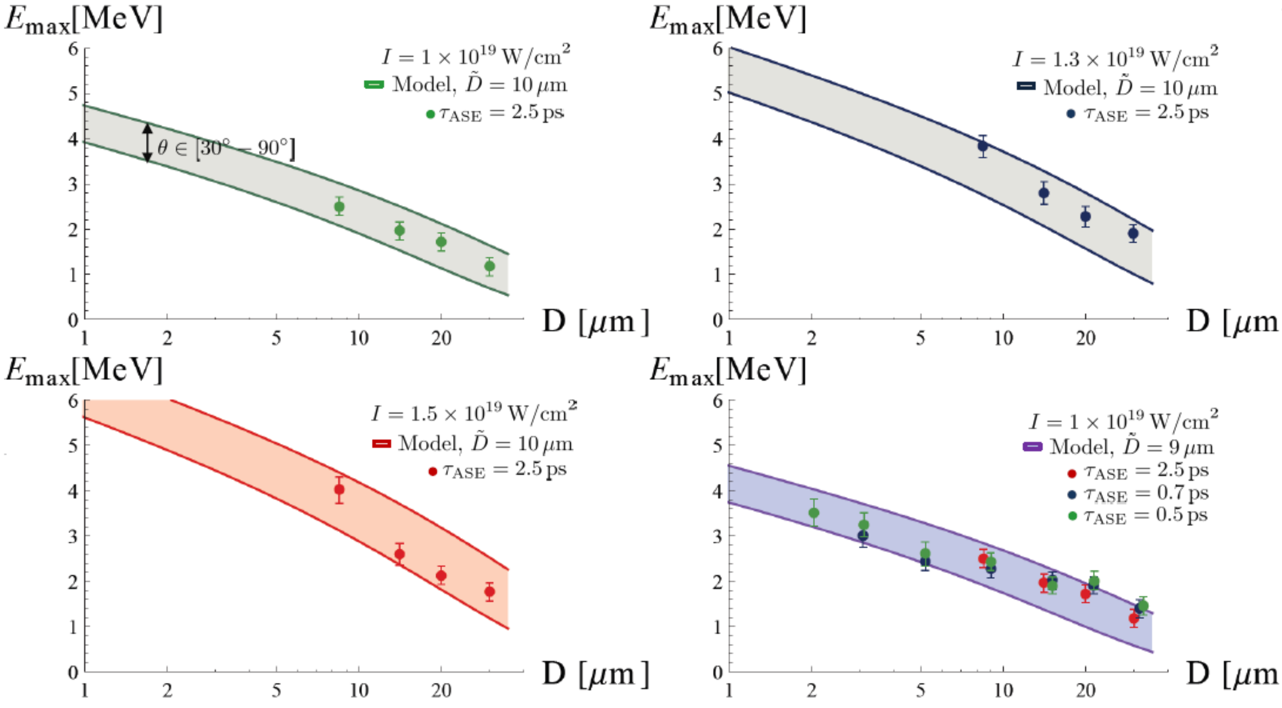
E_L = 5 J

M. Passoni et al, *New J. Phys.* **12,** 045012 (2010)

TNSA theory:
comparison with experiments

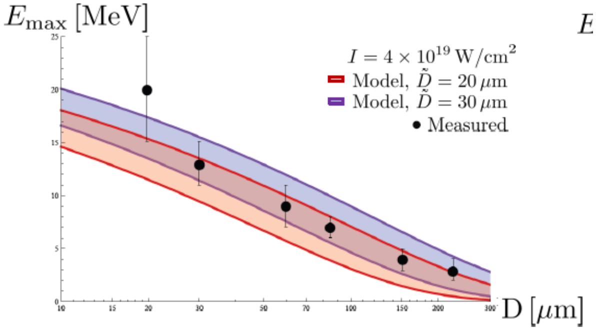
M. Kaluza *et al. Phys. Rev. Lett.* **93** (2004)

ATLAS , MPI Garching 10 TW: Different thicknesses, laser intensities and pre-pulse durations



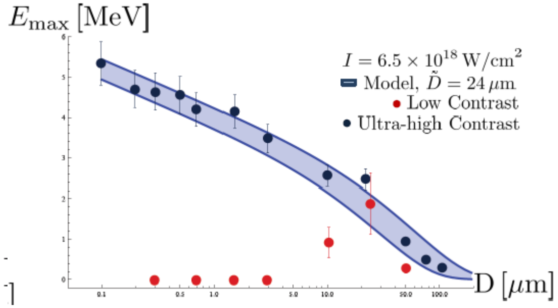
J. Fuchs *et al. Nat. Phys.* **48** (2006)

LULI , 100 TW: higher on target energy and thicker targets, 2 different normalizations

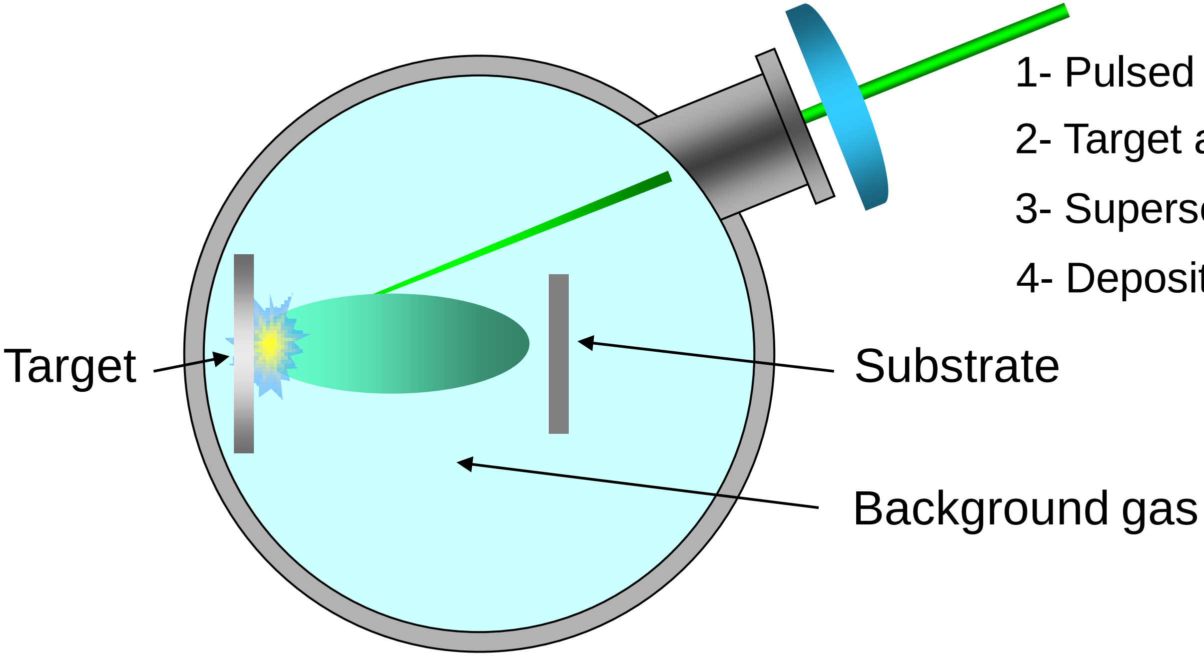


T. Ceccotti *et al. Phys. Rev. Lett.* **99** (2007)

UHI10, Saclay 10 TW: low/ultra-high contrast pulses on Mylar targets



Production of films & coatings with Pulsed Laser Deposition (PLD)

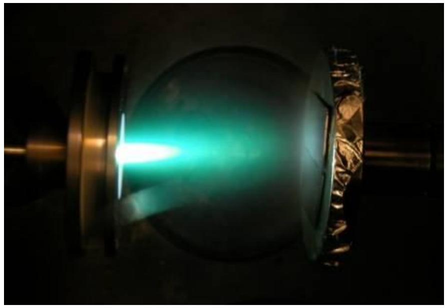


1- Pulsed Laser (nanoseconds)

2- Target ablation: = 300 MW/cm^2

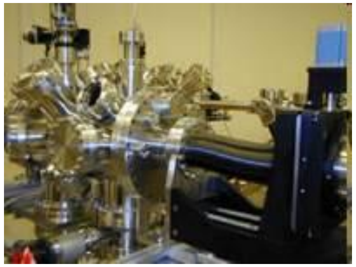
3- Supersonic expansion $E_{at} \approx 1\text{-}100$ eV

4- Deposition on a substrate



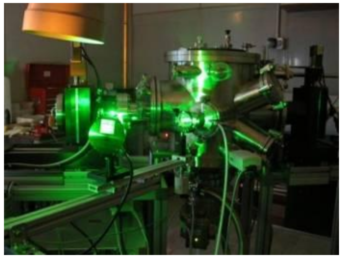
UHV chamber with KrF excimer laser

λ=248 nm, pulsewidth 12 ns 450 mJ



HV chamber with 4th harm NdYAG laser

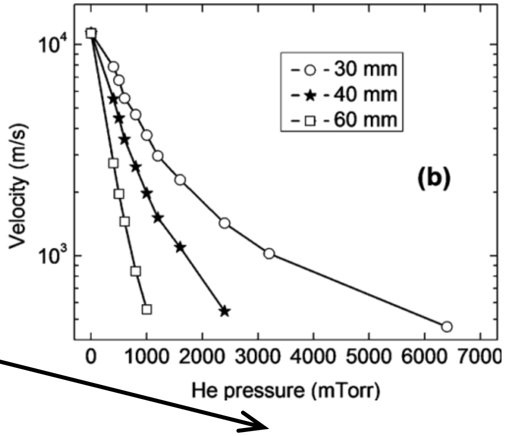
λ=266 nm-1064 nm, pulsewidth 7 ns 160 mJ



Control of morphology-growth in PLD: effect of Gas Pressure

Ambient gas (Atomic mass, Pressure) can affect:

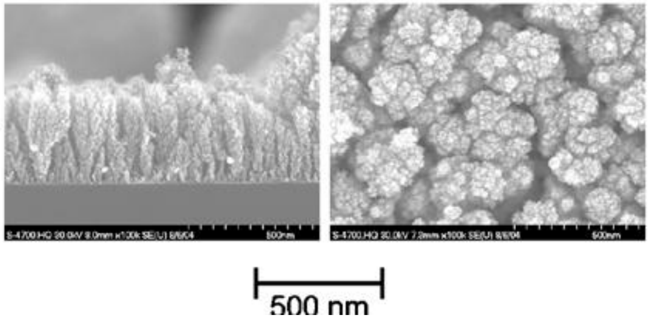
Energy of the ablated species



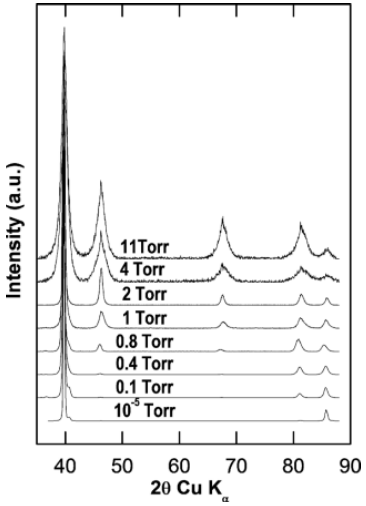
[1]

Morphology

Crystalline Structure



[1]



[1]

Specific aim:

achieve separate control of crystalline domain size and film morphology

[1]D. Riabinina, E. Irissou, et al., JAP **108**, 034322 (2010)

Pulsed Laser Deposition (PLD): Pro and Contra

Advantages in using PLD:

- fine tailoring of the morphology and structure of the deposited film at the nanometric scale (thanks to the high energy of the ablated species)
- possibility of obtaining better thermo-mechanical properties (stress relief, adhesion, fatigue resistance, deformability)
- deposition of multi-layer & functionally graded materials in order to overcome interface problems
- high purity of the deposited material (strong reduction of contaminants)

Drawbacks:

- Deposition of limited areas (tens cm^2) and thicknesses (μm)
- Formation of micro-nano metric droplets

Possible interest of PLD for fusion research:

- First Wall coatings properties – especially W! (JET, AUG, ITER, DEMO)
- permeation barriers
- Nanostructured films for specific devices (diagnostic mirrors, neutron detectors)

Characterizations

- SEM (Zeiss Supra 40 equipped with the GEMINI column)

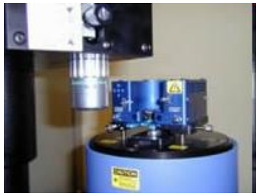
  morphology and substrate adhesion

- EDS (Oxford Instruments)

  composition and contaminations

- STM (Omicron)

  surface analysis

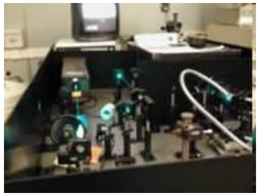


- AFM (Thermomicroscope Autoprobe CP Research)

  roughness

- Raman spectroscopy (1- Jobin-Yvon T64000, 2- Renishaw Invia)

  composition, structure



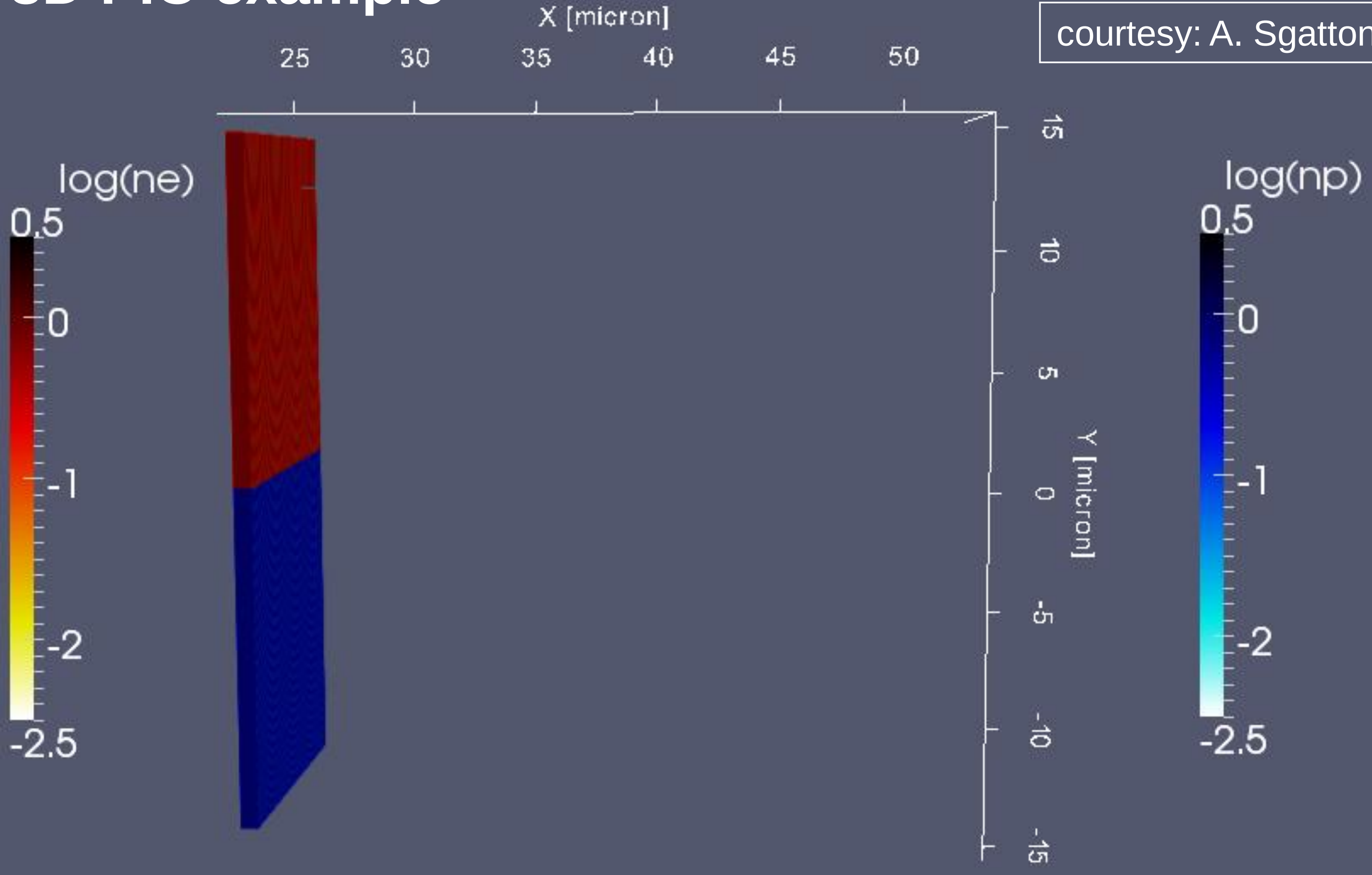
- Brillouin spectroscopy

  mechanical properties, elastic constants

RPDA:
a 3D PIC example

$t = 0$ fs

courtesy: A. Sgattoni



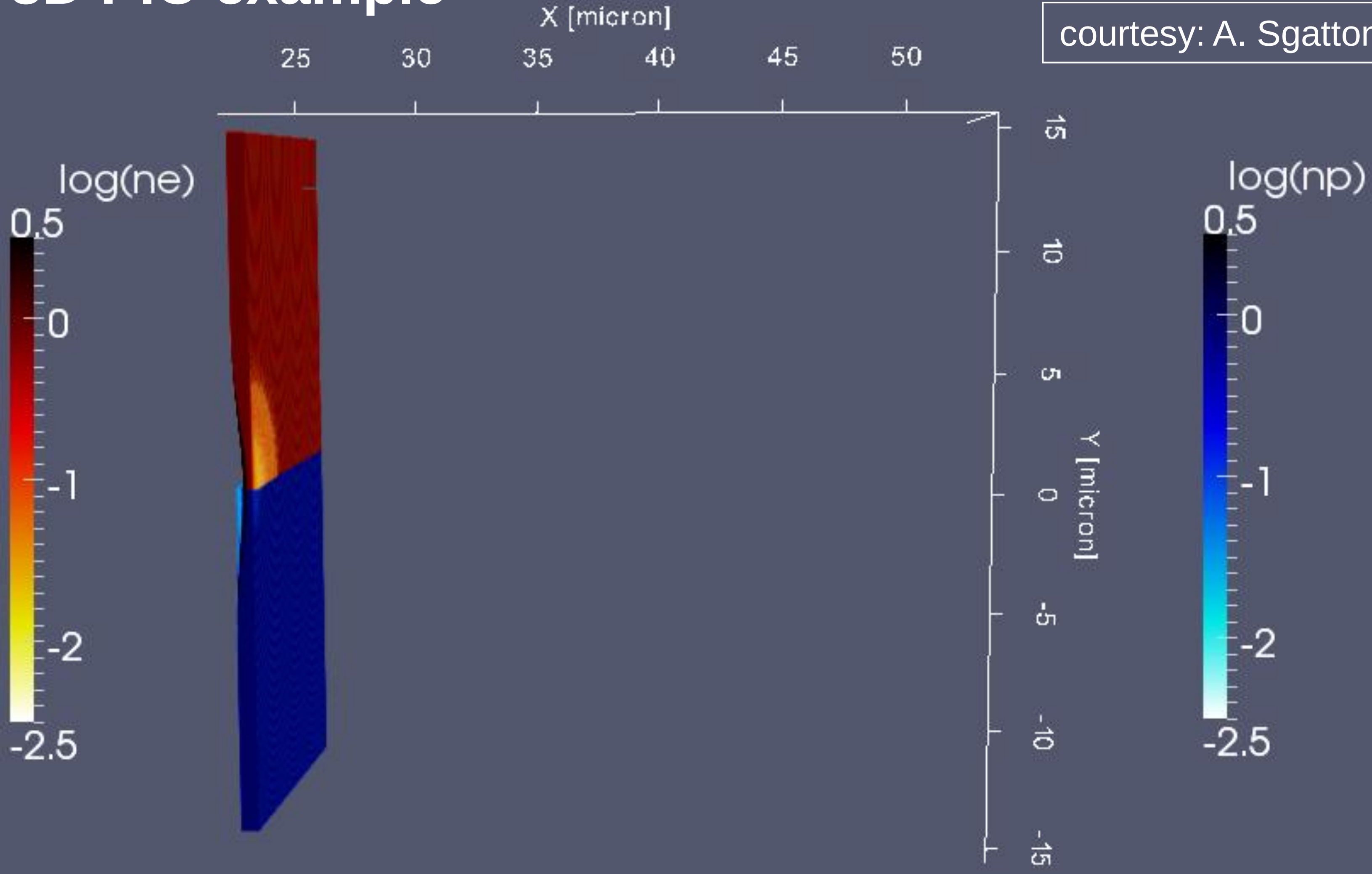
CP laser: $I_0 = 1{,}7 \cdot 10^{23}$ W/cm^2 $w_0 = 3{,}5\mu m$ $\tau = 24fs$ $\lambda = 0{,}8\mu m$

e-p plasma: $l = 0{,}8\mu m$ $n_e = 64n_c$

RPDA:
a 3D PIC example

$t = 16{,}6\ \mathrm{fs}$

courtesy: A. Sgattoni

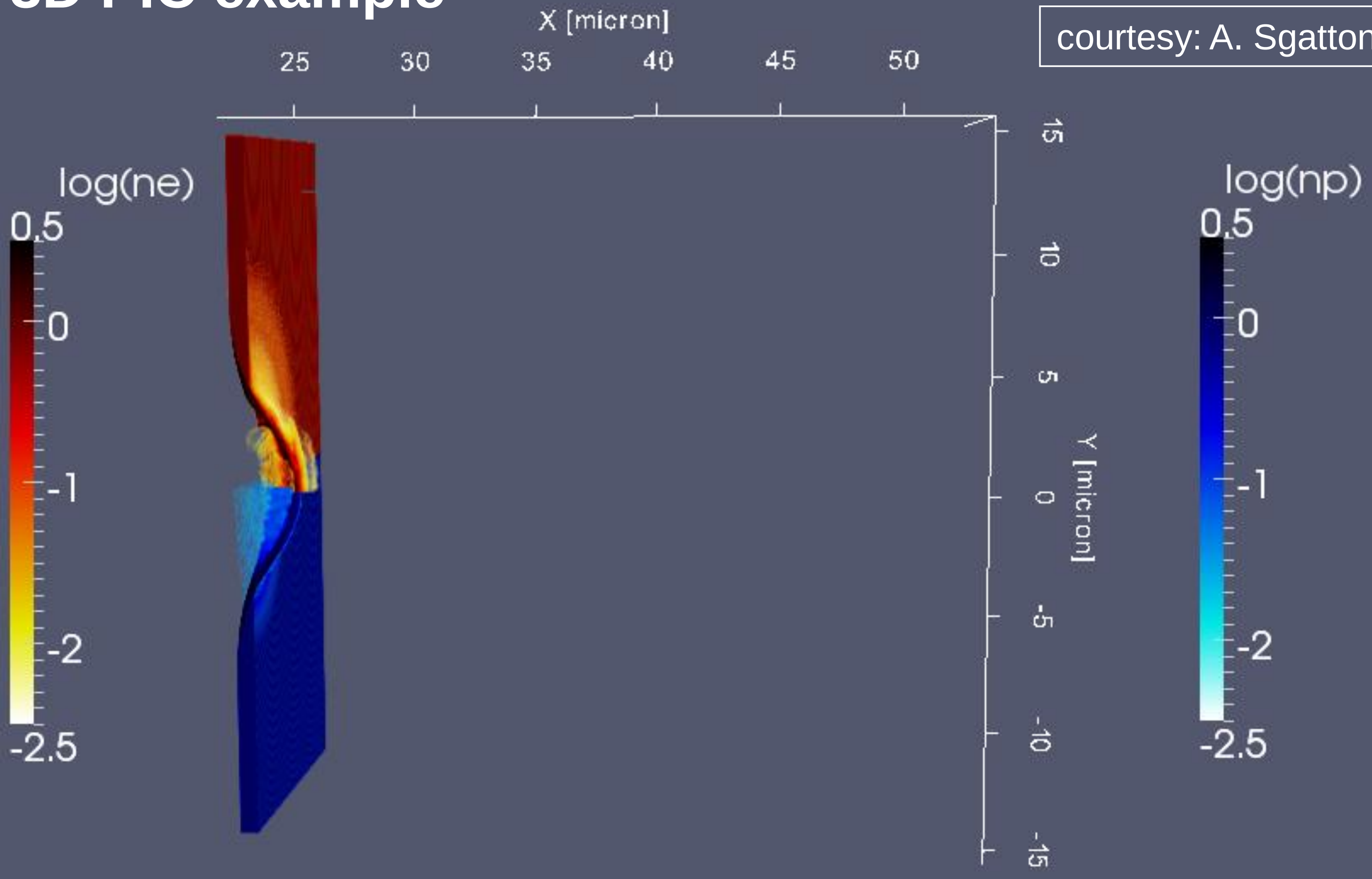


CP laser: $I_0 = 1{,}7 \cdot 10^{23}\ \mathrm{W/cm^2}$ $w_0 = 3{,}5\mu m$ $\tau = 24fs$ $\lambda = 0{,}8\mu m$
e-p plasma: $l = 0{,}8\mu m$ $n_e = 64n_c$

RPDA:
a 3D PIC example

$t = 33{,}3\ \text{fs}$

courtesy: A. Sgattoni



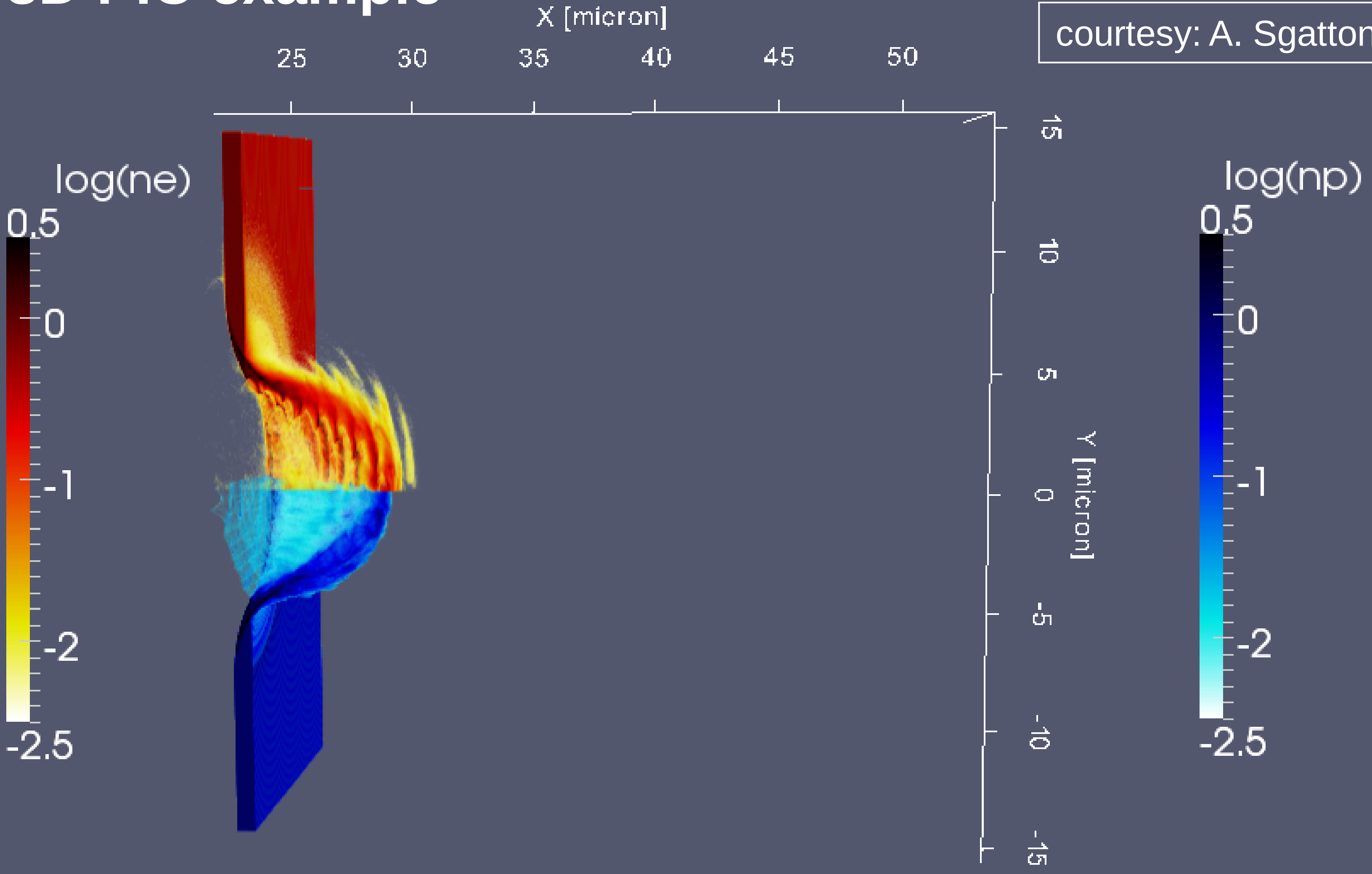
CP laser: $I_0 = 1{,}7 \cdot 10^{23}\ \text{W/cm}^2$ $w_0 = 3{,}5\mu m$ $\tau = 24fs$ $\lambda = 0{,}8\mu m$

e-p plasma: $l = 0{,}8\mu m$ $n_e = 64n_c$

RPDA:
a 3D PIC example

$t = 50$ fs

courtesy: A. Sgattoni



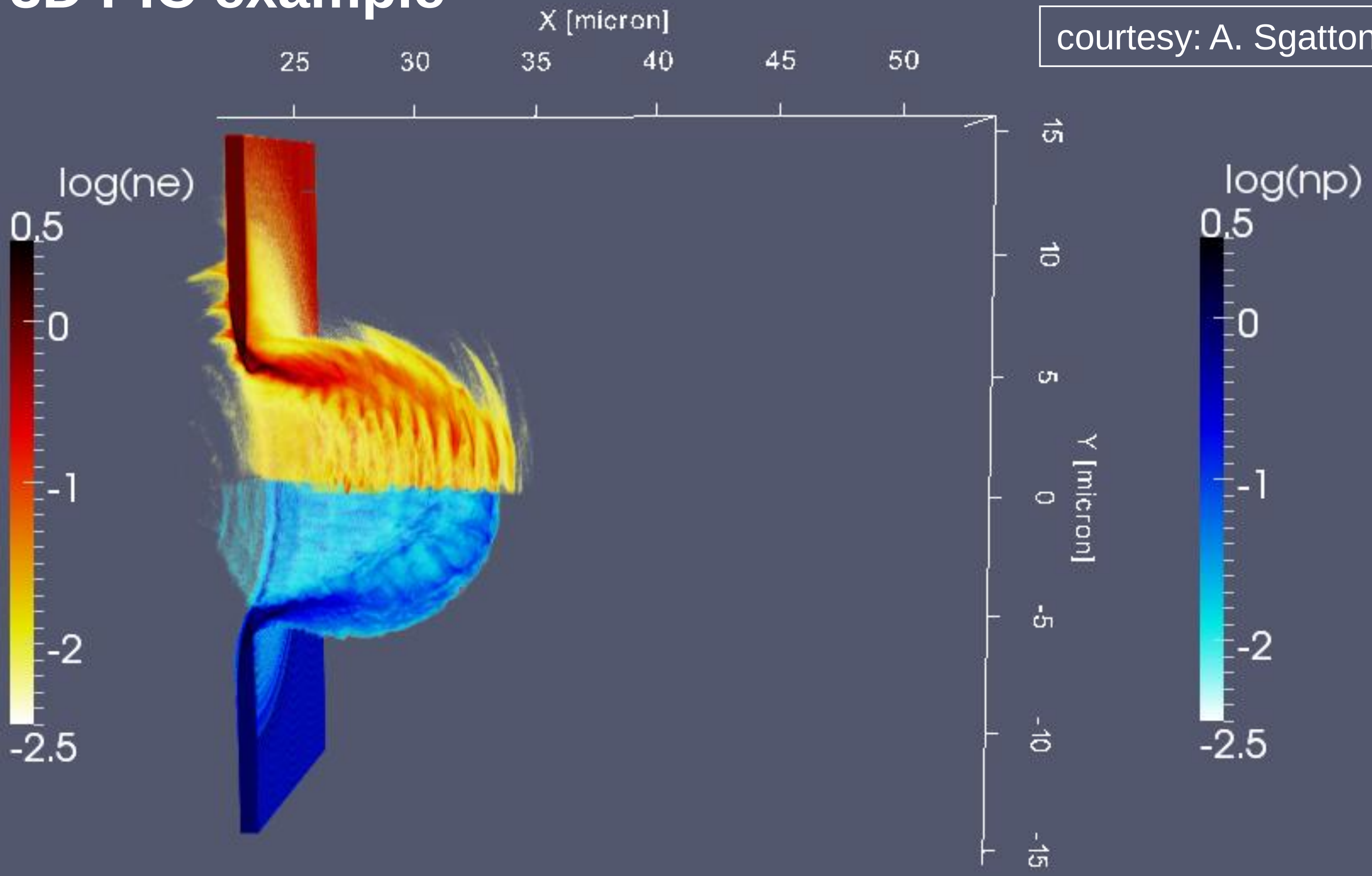
CP laser: $I_0 = 1{,}7 \cdot 10^{23}\,\mathrm{W/cm^2}$ $w_0 = 3{,}5\mu m$ $\tau = 24 fs$ $\lambda = 0{,}8\mu m$

e-p plasma: $l = 0{,}8\mu m$ $n_e = 64 n_c$

RPDA:
a 3D PIC example

$t = 66{,}6\ \mathrm{fs}$

courtesy: A. Sgattoni



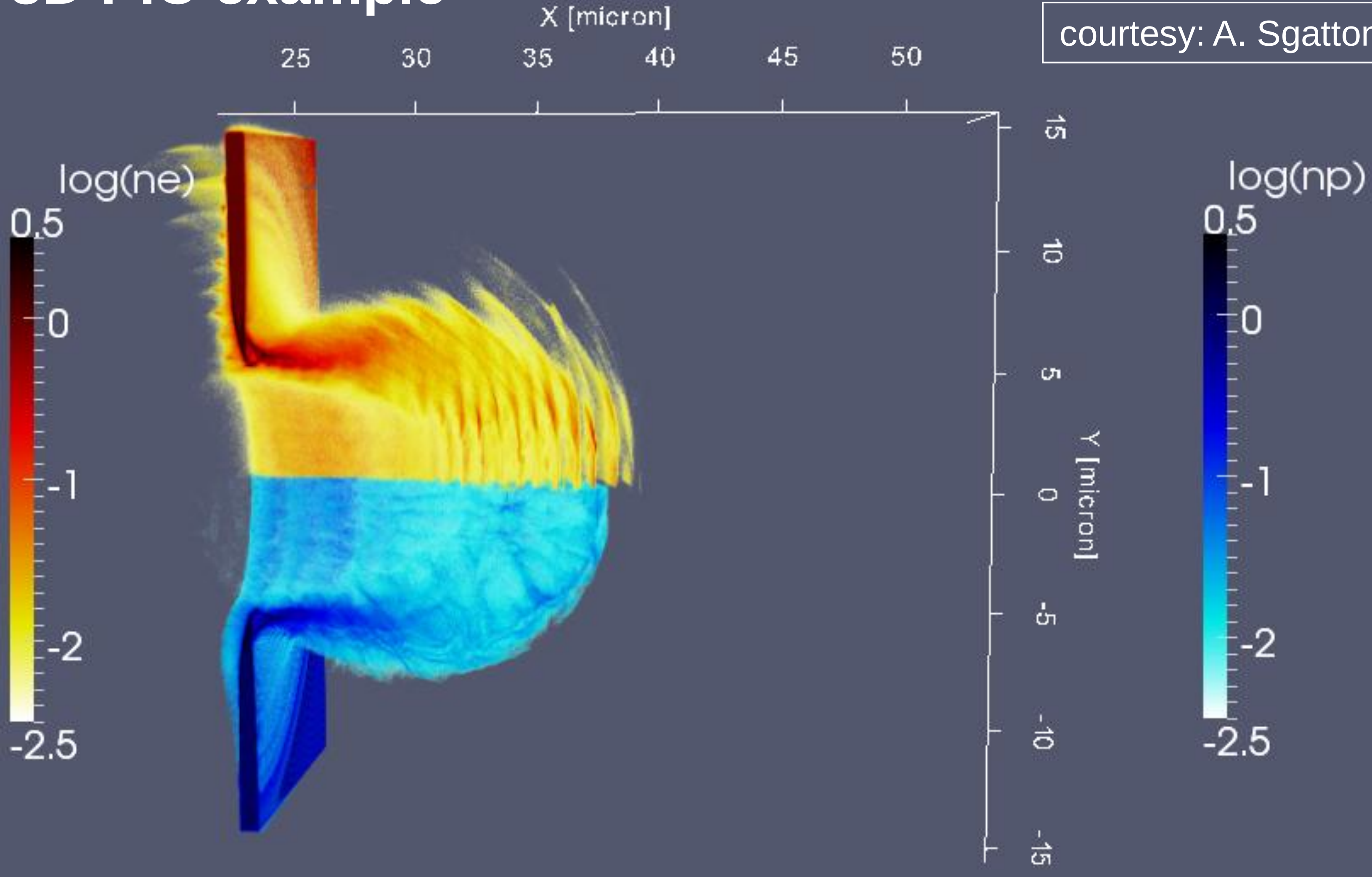
CP laser: $I_0 = 1{,}7 \cdot 10^{23}\ \mathrm{W/cm^2}$ $w_0 = 3{,}5\mu m$ $\tau = 24fs$ $\lambda = 0{,}8\mu m$

e-p plasma: $l = 0{,}8\mu m$ $n_e = 64n_c$

RPDA:
a 3D PIC example

$t = 83{,}3\ \mathrm{fs}$

courtesy: A. Sgattoni



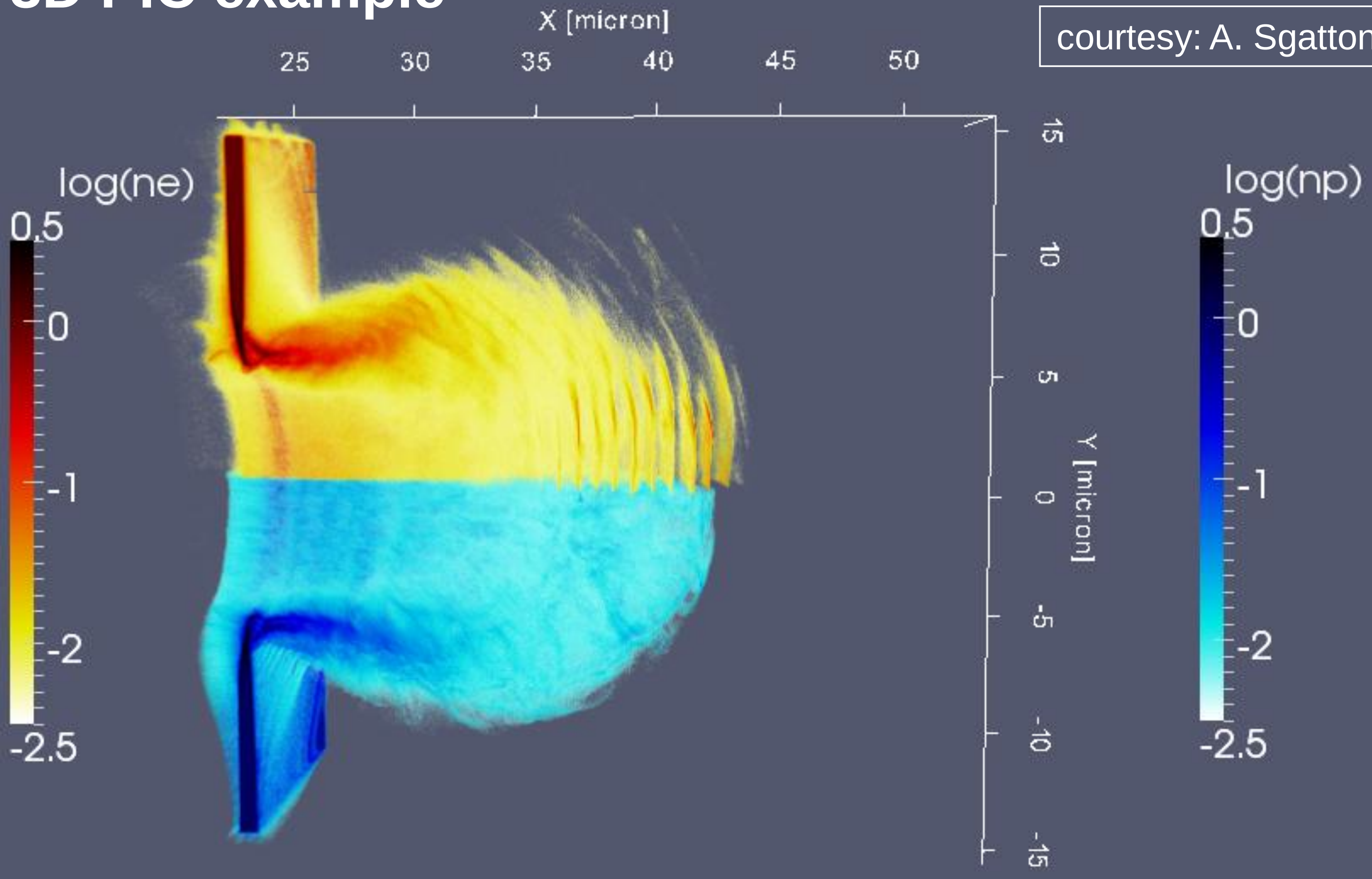
CP laser: $I_0 = 1{,}7 \cdot 10^{23}\ \mathrm{W/cm^2}$ $w_0 = 3{,}5\mu m$ $\tau = 24fs$ $\lambda = 0{,}8\mu m$

e-p plasma: $l = 0{,}8\mu m$ $n_e = 64 n_c$

RPDA:
a 3D PIC example

$t = 100$ fs

courtesy: A. Sgattoni



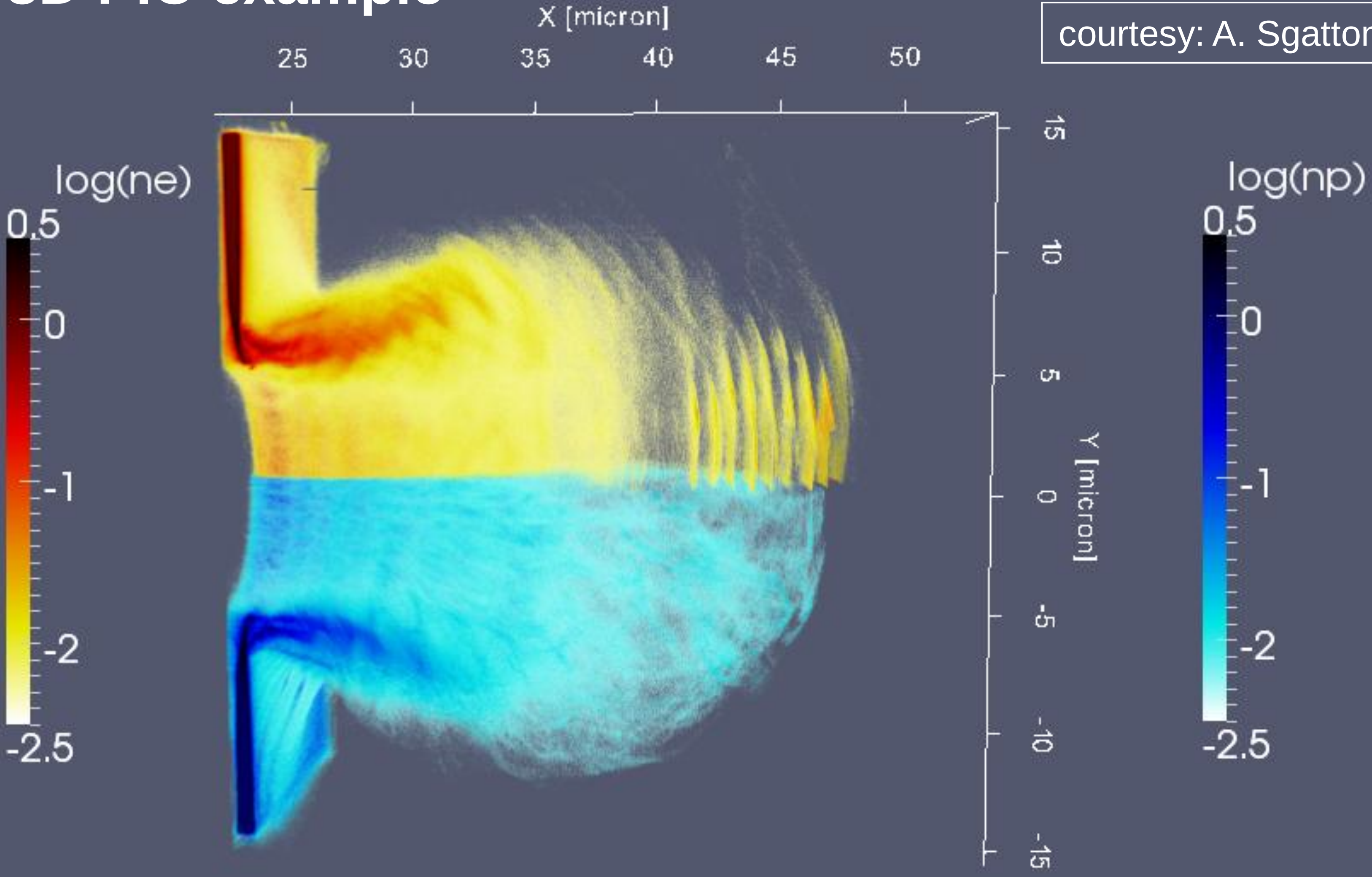
CP laser: $I_0 = 1{,}7 \cdot 10^{23}\,\mathrm{W/cm^2}$ $w_0 = 3{,}5\mu m$ $\tau = 24 fs$ $\lambda = 0{,}8\mu m$

e-p plasma: $l = 0{,}8\mu m$ $n_e = 64 n_c$

RPDA:
a 3D PIC example

$t = 116\ \mathrm{fs}$

courtesy: A. Sgattoni



CP laser: $I_0 = 1{,}7 \cdot 10^{23}\ \mathrm{W/cm^2}$ $w_0 = 3{,}5\mu m$ $\tau = 24 fs$ $\lambda = 0{,}8\mu m$

e-p plasma: $l = 0{,}8\mu m$ $n_e = 64 n_c$

FINAL PROTON ENERGY: ~ 2 GeV