Laser plasma acceleration: emerging physics issues and numerical modelling schemes

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On behalf of the "L3IA" collaboration

Participating units (L3IA) Pisa, Milano, Firenze, Bologna, Napoli, Catania-LNS
Collaboration with CEA-Saclay (FR), STFC-RAL (GB) …

Participating groups (EuPRAXIA) Pisa, LNF, Firenze, Napoli, Milano …

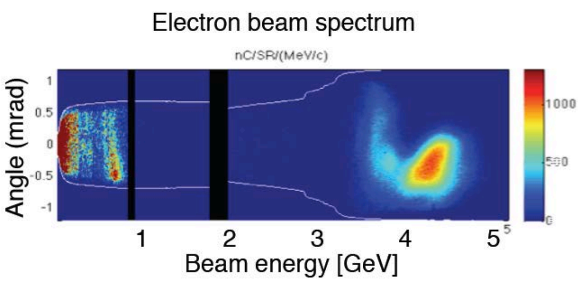
Contents

- Plasma accelerators: introduction
- Emerging physics issues: two examples
- Our strategy
- Conclusions and perspectives

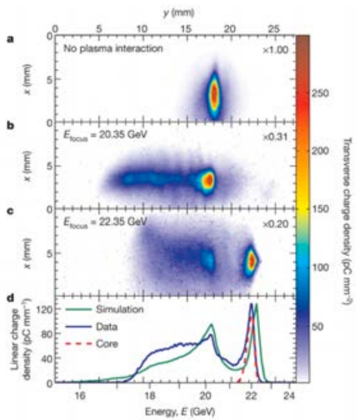
Need for NOVEL accelerators

- **Size, cost and construction time of Synchrotron and FELs based on RF accelerators are those of a large infrastructures, with km scale footprint;**
  - **Limitated exploitation** for interdisciplinary and medical applications;

- NOVEL accelerators demonstrate much higher accelerating gradient, with **<u>potential</u>** much reduced footprint installations,
  - Laser-driven Wakefield acceleration (Bella[#], 4.2 GeV, 50 GV/m);
  - Electron driven Plasma Wakefield acceleration(SLAC[$], 4.4 GV/m);
  - Proton driven Plasma Wakefield acceleration (Est.[&] 1.3 GV/m)
  - Dielectric laser acceleration …



BELLA @ LBNL, USA



SLAC, USA

AWAKE

CERN

[#] W.P. Leemans et al., PRL. 113, 245002 (2014), [$]M. Litos et al., Nature 515, 92–95 (2014) [&] A. Caldwell, K. Lotov, POP, 18,103101 (2011)

Large EU collaborations

Future projects will greatly benefit from the forthcoming operation of ELI and synergy with accelerator community

eli – eXtreme light infrastructure

EuCARD²

EuroNNAc²
European Network for Novel Accelerators

Increasing needs of numerical modelling and benchmarking

The ELIMED application

Geant 4

http://www.geant4.org

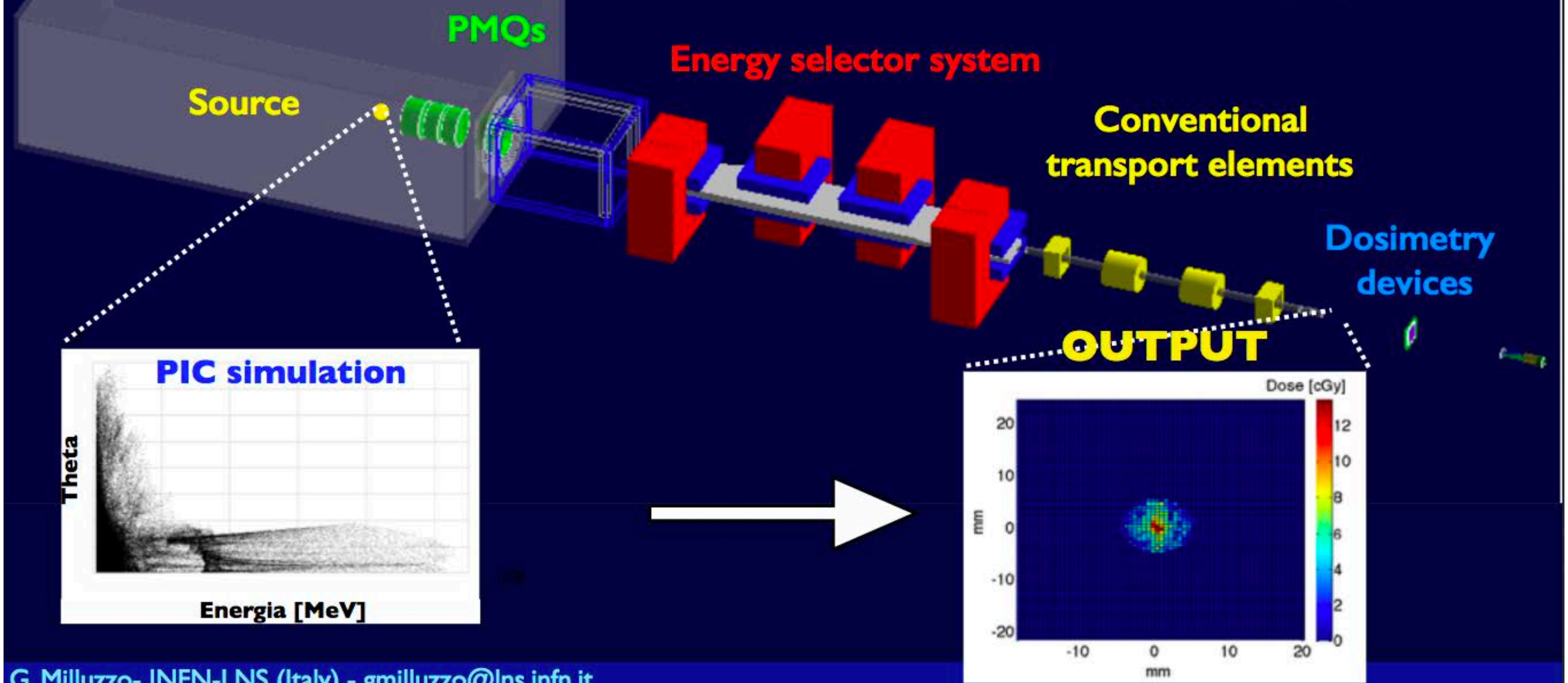
Geant4 (Geometry ANd Tracking)

"Toolkit for the simulation of the passage of particles through matter."

Application structure

Geometry
- Component realistic model
- Magnetic and electric field implementation

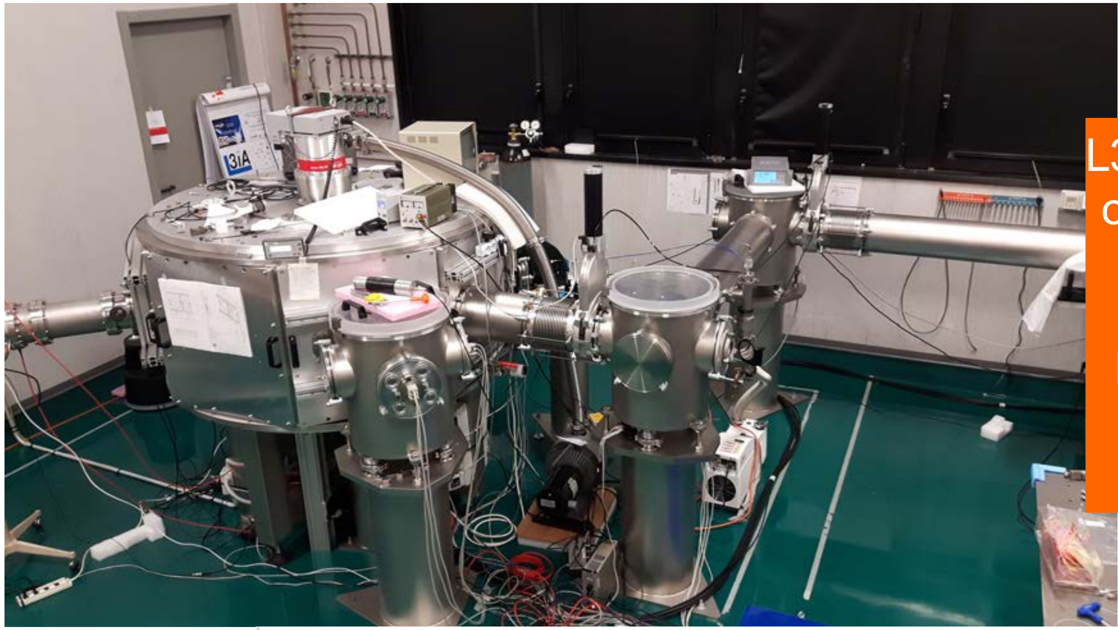
Source
- Realistic laser-driven particle source
- Information scoring along the beamline



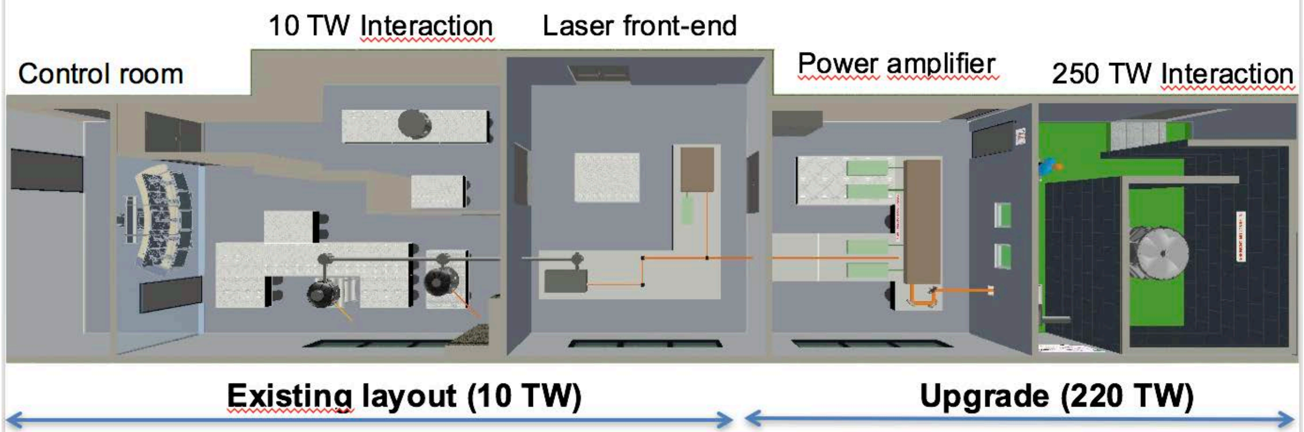
G. Milluzzo- INFN-LNS (Italy) - gmilluzzo@lns.infn.it

L3IA - a laser-driven proton-beamline in Italy

Line for Laser Light Ions Acceleration (L3IA)



L3IA includes design and construction of a 12 MeV laser-riven proton beam line for diagnostics and beam handling applications.
L3IA will be based on the ILIL laser installation at INO-CNR, currently undergoing 220 TW upgrade.



Intense Laser Irradiation Lab - Pisa

Italian community of LPA modelling

Project Driven Modelling and Codes Development

2nd Workshop of the series

May 18th, 2017
Aula Magna, Dipartimento di Fisica e Astronomia
via Irnerio 46, 40129 Bologna (ITALY)

INFN Istituto Nazionale di Fisica Nucleare

Dipartimento di Fisica

Ongoing national and European projects dealing with laser-driven particle acceleration require advanced modelling capabilities based on established codes and significant computing resources. Current effort by several groups in Italy is oriented towards both electron and ion acceleration. Generation of high quality, high-energy electron bunches is required for future demonstration of free electron laser operation in the X-ray range and other high brightness radiation sources (e.g. EuPRAXIA). Ion sources with energy in the domain of hadron therapy are being expected from the next generation of laser drivers (e.g. ELI-beamlines) while reliable operation of beam-lines based on established processes are being commissioned (e.g. L3IA).

In this context, laser-driven wakefield acceleration is aiming at controlled injection schemes while both laser and beam driven acceleration require well reproducible plasma structures, with optimized longitudinal and transverse density profiles.

Progress with ion acceleration relies on the optimization of target normal sheath fields on one side, with tailored target specifications, and advances in radiation driven schemes on the other side, with extreme intensities or polarization control, and an entirely new generation of targets.

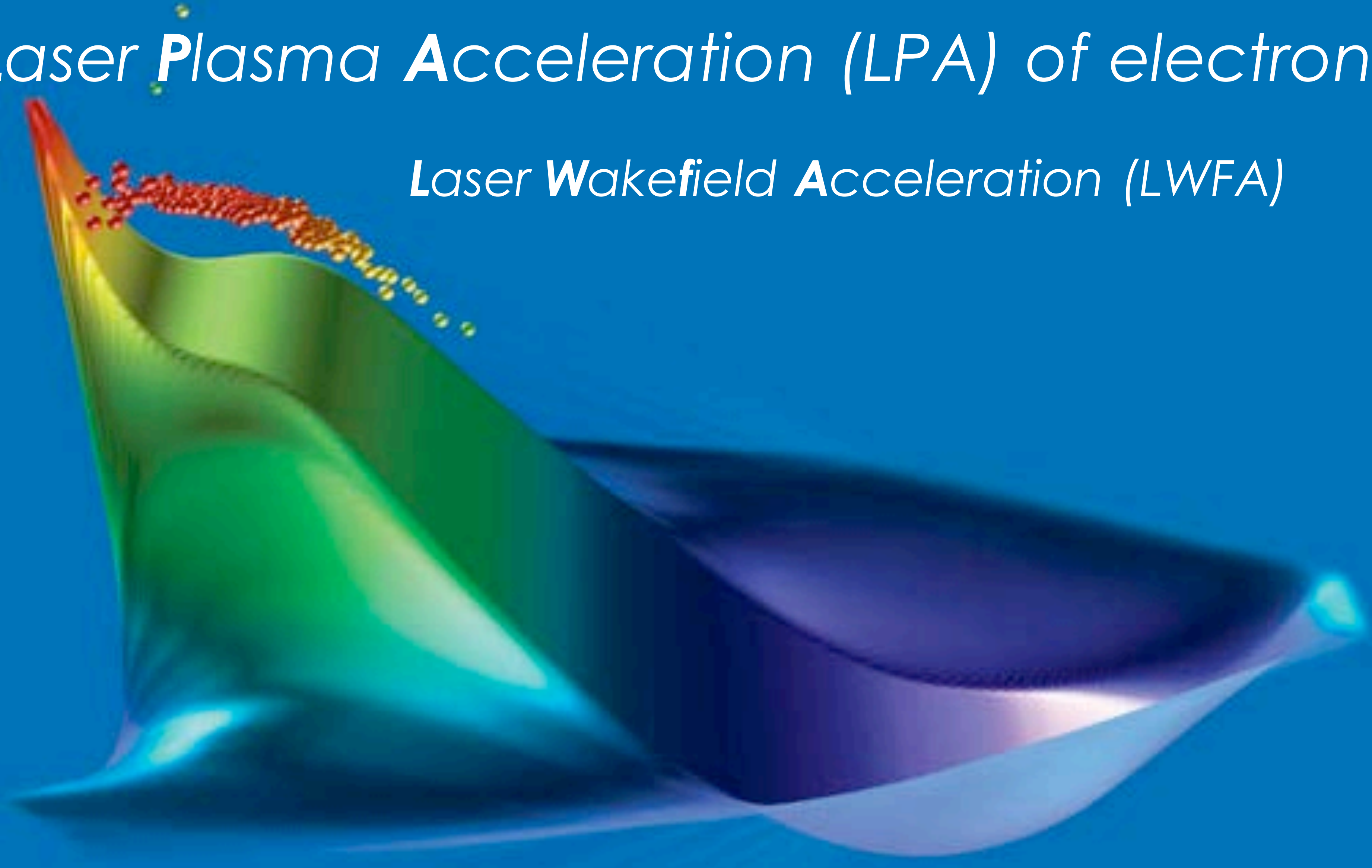
To accomplish these objectives, start-to-end simulations are being conceived, capable of describing not only the relevant laser-plasma interaction physics, but also the detailed, realistic laser specifications and any post acceleration phase.

"Project Driven Modelling and Codes Development" (PDMCD) is a series of workshop meant to give an opportunity to all the groups to present their current activity in the above framework to give an overview of the existing project-oriented effort in this area of research, with special attention to modelling and code development.

The workshop presented in this webpage is the second in the series, following the opening one in Pisa. If you are looking for the material presented in that session, please look at this page.

***L**aser **P**lasma **A**cceleration (LPA) of electrons*

***L**aser **W**ake**f**ield **A**cceleration (LWFA)*

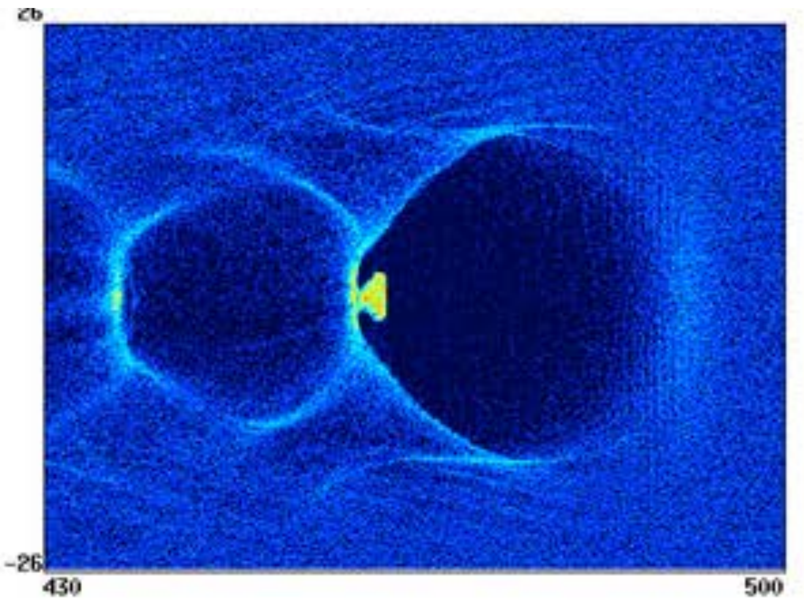


C. Huang, Los Alamos National Laboratory

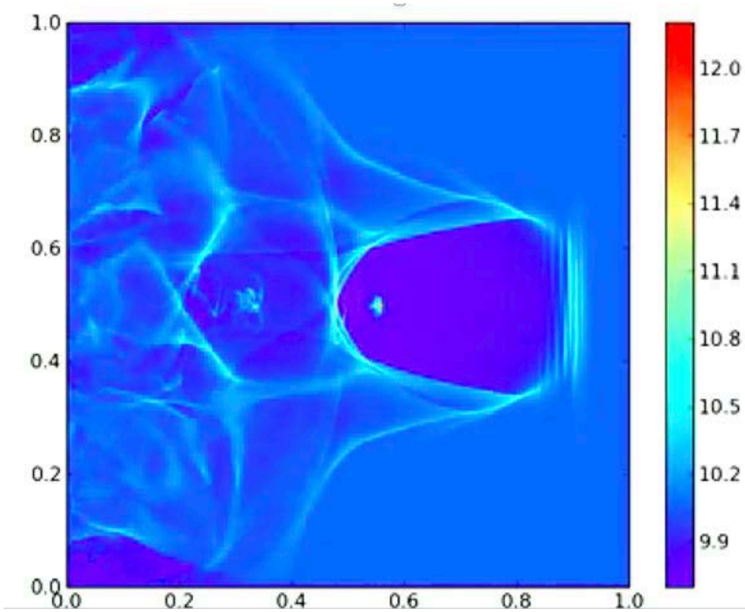
LWFA "bubble regime" of LPA

Particle-in-cell (PIC) simulation is the standard for LWFA
HPC with CPU (or GPU) based parallel architecture

Aladyn PIC code (C. Benedetti, A. Sgattoni, G. Turchetti, P. Londrillo, IEEE Trans. Plasma Sci., 36, 1790, 2008



Aladyn (CPU)



Jasmine (GPU)

Jasmine - a hybrid (CPU+GPU) e.m. particle in cell codes, F.Rossi, P. Londrillo (Univ. and INFN, Bologna)

L.A. Gizzi et al., NIM **B355**, 241–245 (2015)

Towards high quality acceleration

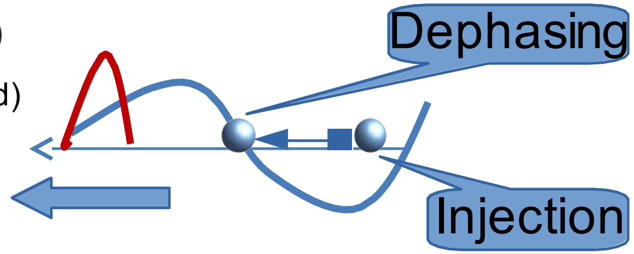
- Ultra-high gradient LWFA (100 GV/m) relies on strongly non linear wake-field regime where control of bunch properties (energy spread, emittance) is hard;
- Weakly non-linear LWFA (1-10 GV/m) can be controlled to a much greater degree using engineered laser and plasma profiles;
- Separation of injection and acceleration process is key to enable such control, since plasma conditions for injection are quite different from acceleration;
- Manipulation and control of phase space electron distribution during injection and acceleration becomes feasible.

High-quality bunches generation roadmap

Low energy spread/emittance bunches require *accurate control* in

- **<u>Particle's injection</u> (either internal trapping or external injection)**

  At injection/trapping **transverse emittance** ε_n must be very low (<<1 mm mrad)

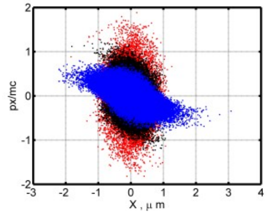


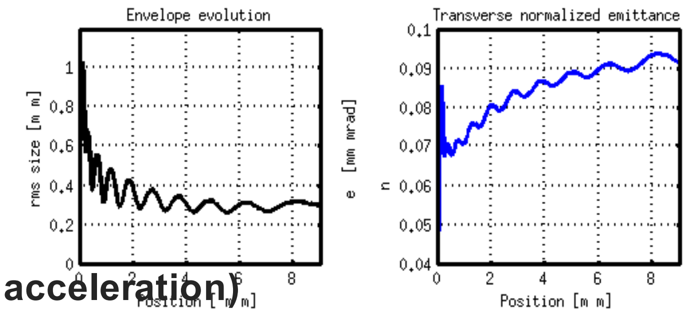
- **<u>Phase evolution</u> (longitudinal position variation into the bucket)**

  Dephasing length $L_{deph} \approx \lambda_p^3/\lambda_0^2 \cong \lambda_0 (n_c/n_e)^{3/2}$

- **Betatron oscillation induced emittance growth**

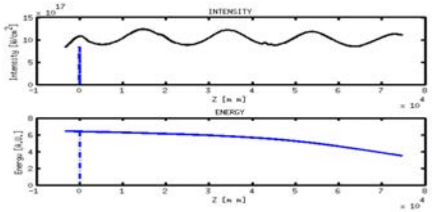
  Matched radius $r_{matched} \cong 4\sqrt{\frac{2}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}}$





- **Laser pulse guiding, pump depletion (only for high energy acceleration)**

Diffraction is compensated by positive-lens effect of plasma channels (and nonlinear effects)



Beam loading detrimental effects must be reduced

- **Bunch extraction from the plasma and beam optics**

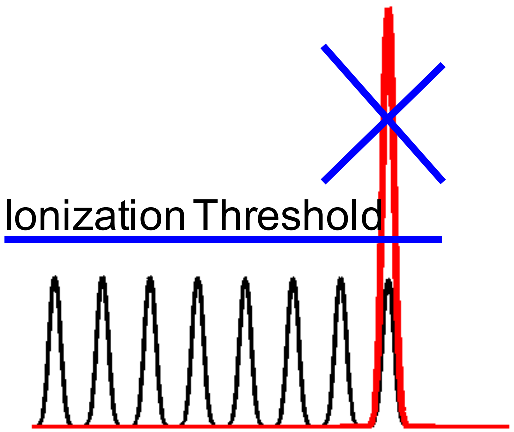
- Phase/amplitude variation of wakefield @ plasma exit; space charge issues; standard beam optics/plasma lens optimization

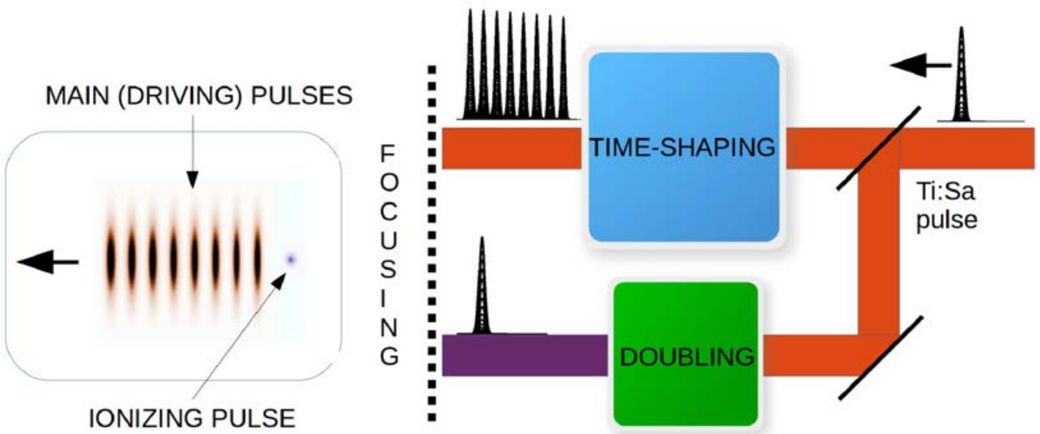
Novel injection/acceleration scheme

Resonant Multi- Pulse Ionization Injection (ReMPII)

The Resonant Multi-Pulse Ionization injection [P. Tomassini et al, 2017 (submitted)] is a new bunch injection scheme aiming at generating extremely low-emittance bunches [as low as 0.07 mm mrad].

RMPII the model combines multi-pulse resonant wakefield and ionization injection. It requires ONE short-pulse 100-TW class (e.g Ti:Sa) laser system. Since a unique very large-amplitude Ti:Sa pulse would fully ionize the atoms (Ar8+ in our selected example), the pulse is shaped as a <u>resonant</u> sequence of sub-threshold amplitude pulses.

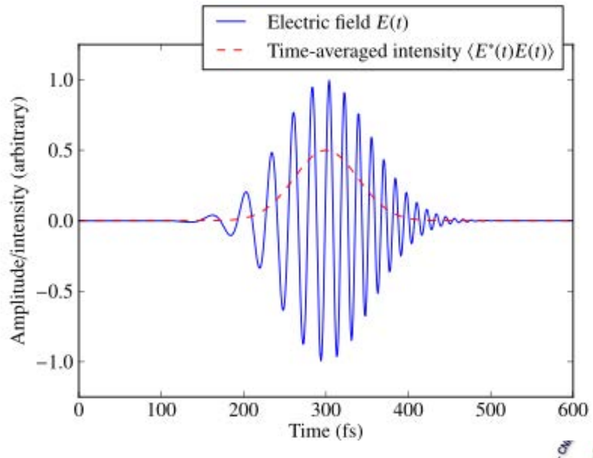




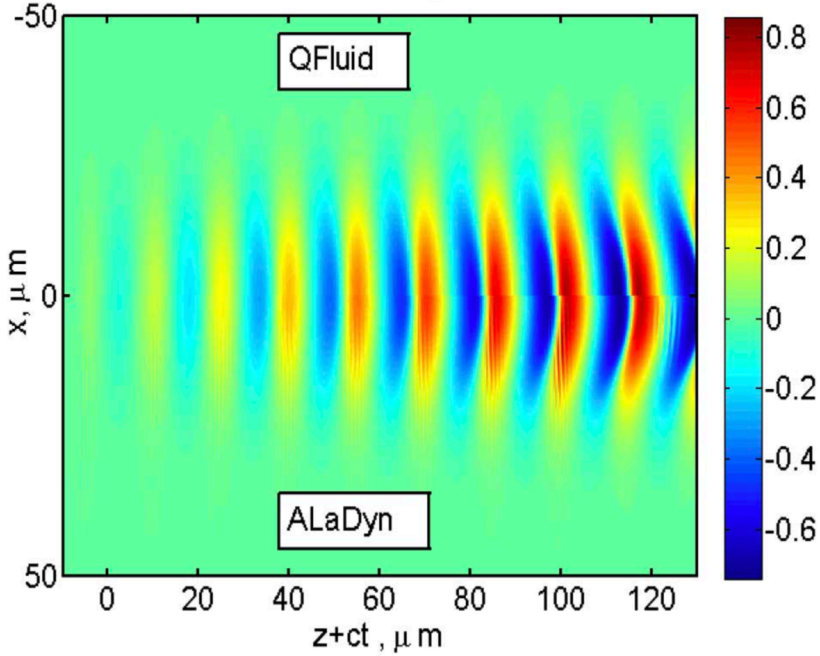
Ideally, modelling with full PIC codes, 3D, would provide robust design specs

Our strategy for high quality LWFA

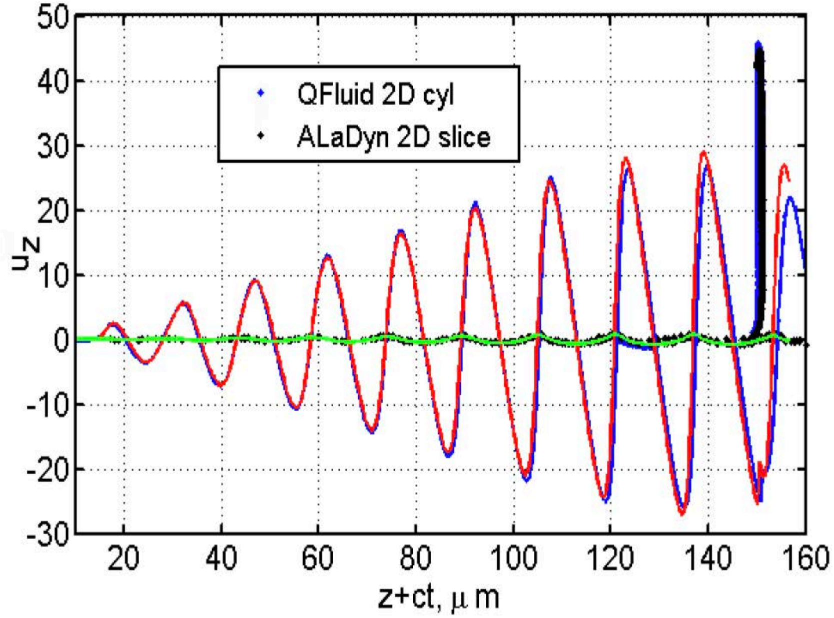
- Current schemes rely on extended propagation in weakly non-linear regime;
- Extended (cm) propagation is well beyond the capabilities of full particle-in-cell (PIC) codes;
- Strategy includes reduced dimensionality (2D) and tailored approximations:
  - Fluid approximation
  - Envelope approximation



Cross-checking of codes



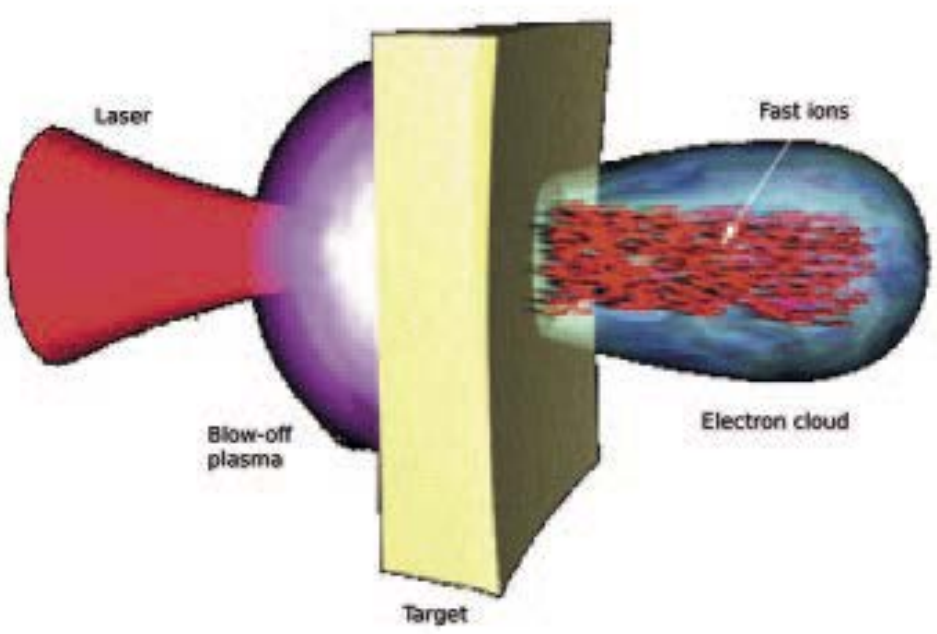
Fluid code accuracy is checked against full PIC for specific conditions

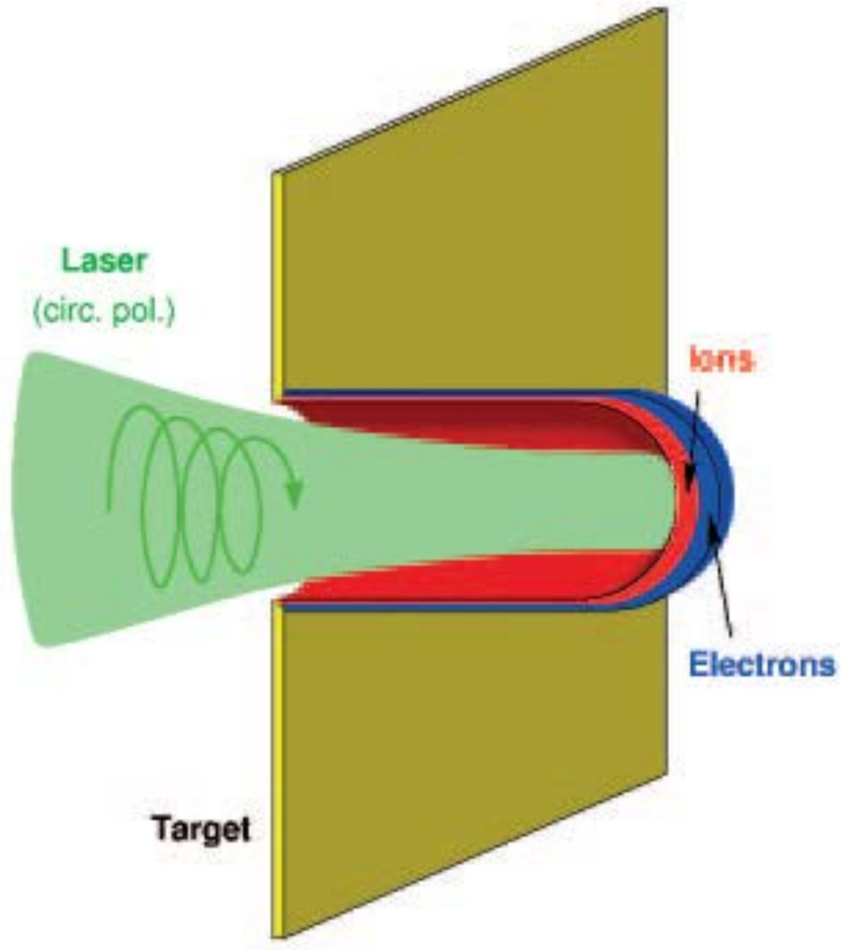


Example: Wakefield excitation is described accurately by fluid approximation

Laser plasma acceleration of ions

Target Normal Sheath Acceleration (TNSA)

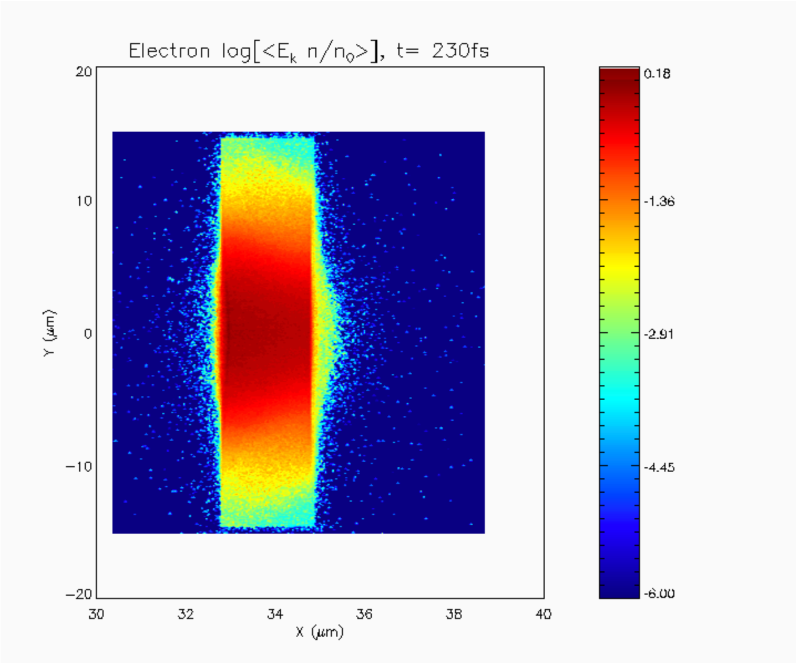


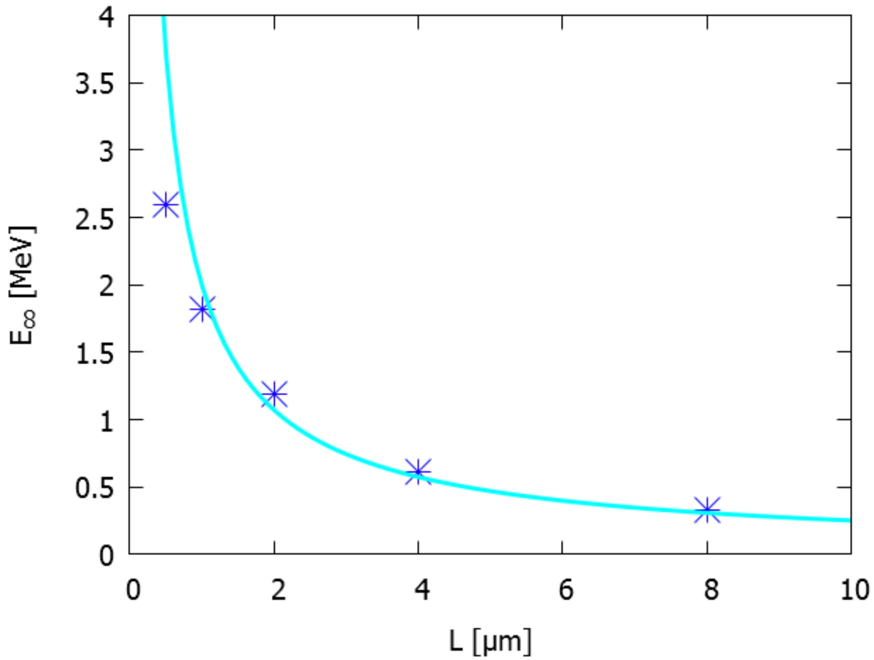


T. Tajima, K. Nakajima and G. Mourou, Laser acceleration, Rivista del Nuovo Cimento, 33, **40**, (2017)

Laser plasma acceleration of ions

Predictive simulations of Target Normal Sheath Acceleration (TNSA) for L3IA pilot experiments and scaling from 2D to 3D





Aladyn simulations: P. Londrillo et al., 2016

L.A. Gizzi et al., NIM A **A829**, 144–148 (2016)
J. Babaei et al., Physics of Plasmas 24, 043106 (2017)

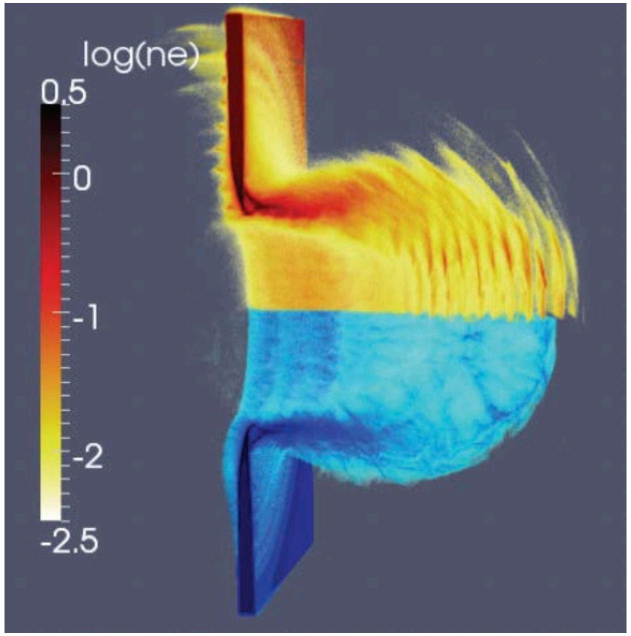
Ion accelerations: beyond TNSA

TNSA scaling with laser intensity: $E_p \propto a_0 \sim \sqrt{I_L \lambda^2}$

Looking for mechanisms with better scaling: Radiation Pressure Acceleration in the so-called light sail regime:

Laser

Intensity a_0>>1



Simulation by A.Sgattoni, L.Fedeli, A.Macchi,

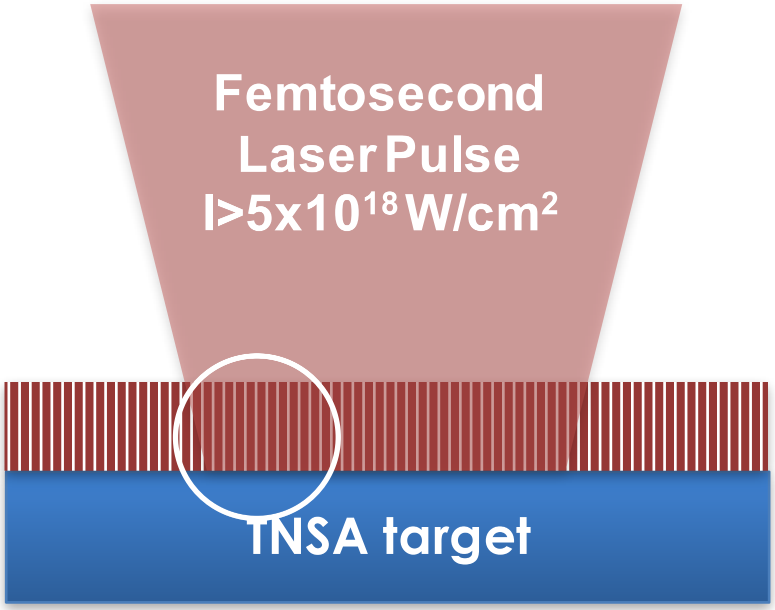
T. Esirkepov, et al. PRL., **92** (2004)
APL Robinson et al, NJP, **10** (2009)

Sgattoni et. al. APL 105 (2014)

First data with experimental evidence of LS regime emerging

Ion acceleration: smart targets

- Laser interacts with a layer of nanostructured velvet. Nanostructures increase the effective surface of interaction and absorption

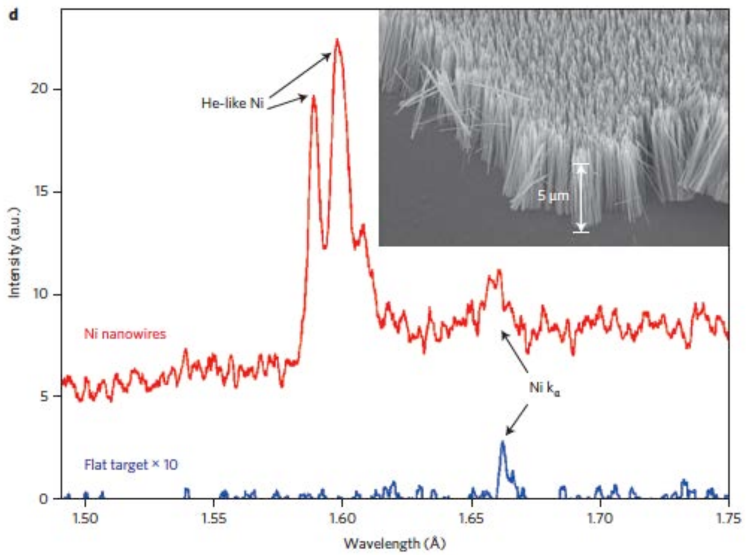


Fundamental issues:

- Survival on nanostructures at the peak of the pulse'
- Critically depends upon laser intensity evolution before the peak of the pulse;
- Gaps between the nanowires can be filled with plasma in picoseconds or less, at relatively low intensities;
- Plasma can become overdense and prevent laser propagation.

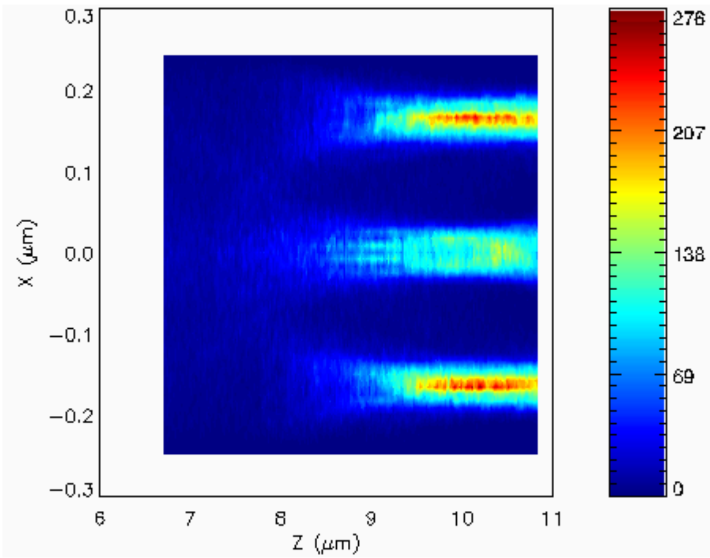
Experimental evidence

- Laser interaction with nanostructured materials can provide an alternative for femtosecond driven Gbar pressure.



Evidence of hot (3keV) dense (1E23 cm-3) volume plasma

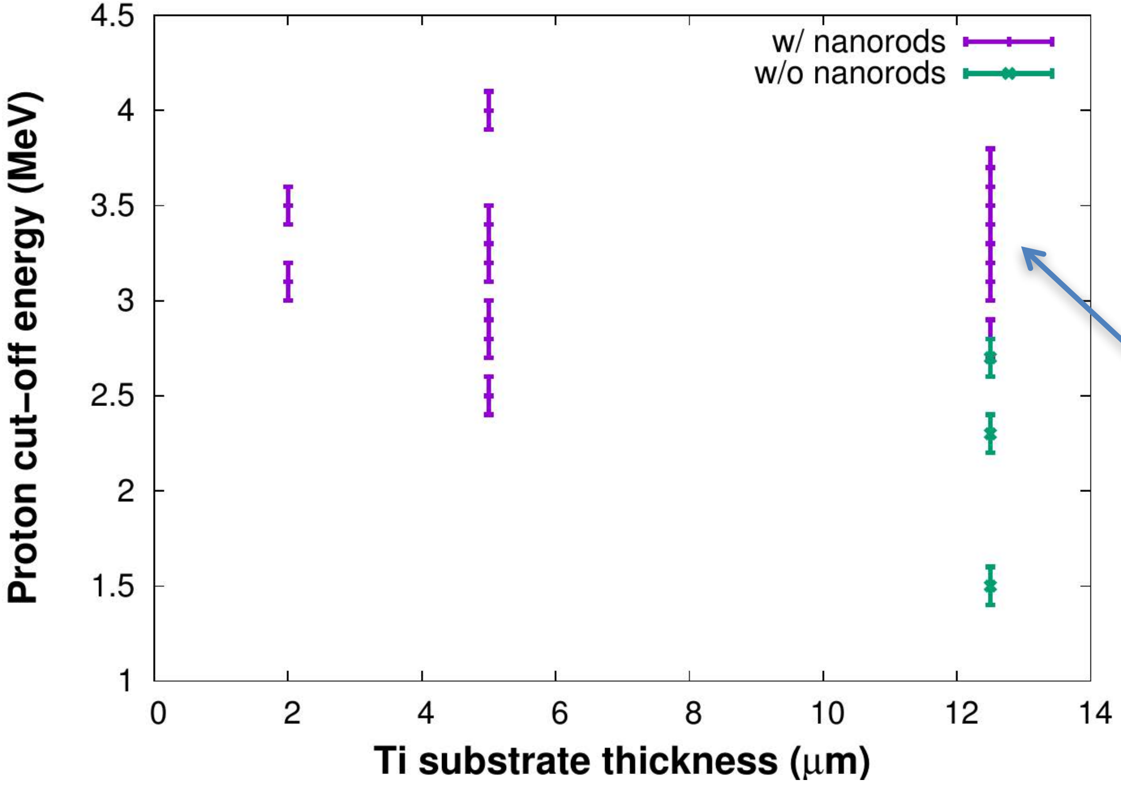
Irradiation of targets with a µm thick layer of packed nanostructures generates a high density plasma (Aladyn PIC simulations)

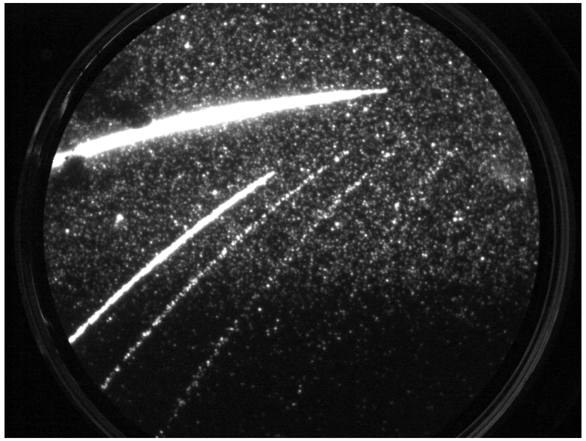


M. Purvis et al., Nat. Phot., 7(10), 796 (2013);
Bargsten et al. Sci. Adv. 2017;3: e1601558
G. Cristoforetti et al. *Sci. Rep.* (2017);

Enhanced ion energy

Protons cut-off energy with and without nanorods



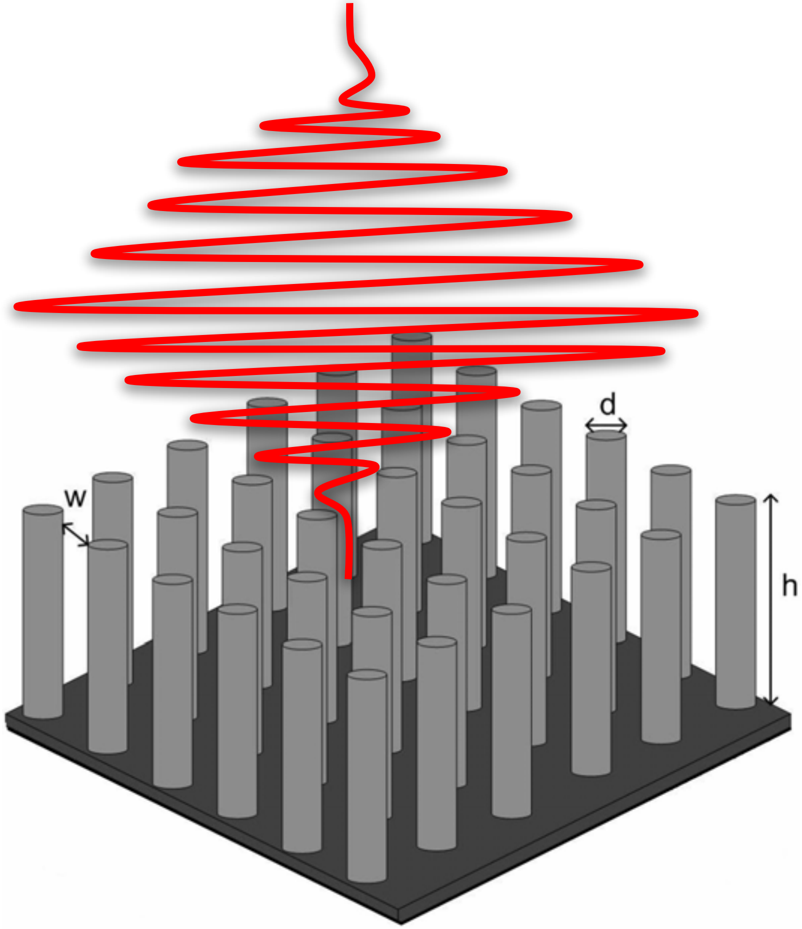


- Sytematically higher proton energy is achieved from targets with nanorods.

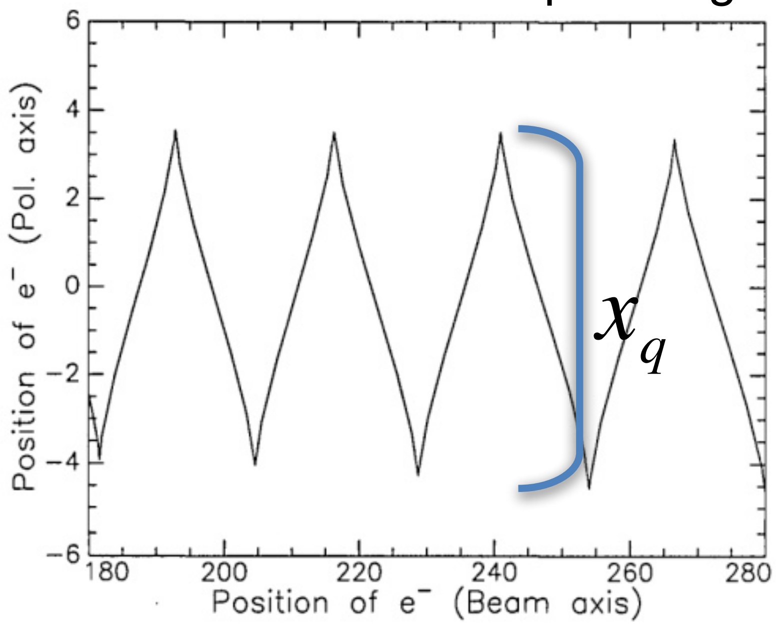
(*) Funded by LASERLAB, proposal SLIC 002112, PI L.A. Gizzi, participating teams CNR-INO Pisa, CNR-INO Sesto Fiorentino, CNR-INO Brescia, CNR-IMEM Parma, UniRoma1, UniBO, INFN-Bo, INFN-Pi, SLIC-CEA-Saclay

A simplified picture

Nanostructures geometry and survival plays a key role in the interaction process



Relativistic electron quivering



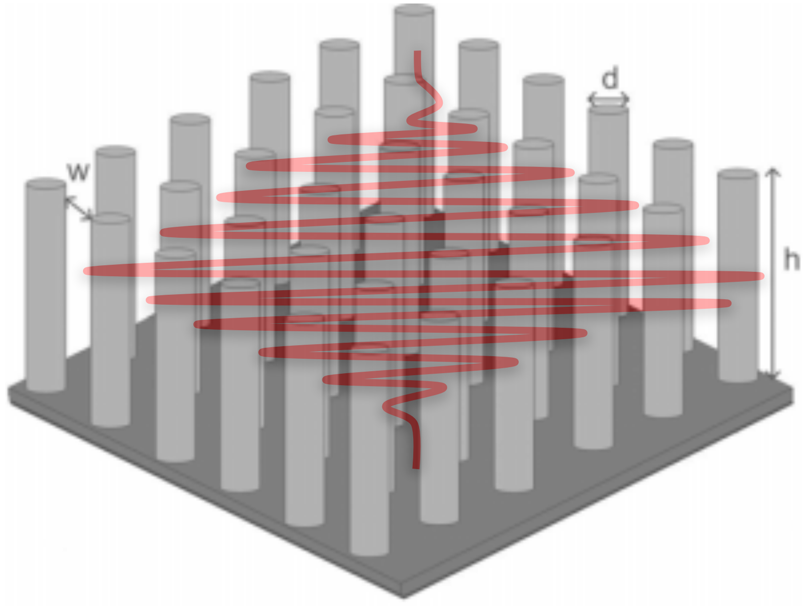
Ruling parameter

$$\delta = \frac{x_q}{w}$$

Collisional effects

1. Collisional effects are important: fast electrons wiggle through the nanowires and drive collisional impact ionization in the core of nanowires

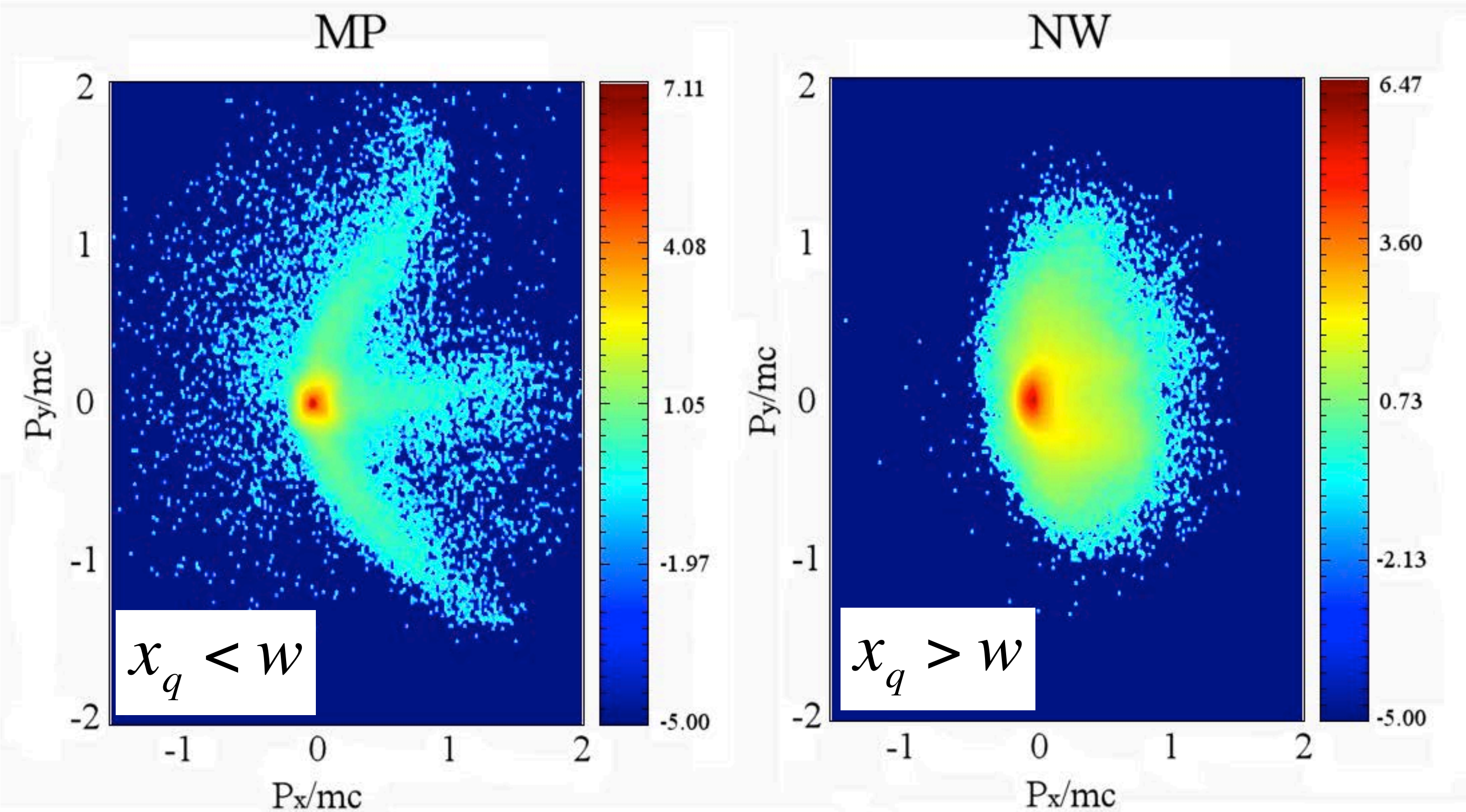
2. Ionization degree is higher than that produced by optical field ionization alone – this is particularly relevant for medium-higher Z targets



Modelling of this scenario needs full PIC with very fine temporal and spatial resolution and high density

Fast electrons (PIC)*

Momentum distribution of heated electrons depends strongly upon geometry



*Aladyn: C. Benedetti, A. Sgattoni, G. Turchetti, P. Londrillo, IEEE Trans. Plasma Sci., 36, 1790, 2008.

G. Cristoforetti et al. *Transition from Coherent to Stochastic electron heating,* 2016

Fast electrons

- In principle, target parameters could be tuned to control fast electron distribution in a highly absorbing scenario;
- Higher absorption leads to higher number of fast electrons;
- Optimum wire spacing may also lead to higher energy fast electrons => higher energy ions?
- Major computing effort is required to address these issues.

Conclusions

- Laser-plasma acceleration evolving towards precision start-to-end modelling with engineered laser-target configuration;
- Full PIC simulations are the standard for description and prediction. However, full PIC 3D of extended propagation is unfeasible (weeks of execution HPC);
- 3D requires approximation (e.g. fluid, envelope) currently under development;
- Ion acceleration from solid/smart targets still requires full PIC, plus increasing need of collisional effects (ionization);
- Accurate modelling may enable control over the fast electron distribution function: very challenging
- **L3IA** is preparing to explore these configurations to provide experimental proof of principle and cases of study for simulation.