Challenges in modeling beam driven plasma accelerators

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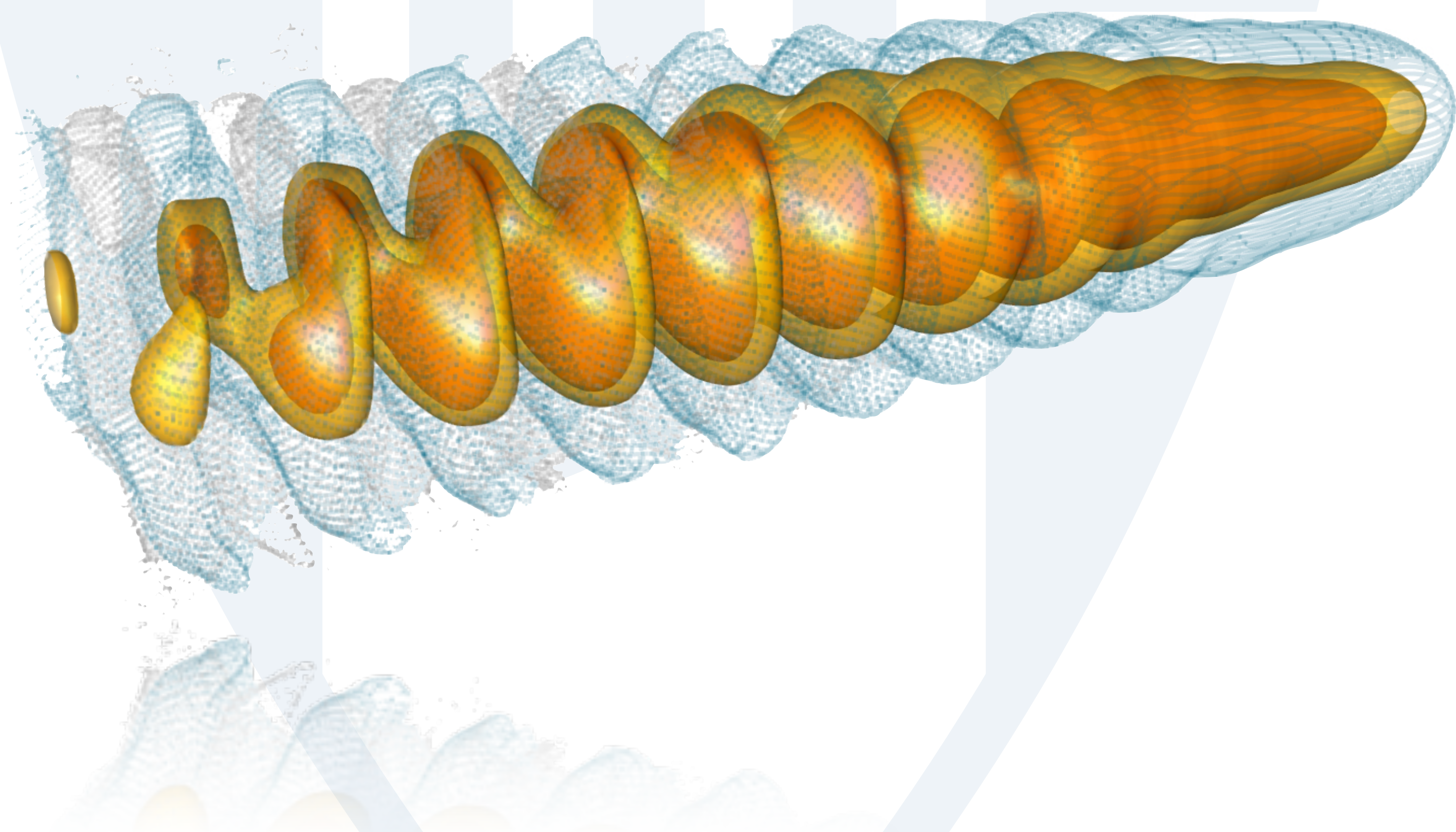

Contributions and acknowledgements

- Contributions from

  R. A. Fonseca, L. O. Silva (IST), P. Muggli (MPP), Y. Fang (USC), W. B. Mori (UCLA), S. Karsch (MPQ), A. Flacco, V. Malka (LOA)

- Simulation results obtained at

  IST Cluster (IST), Jüqueen (Jülich, Germany), SuperMUC (Munich, Germany), Jaguar (Oak Ridge National Laboratory)

FCT Fundação para a Ciência e a Tecnologia
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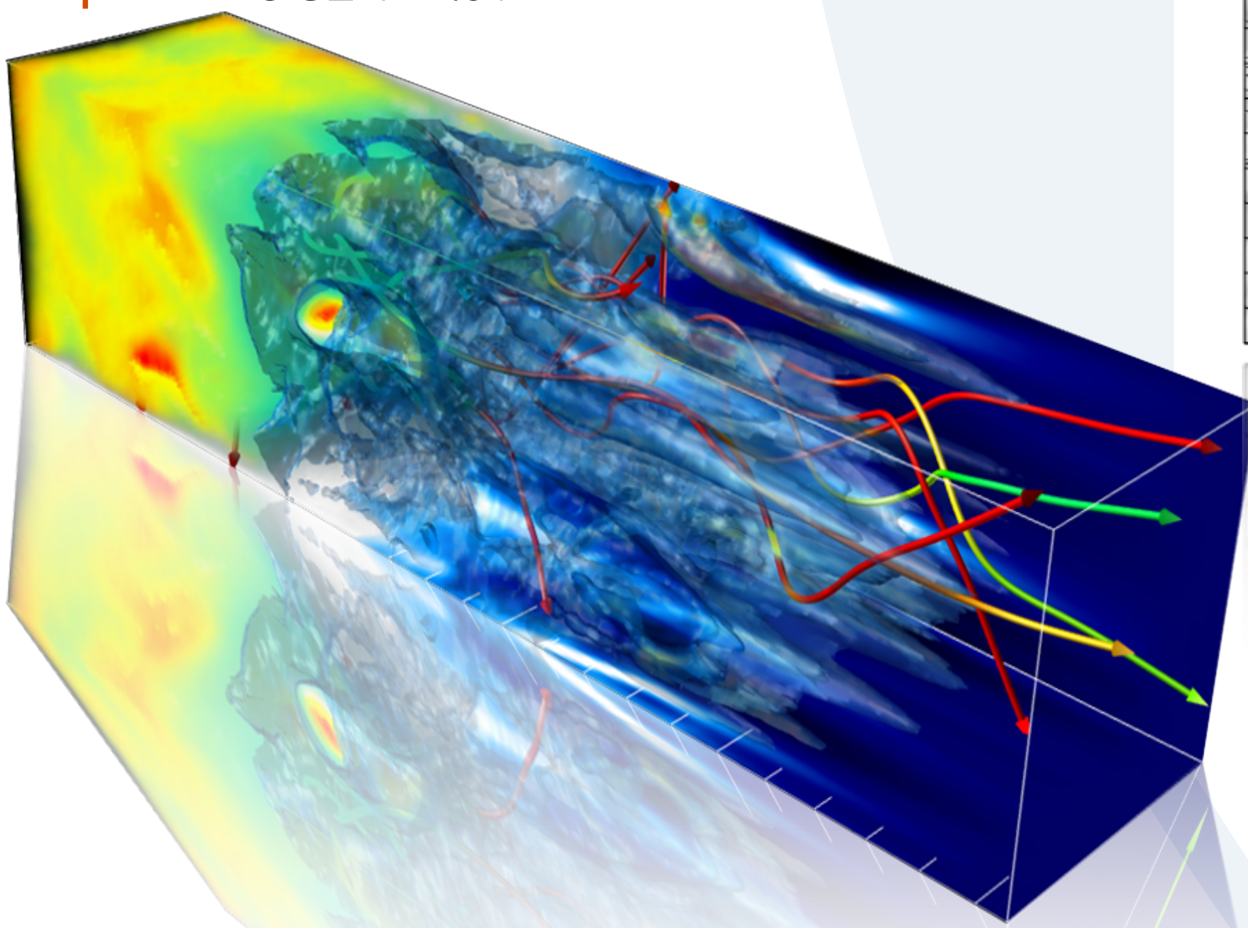
Oak Ridge National Laboratory
Managed by UT-Battelle for the Department of Energy

Alexander von Humboldt
Stiftung / Foundation

OSIRIS 2.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST



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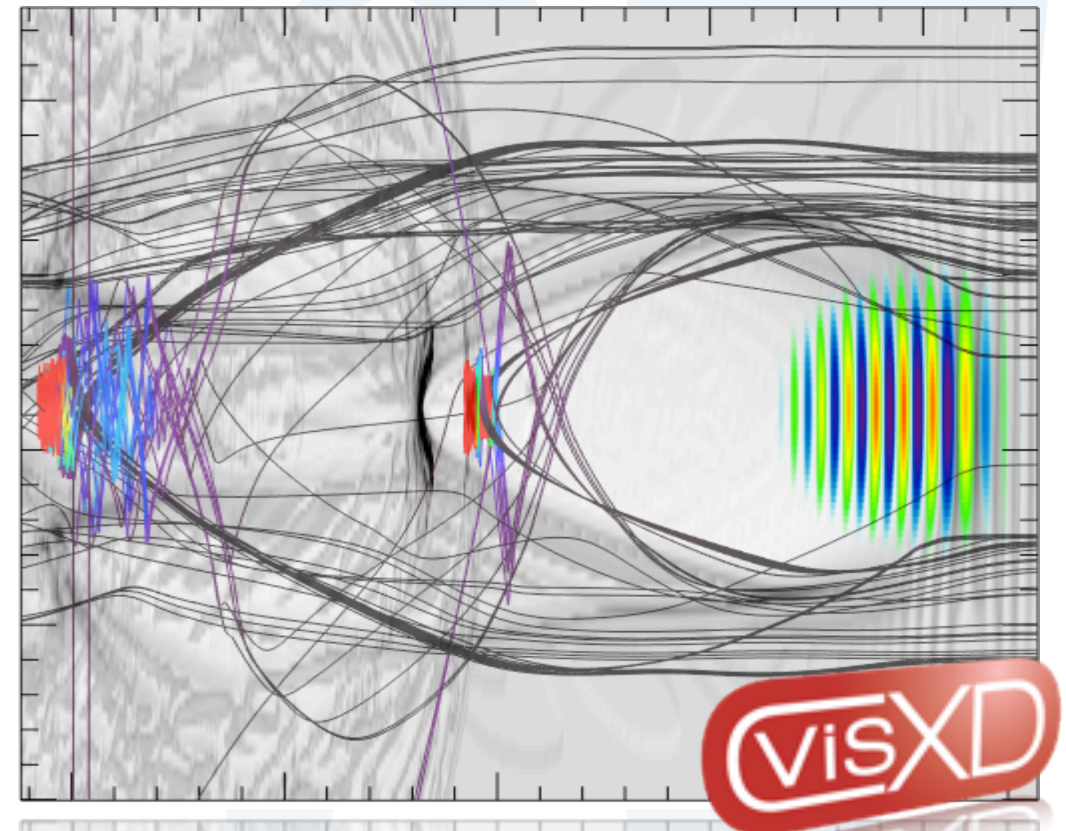


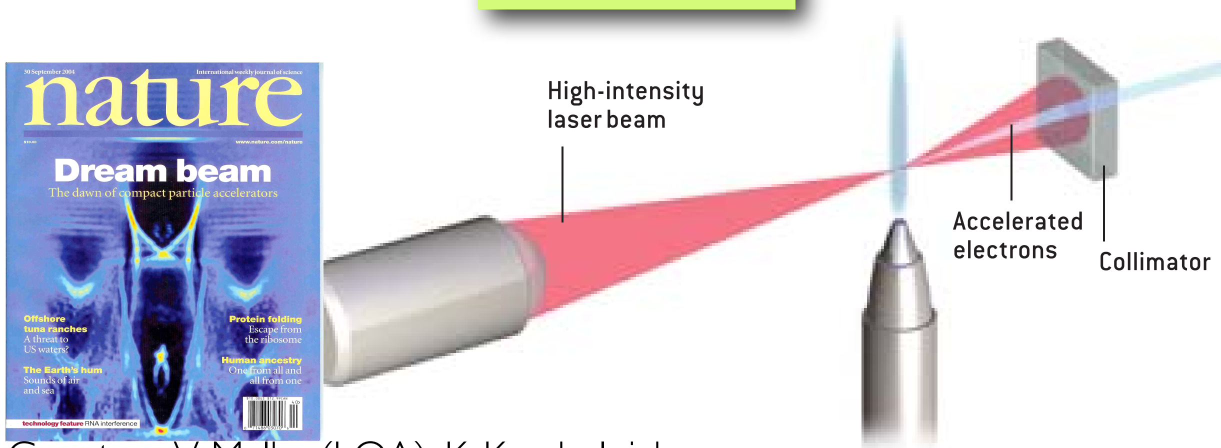
code features

- Scalability to ~300 K cores
- SIMD hardware optimized
- Tunnel (ADK) and Impact Ionization
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D
- Ponderomotive guiding center

Advancing plasma based wakefield acceleration requires synergistic approach between experiments and simulations

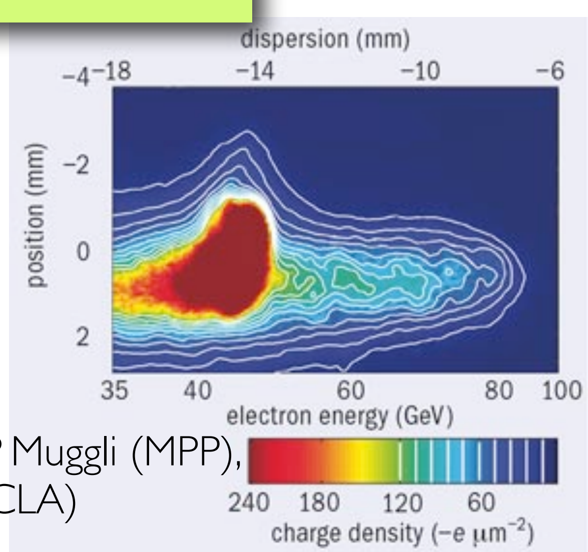
Experiments

LWFA



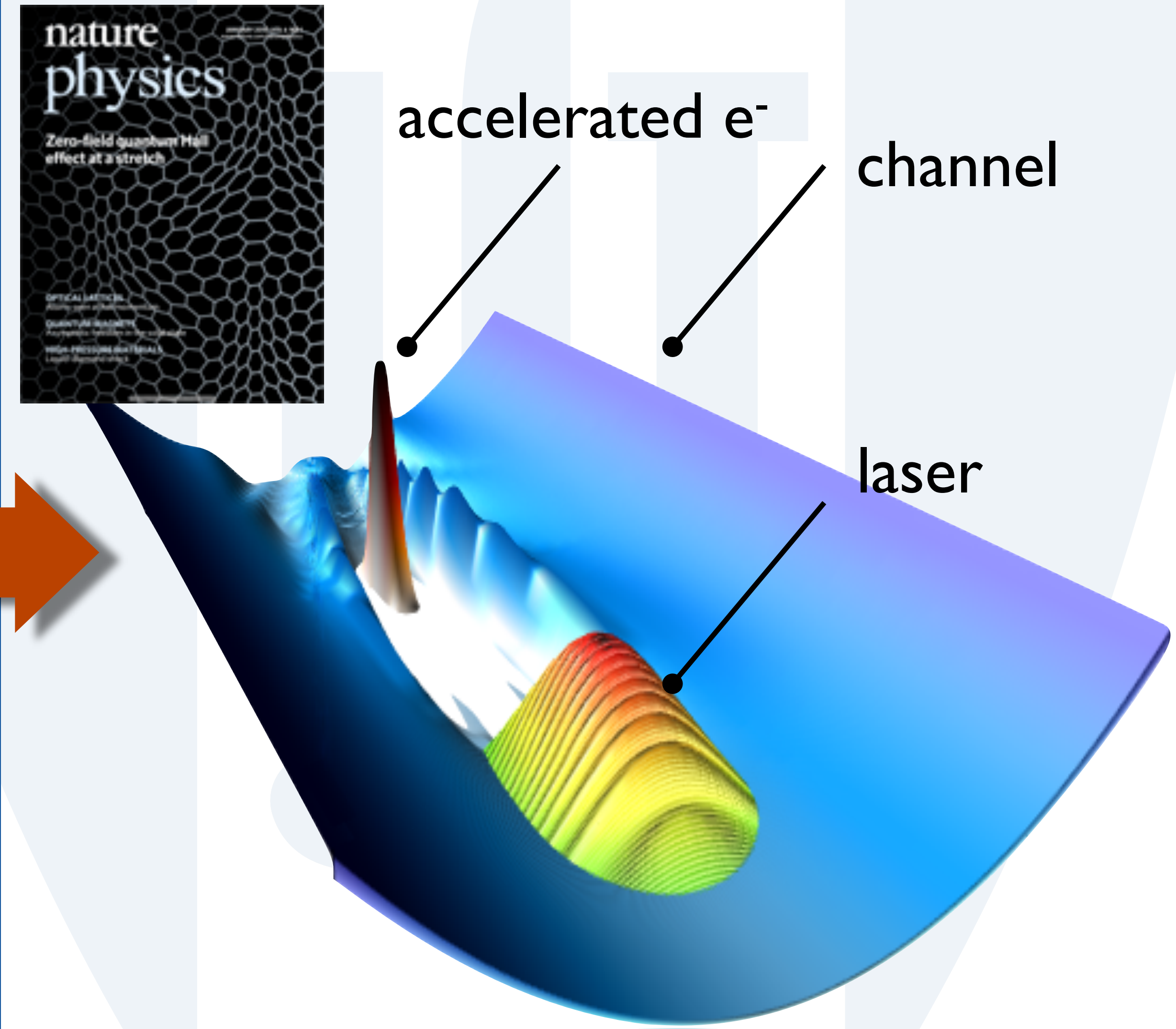
Courtesy: V. Malka (LOA), K. Krushelnick (IC/RAL), W. Leemans (LBL)

PWFA



Courtesy: P. Muggli (MPP), C. Joshi (UCLA)

Simulations



Courtesy: L. O. Silva (IST)

Challenges:

- accurate modeling/interpretation of state-of-the-art experiments
- designing near-future plasma-based wakefield acceleration experiments

Contents

Laser wakefield accelerators
Importance of laser profiles
Full scale modeling with boosted frames and envelope equation for laser

Self-modulated plasma wakefield accelerators
1-10 meter long plasma simulations of future proton and lepton driven experiments.

Conclusions

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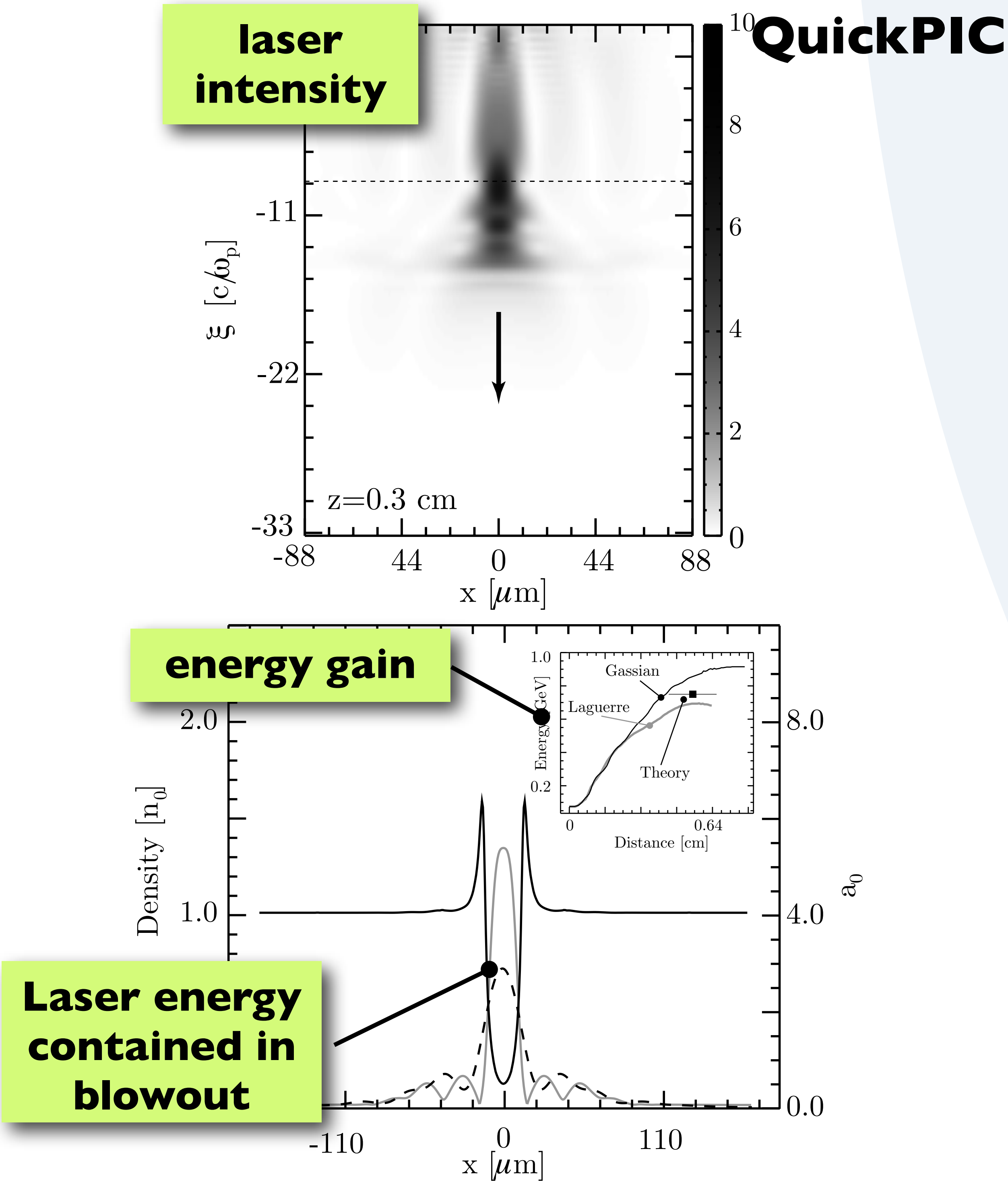
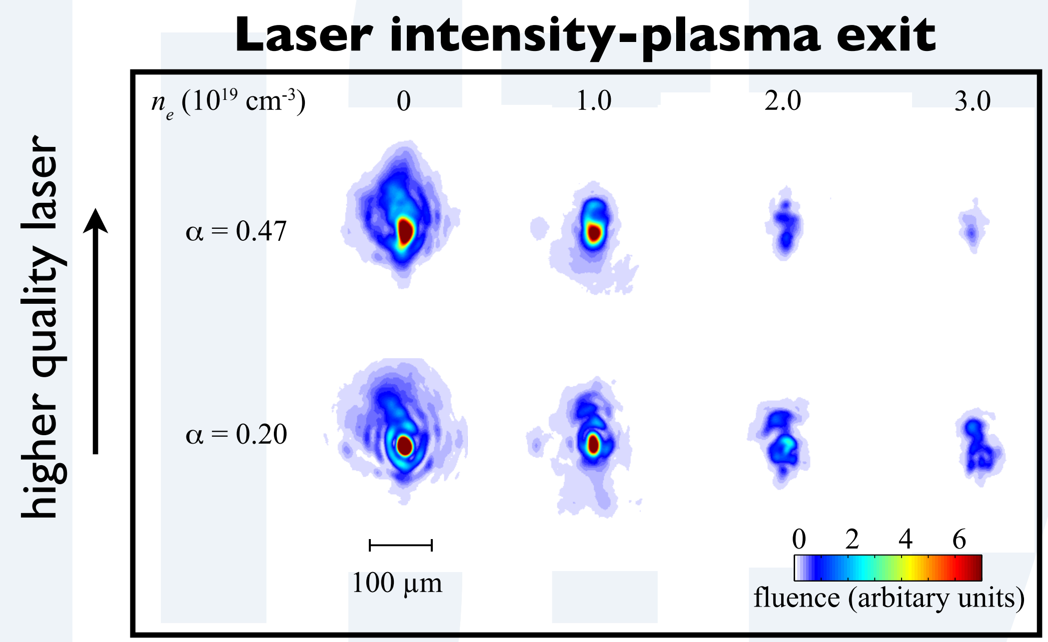
Understanding experimental results requires accurate description laser profile

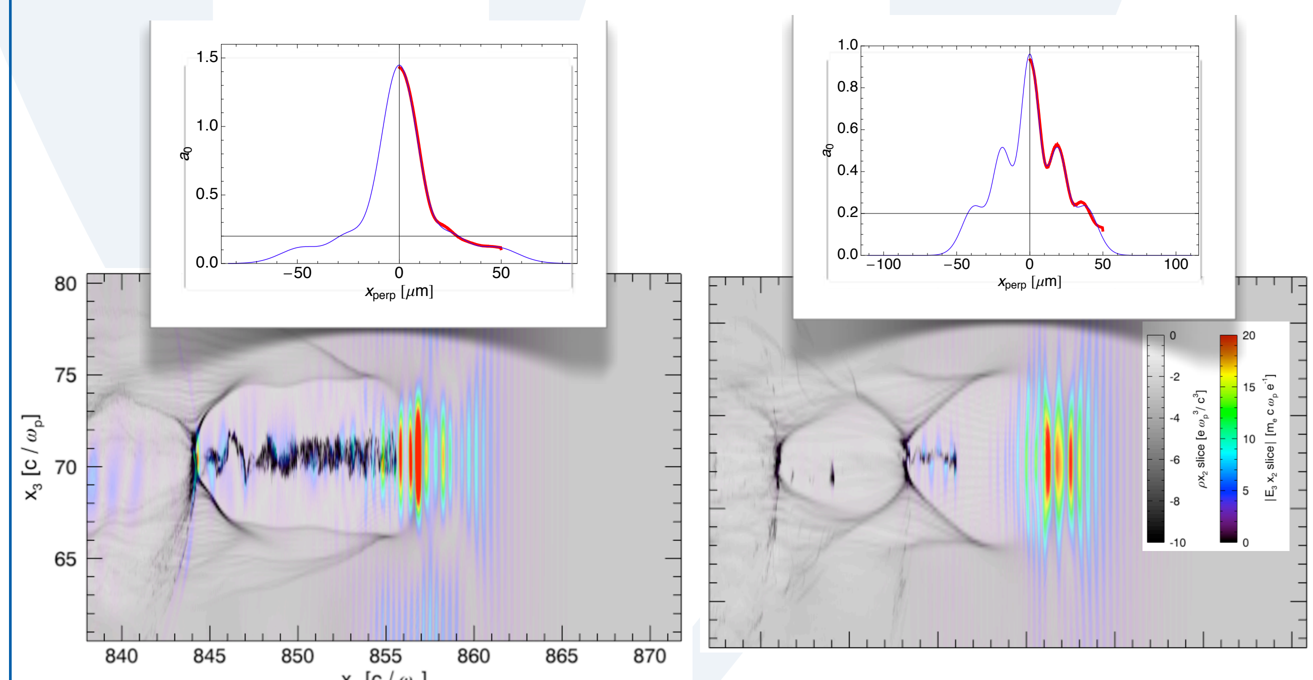
Final energies depend on initial laser profile



J.Vieira et al Plasma Phys. Control. Fusion (2012)

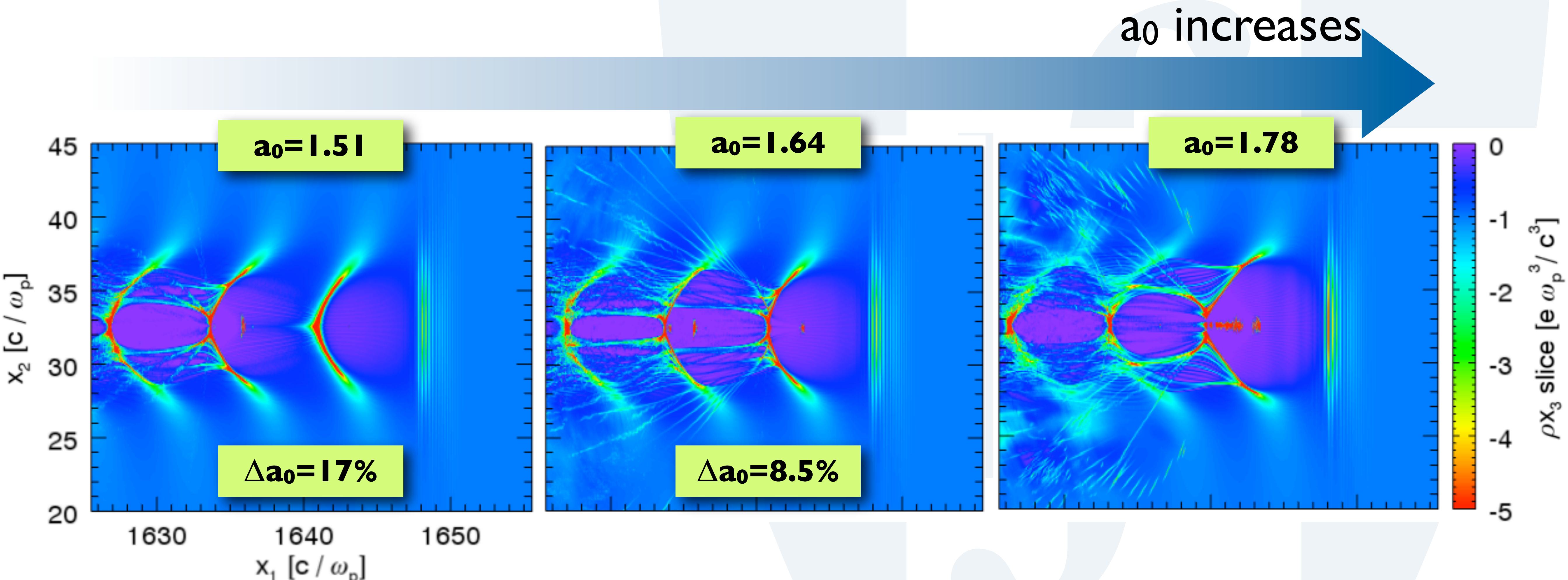
Recent exp. results explained by simulations





G. Genoud et al Phys. Plasmas (2013)

Knowledge of a_0 to % level accuracy required to reproduce experiments near threshold for self-injection



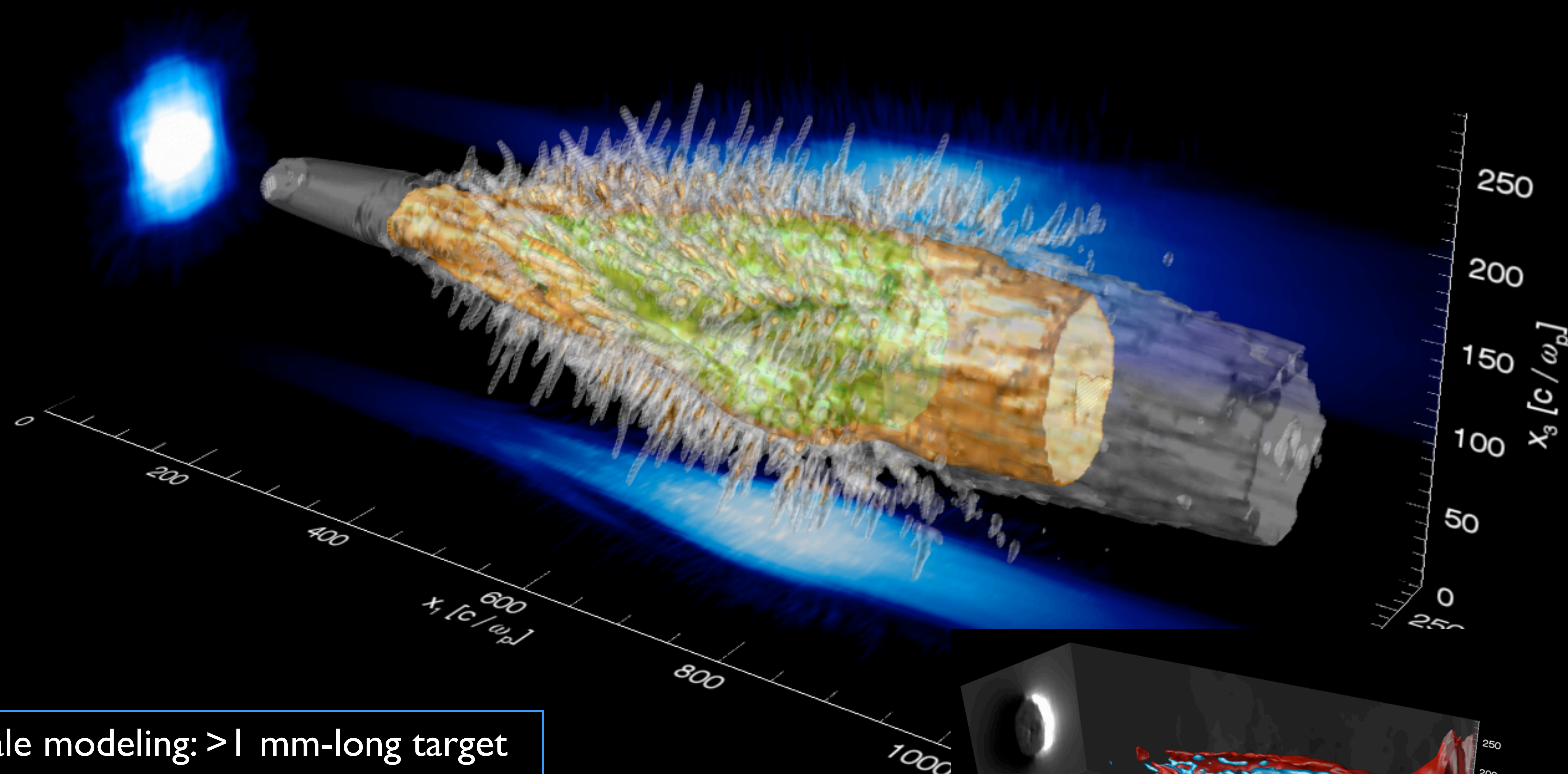
Short injection in second bucket

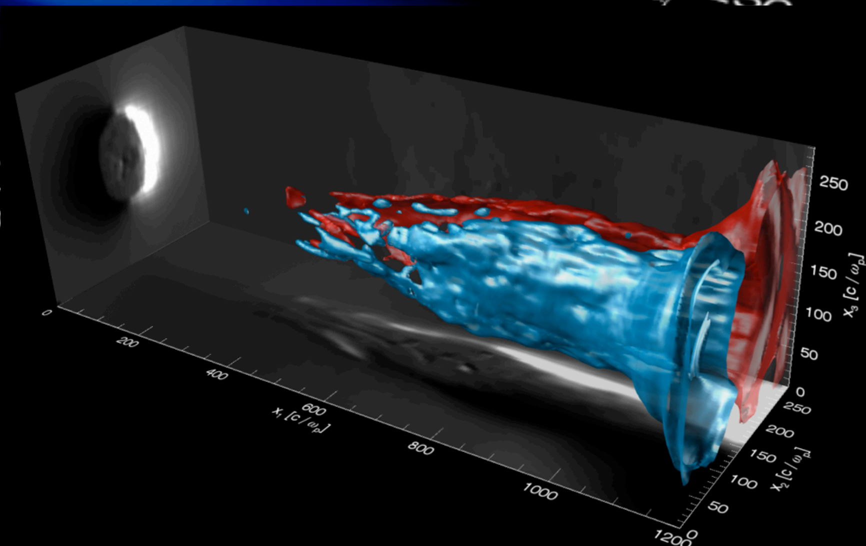
Short injection in first and second bucket

Continuos injection first bucket

Dark current suppression near self-injection threshold. Experiments with no dark current may be operating near threshold.

State-of-the-art LWFA modeling with full PIC: Full-scale 3Dof entire mm-long gas jets





- full-scale modeling: >1 mm-long target
- Multi-level ionization
- 3×10^{10} cells
- 6×10^{10} particles
- 3×10^{4} time-steps
- ~ 0.4 million CPUh/run

Full-scale 3D modeling of next generation LWFA experiments is very challenging

Laser is bottleneck for LWFA simulations

Accurate simulations resolve smallest structure

laser wavelength ~ 1 μm

cell size ~ 0.025 μm

Time step is bounded to cell size

c dt ~ 0.025 μm

1 m plasma ~ $1\times10^6/0.025$ dt's ~ **10^8 dt's**

Number of particle pushes

4 particles in each grid cell

$(10^6\times10^4)$part. $\times10^8$pushes~**10^{18} pushes**

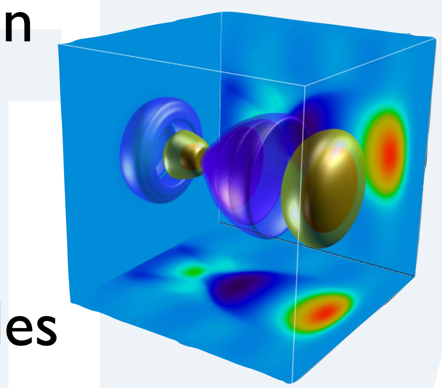
Simulation time and cost

$10^{18}\times1\mu s$ ~ **10 million CPU hours**

10million-CPUh*0.04Eur/CPUh ~ **100KEur!**

Reduced models

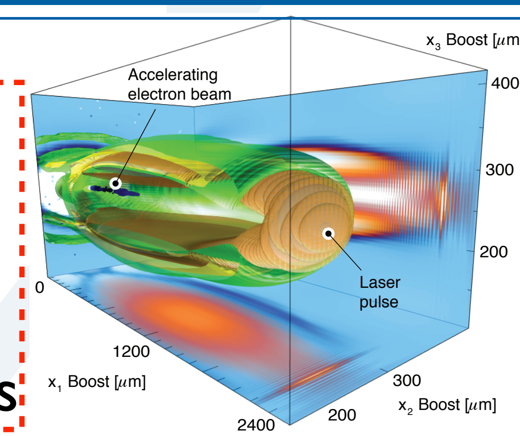
- Quasi-static approximation
- Ponderomotive guiding center approximation
- Expansion in Fourier modes



Full scale PIC

Boosted frames

- No approximations
- High comp. savings
- Large boost instabilities



Ponderomotive guiding center approximation

Ponderomotive guiding center algorithm

Laser pulse envelope equation:

$$\frac{\partial a}{\partial \tau} = \frac{1}{2i\omega_0}\left(1+\frac{1}{i\omega_0}\frac{\partial}{\partial \xi}\right)\left(\chi+\nabla_\perp^2\right) a$$

τ=t

laser frequency

laser envelope

Ponderomotive guiding center pusher:

$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}\tau} = q\left(\mathbf{E}+\mathbf{v}\times\mathbf{B}-\frac{1}{4}\frac{q}{\langle m\rangle}\nabla|a|^2\right)$$

slow varying momentum

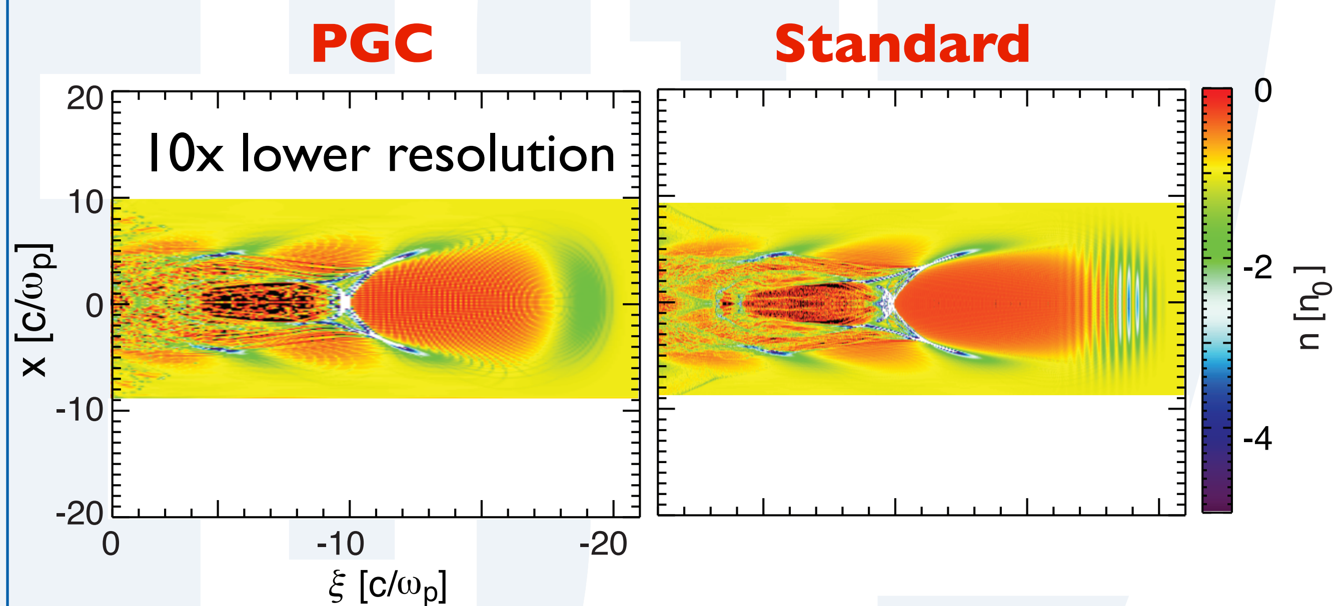
slow varying electric (**E**) and magnetic (**B**) fields

Features:

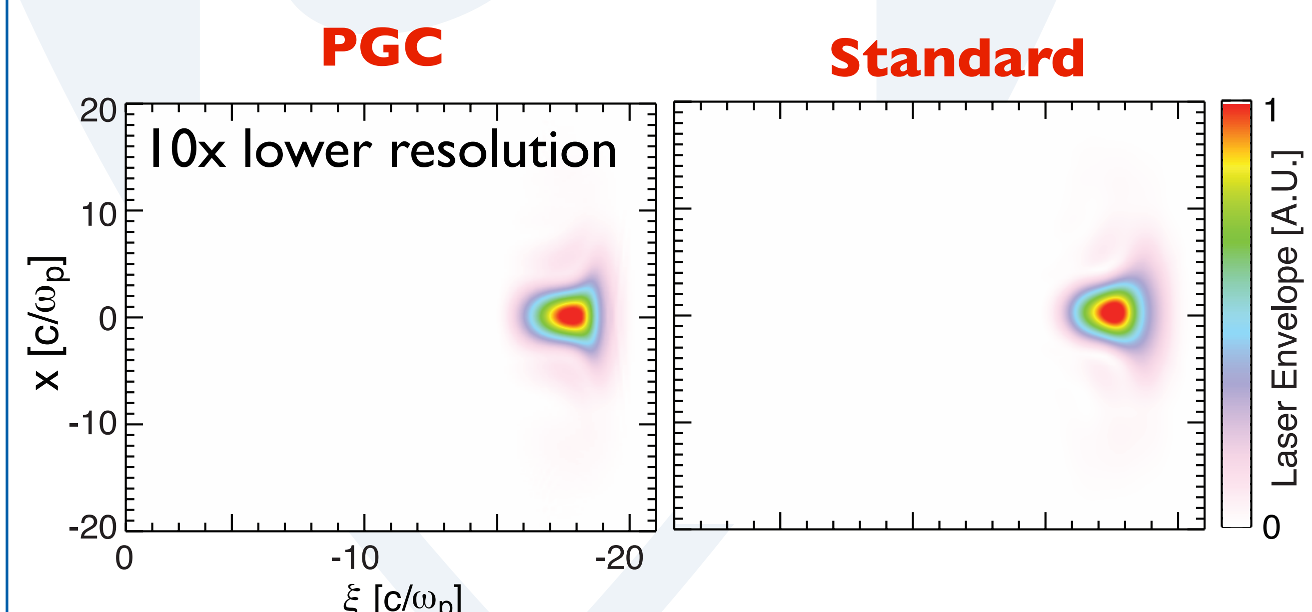
- ✓ Large boosted frame like computational savings (ω_0^2/ω_p^2)
- ✓ Ionization seeding for self-modulated wakefields in 10-100 meter plasmas
- ✓ Ionization energy depletion

Excellent agreement with standard Osiris

Blowout - plasma density t=0



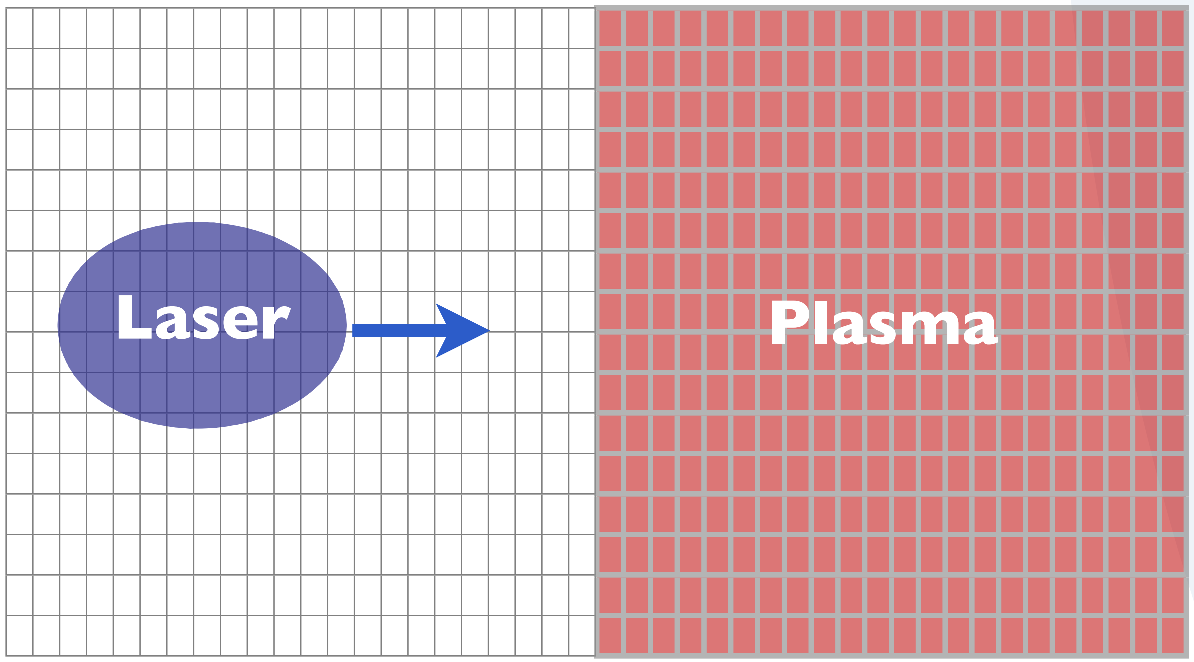
Blowout - laser t~Z_r/2



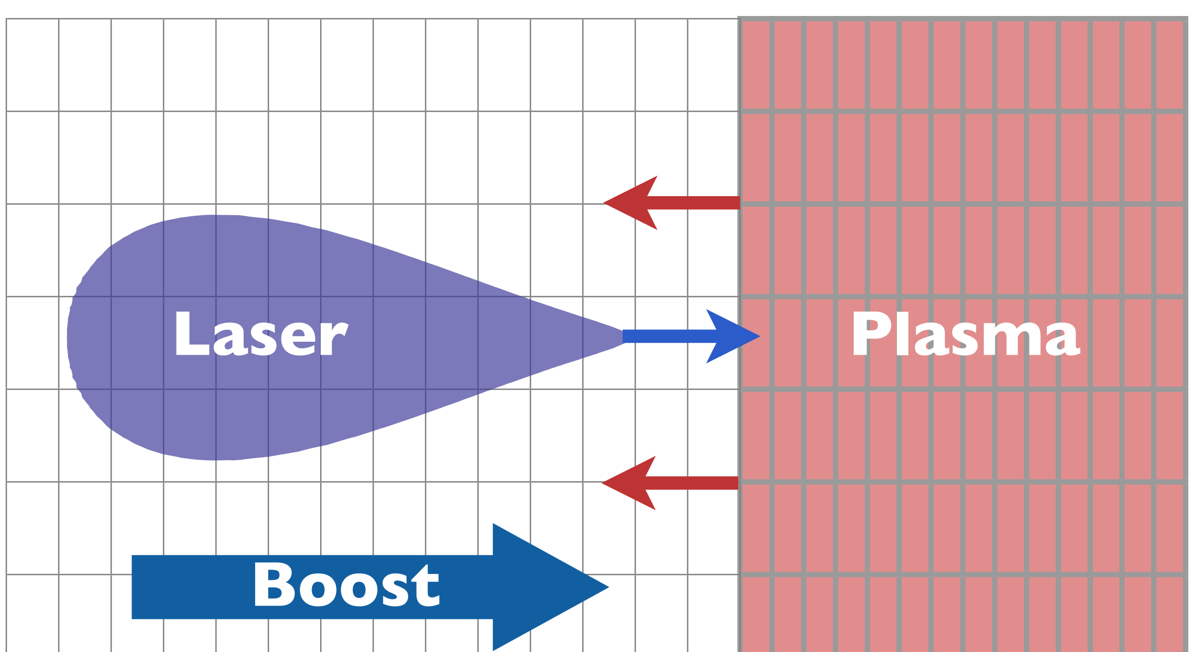
D. Gordon, W. Mori, T. Antonsen, IEEE-TPS, **28** 1135-1143 (2000).

Boosted frame simulation set-up

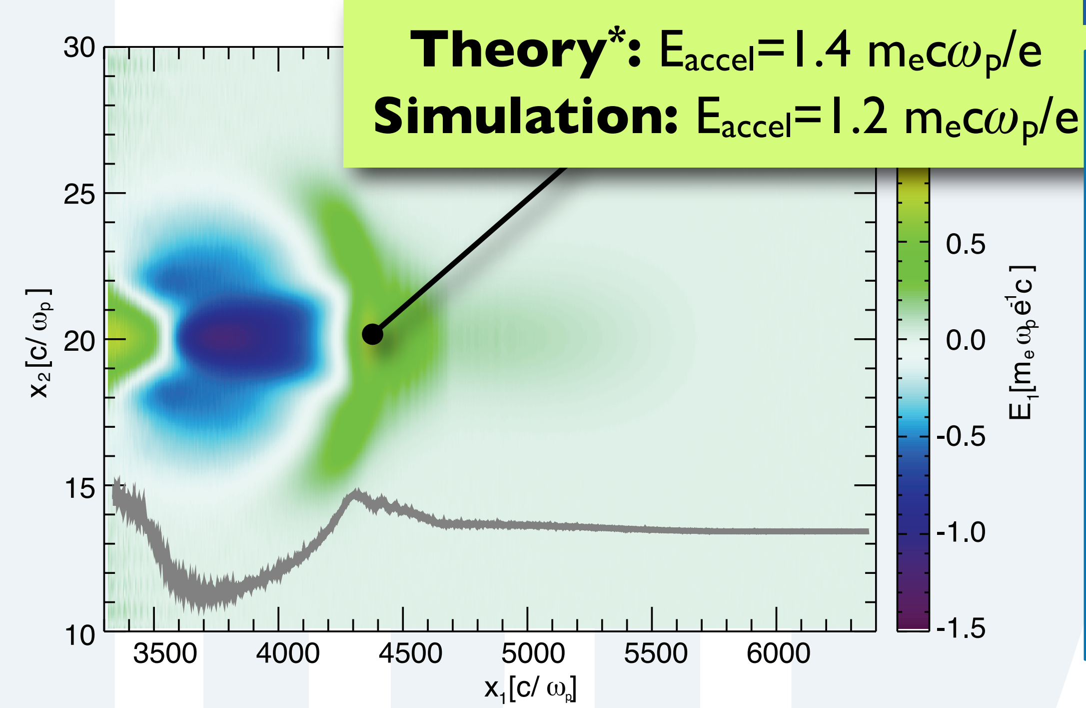
Lab frame simulation

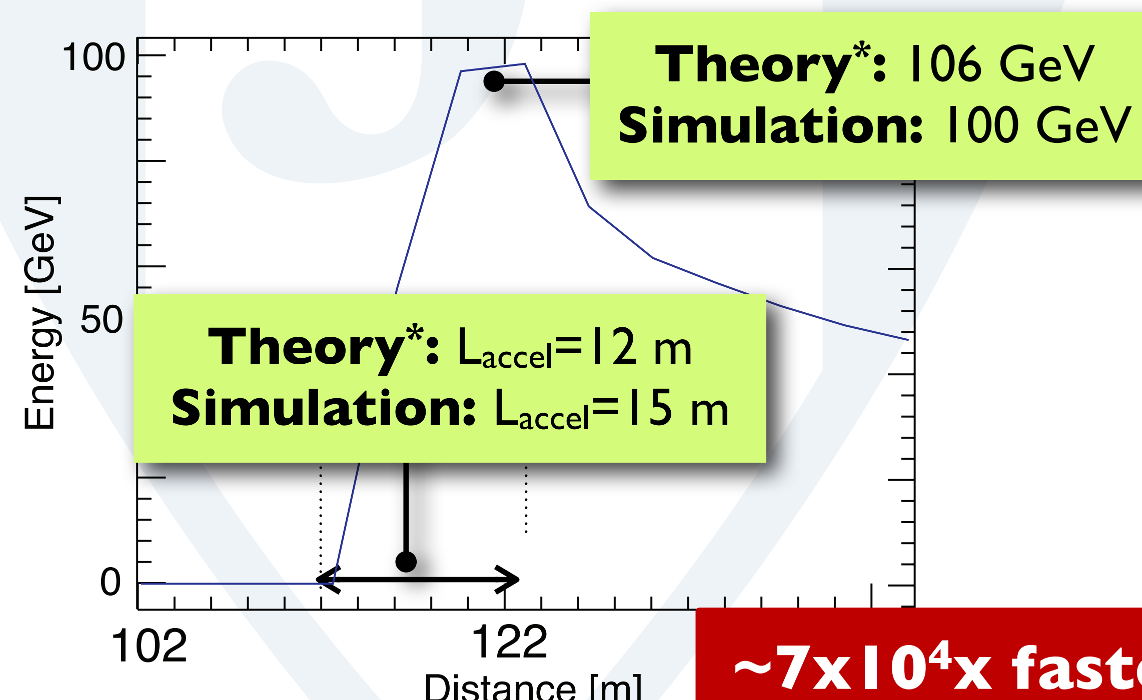


Boosted frame simulation



Simulations with $\gamma^{boost} \sim 400$





~7x10⁴x faster than lab.

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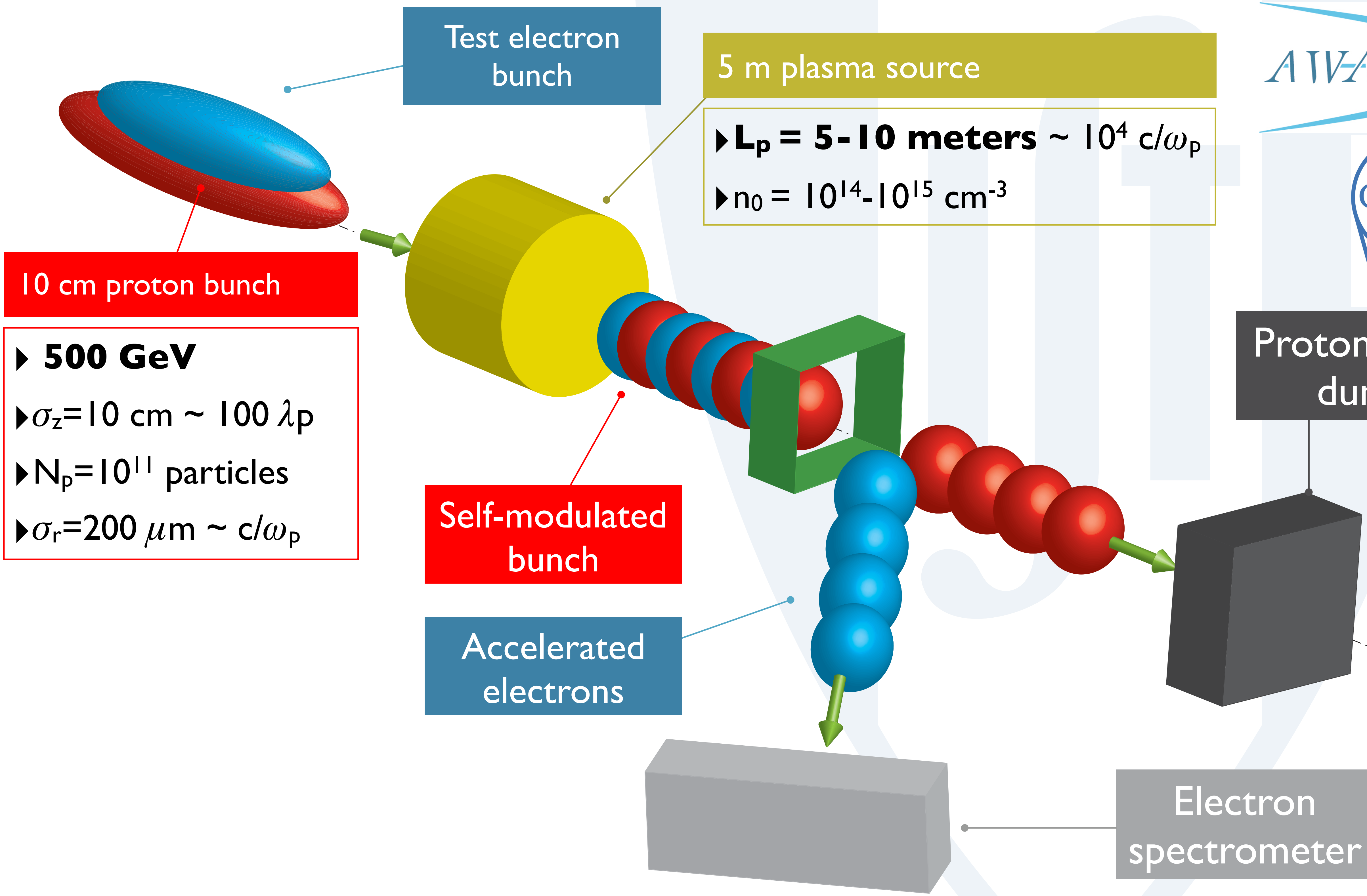
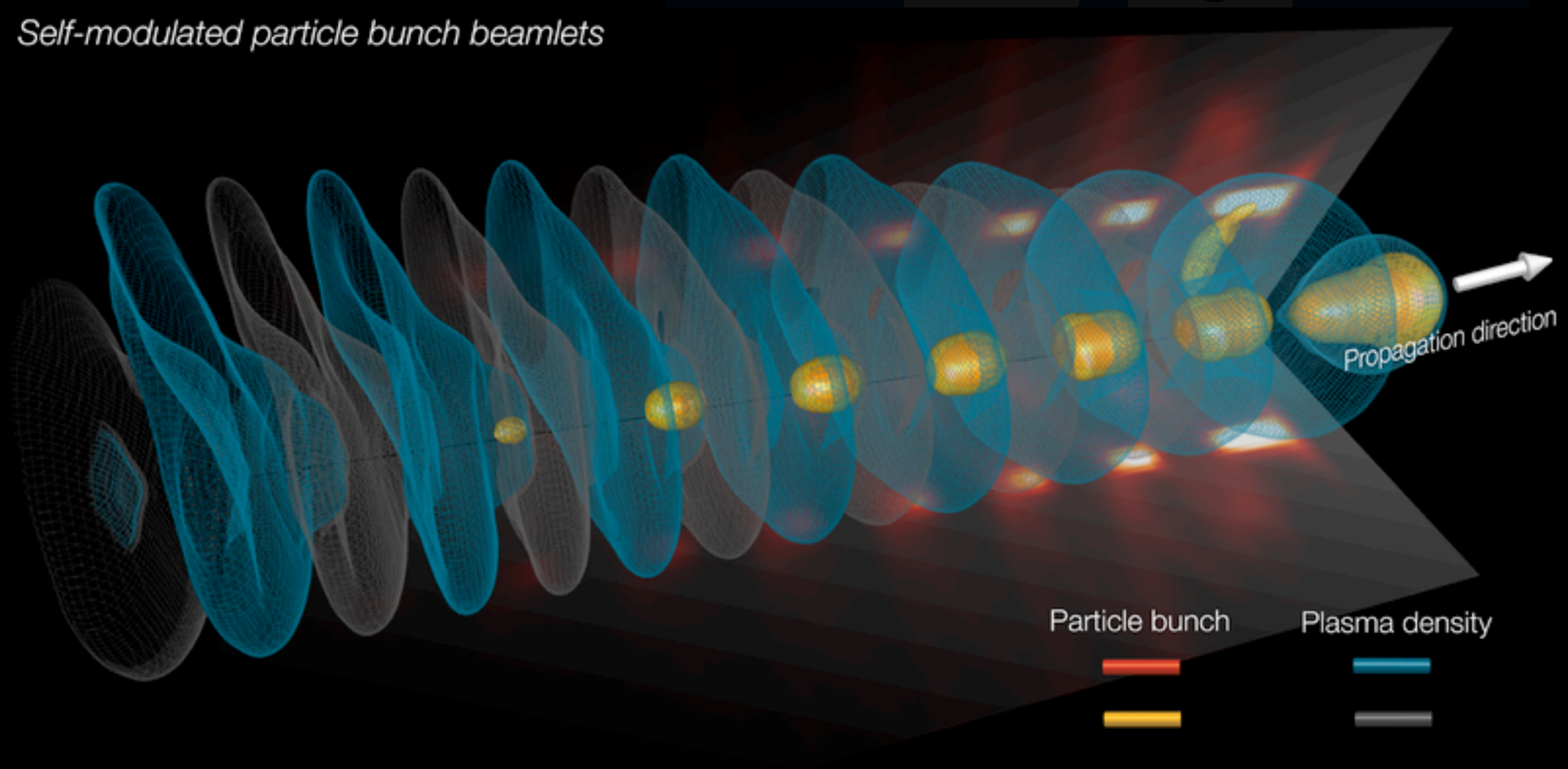
Self-modulated proton driven wakefield accelerator
Experiment at CERN to occur in 2-4 years



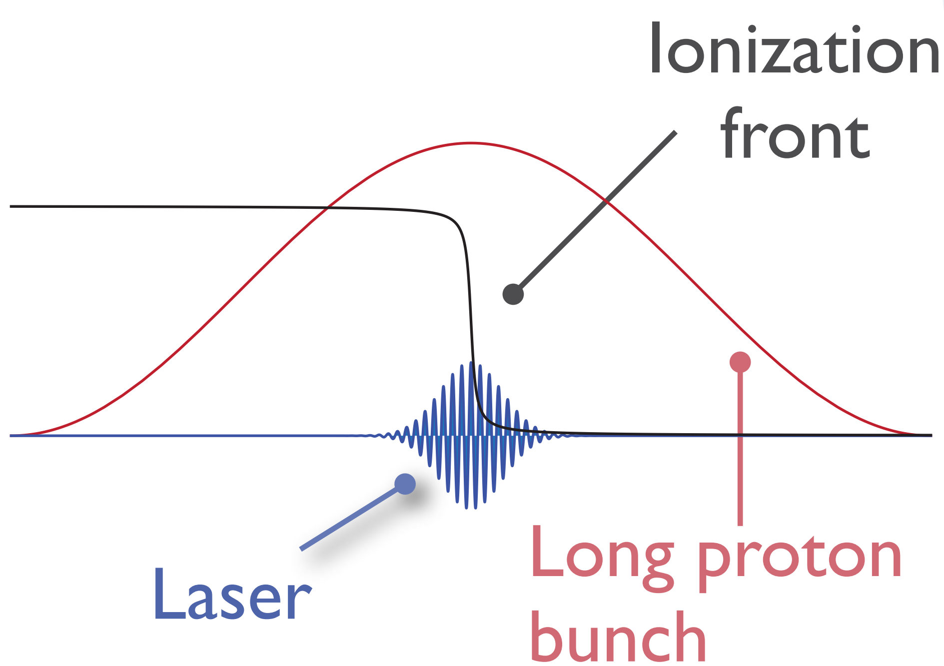
N. Kumar et al PRL **104** 255003 (2010)
C. Schroeder et al PRL 107 145002 (2011)
A. Pukhov et al PRL 106 145003 (2011)

Self-modulation instability in 3D



Creating plasma and cut proton bunch simultaneously
Ionizing laser pulse

Ionization seeding is similar to cut bunch

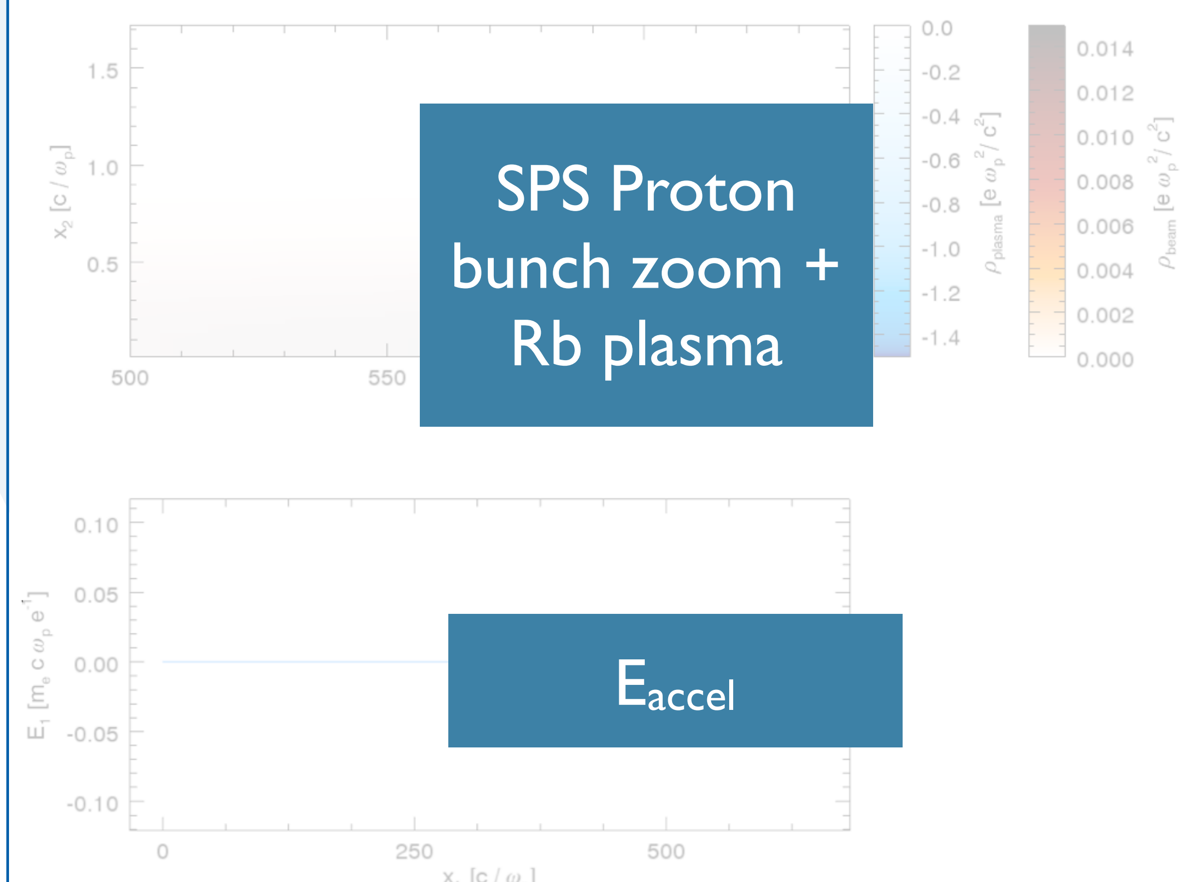


- Laser pulse creates ultra-relativistic ionization front
- Ionization front acts as if long proton bunch is sharply cut giving initial kick to plasma e⁻s
- Resolving 1 micron laser wavelength for 10 meters requires Ponderomotive Guiding Center Approximation

D. Gordon et al, PRE, **64** 046404 (2001).

Rubidium ionization and SMI seeding

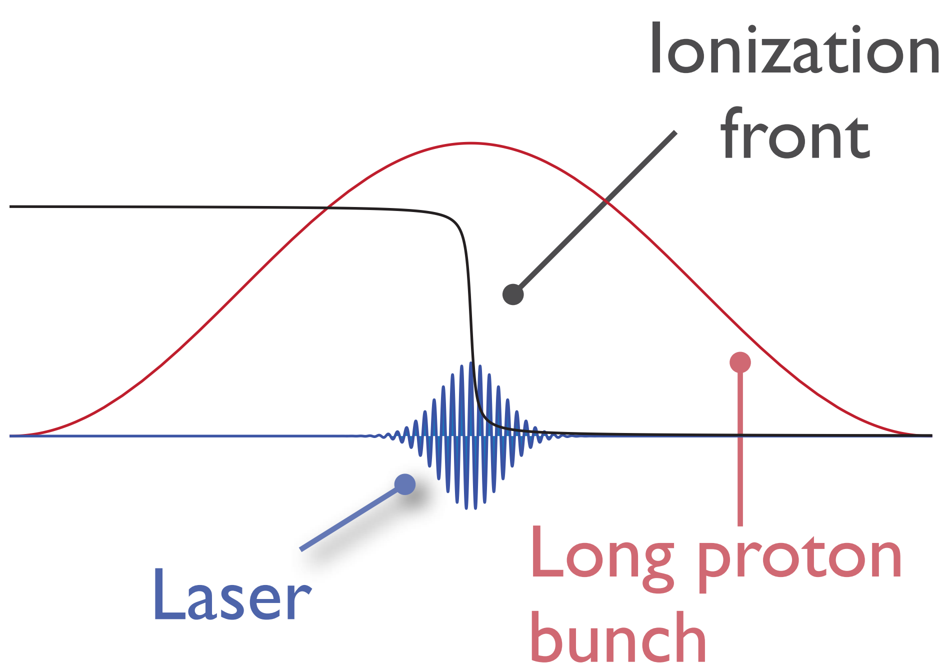
I :: 5×10^{13} W/cm^2
τ :: 700 fs
W_0 :: 1 mm
E :: 1 J



Immobile ions to avoid ion motion
J.Vieira et al PRL **109** 145005 (2012)

Creating plasma and cut proton bunch simultaneously
Ionizing laser pulse

Ionization seeding is similar to cut bunch



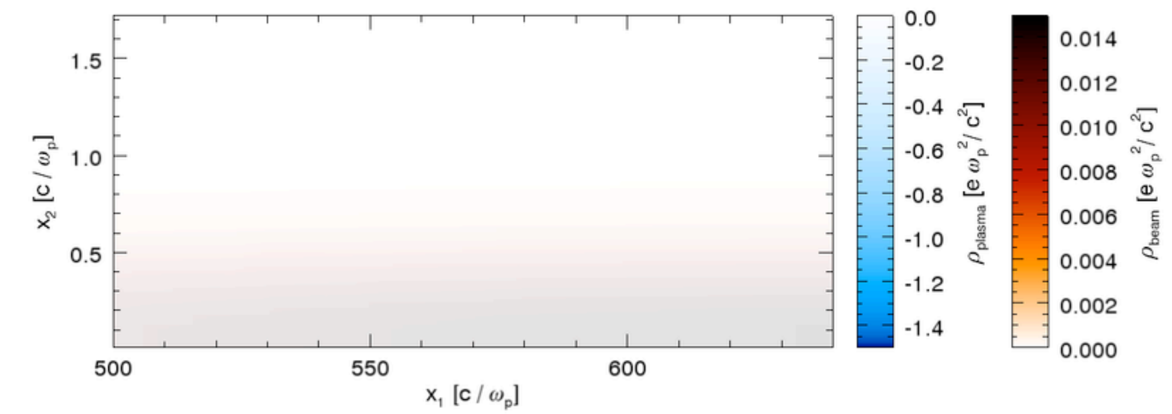
- Laser pulse creates ultra-relativistic ionization front
- Ionization front acts as if long proton bunch is sharply cut giving initial kick to plasma e⁻s
- requires **0.1-1.0 J** laser pulses for Rubidium (high Z material)

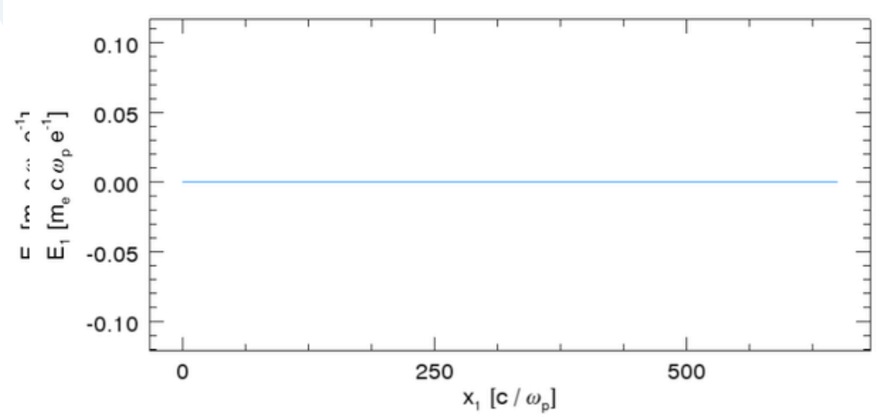
D. Gordon et al, PRE, **64** 046404 (2001).

Rubidium ionization and SMI seeding

I :: 5×10^{13} W/cm^2
τ :: 700 fs
W_0 :: 1 mm
E :: 1 J

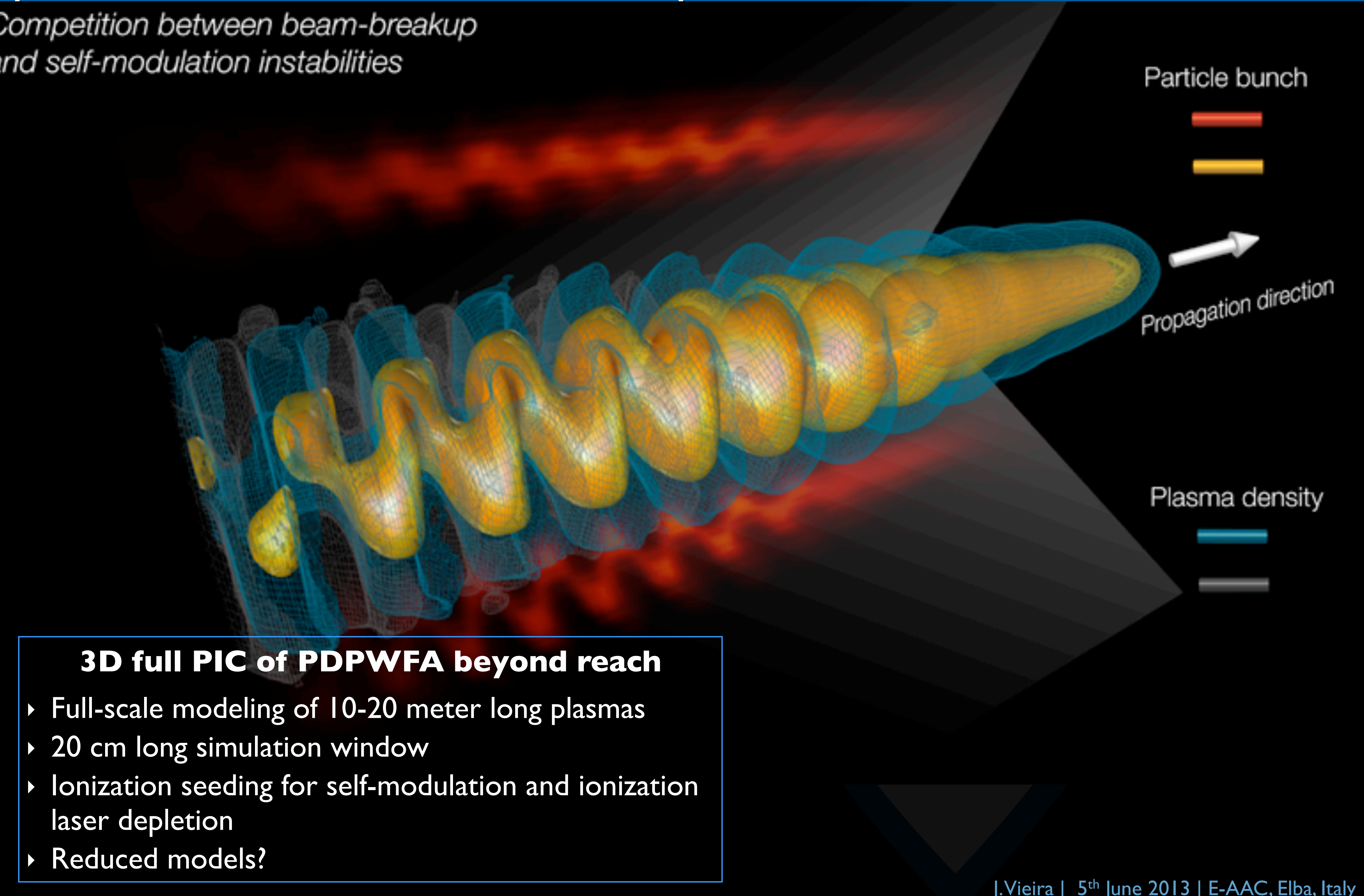
>100000x faster than full PIC!





Immobile ions to avoid ion motion
J.Vieira et al PRL **109** 145005 (2012)

Study of beam break-up instabilities in self-modulated plasma wakefield accelerators requires 3D simulations

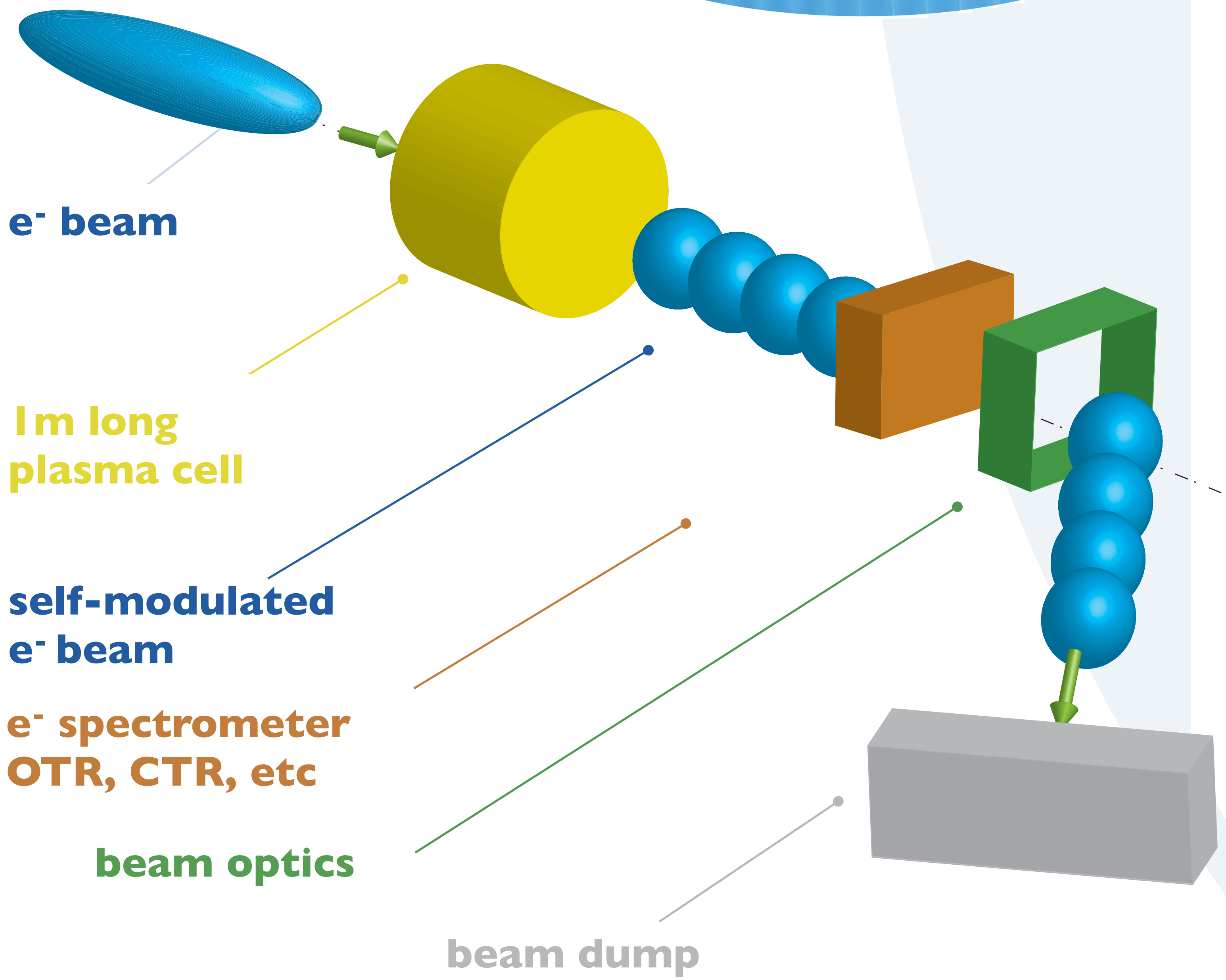


3D full PIC of PDPWFA beyond reach

- Full-scale modeling of 10-20 meter long plasmas
- 20 cm long simulation window
- Ionization seeding for self-modulation and ionization laser depletion
- Reduced models?

E209 SLAC FACET self-modulation experiment of long e^- and e^+ beams

P. Muggli, J. Vieira et al,
E209 experiment
(SLAC/FACET)



Self-modulation @ SLAC

- n_0 :: 2.3 x 10^{17} cm^{-3}
- γ_b^{SLAC} :: 4x10^4
- σ_z^{SLAC} :: 700 μm = **60 λ_p**
- $(n_b/n_0)^{SLAC}$ :: **0.01-0.1**

Goals

- Measure self-modulation instability
- Competition between hosing and self-modulation
- Role of ion motion, etc.

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Laser wakefield acceleration

- Accurate descriptions of laser intensity profile are critical for excellent agreement between theory and simulations
- Boosted frames + ponderomotive guiding center algorithms enable high computational savings

Self-modulated plasma wakefield acceleration

- Self-modulation vs hosing competition requires 3D simulations
- 3D modeling of proton driven wakefields with full PIC is beyond reach
- Ponderomotive guiding center: ionization seeding including extra physics (ionization laser energy depletion, etc.)
- Reduced models for 3D: Quasi-static, Hybrid. **Is physics the same?**