# Status on plasma accelerators R&D [Portugal 2011]


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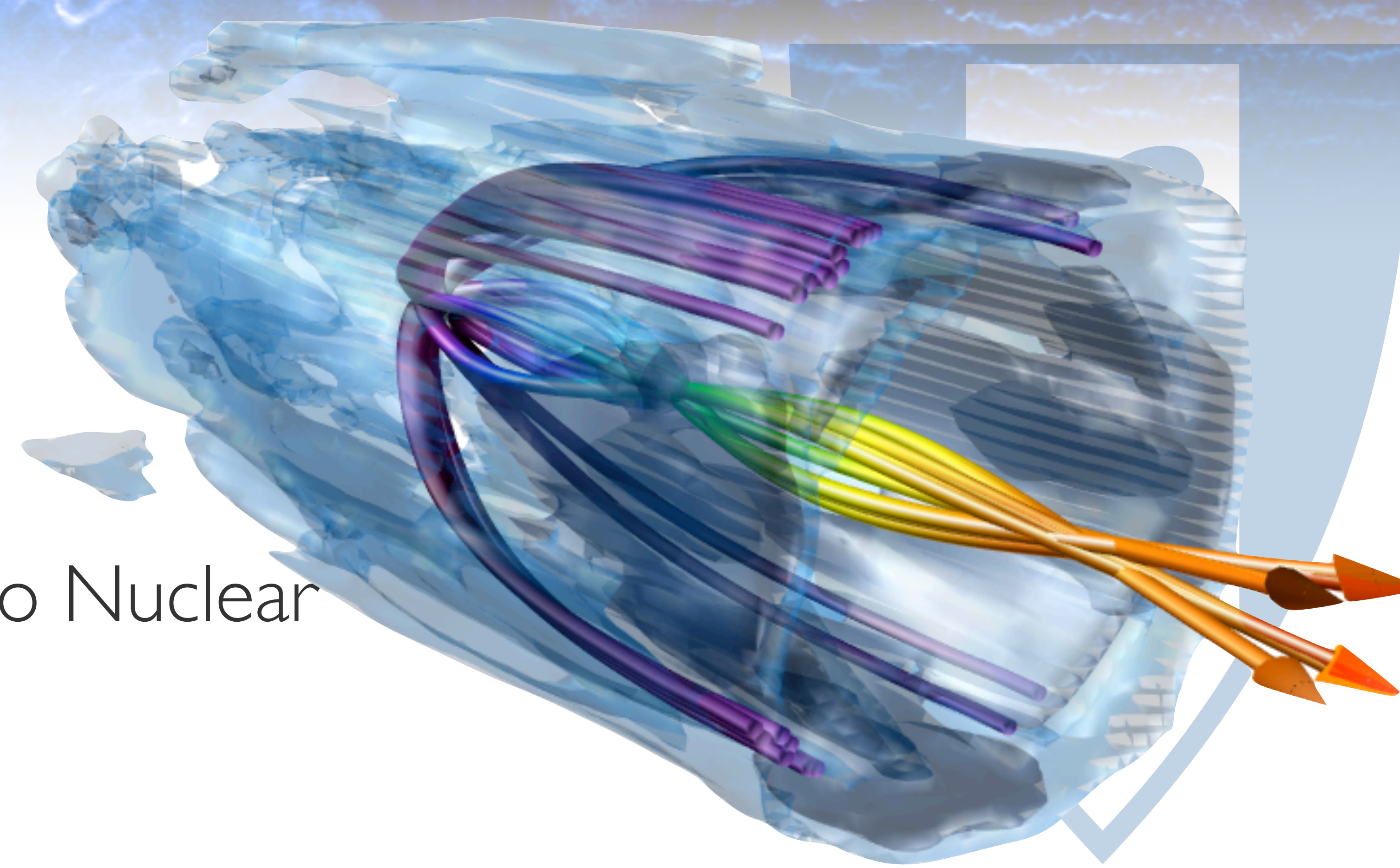
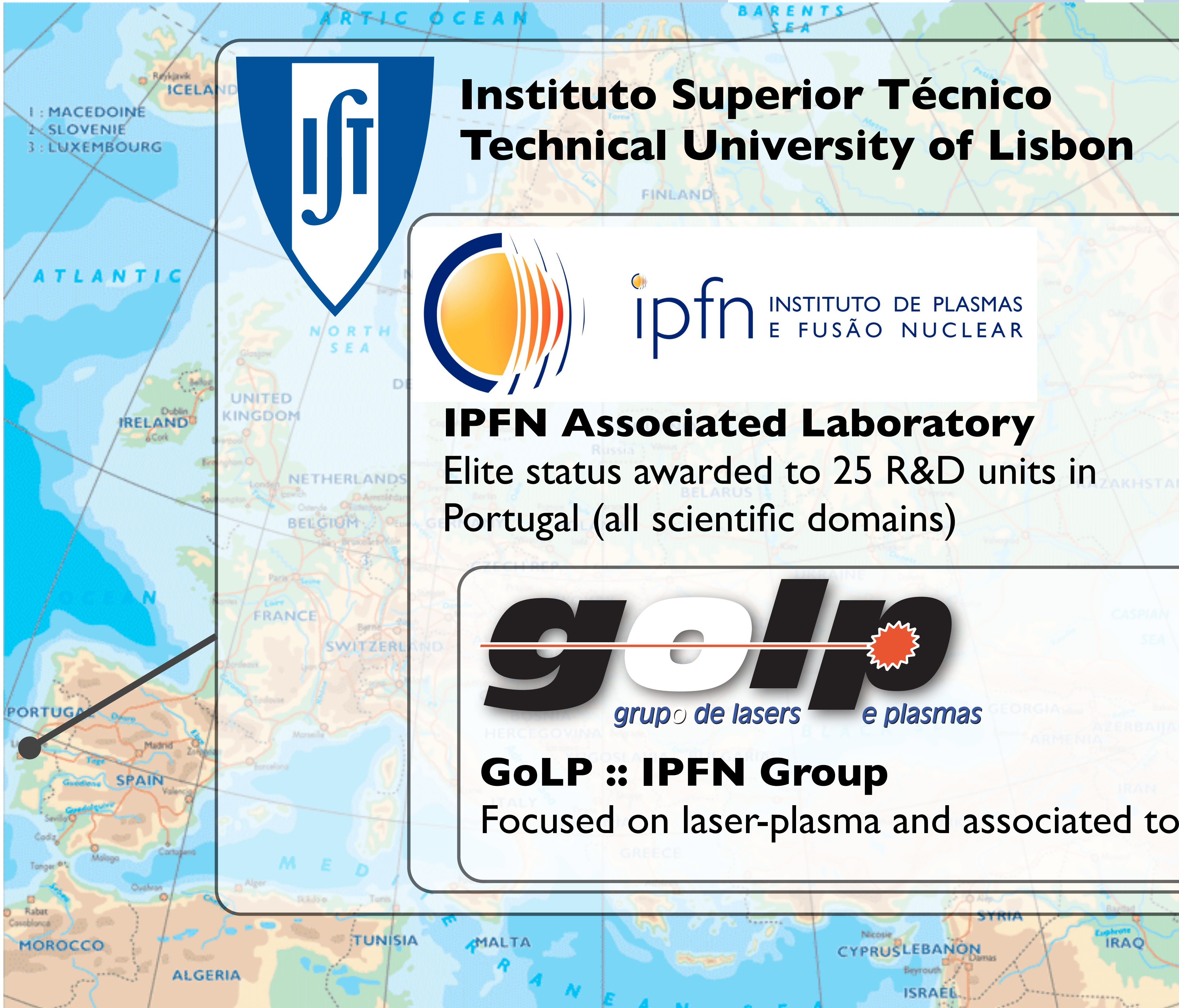
*Lisbon*
***Portugal***

GoLP/IPFN Instituto Superior Técnico

ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

# Institutional context




**Instituto Superior Técnico**
**Technical University of Lisbon**

ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

**IPFN Associated Laboratory**

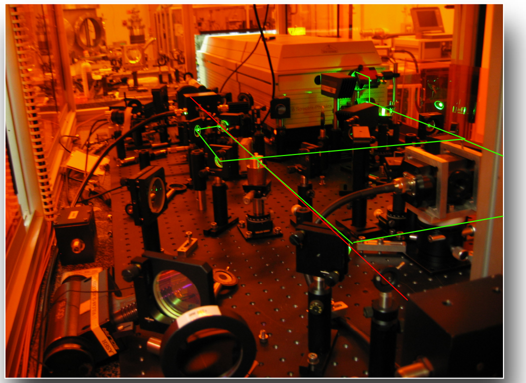
Elite status awarded to 25 R&D units in Portugal (all scientific domains)

golp grupo de lasers e plasmas

**GoLP :: IPFN Group**

Focused on laser-plasma and associated topics

# Available resources



## Laboratory for Intense Lasers

A unique facility with a wide range of optical, IR, VUV, X-ray, particle diagnostics, target zones for HHG, channels, laser-gas/solid interactions with +10 TW laser pulses in the 100s fs range


## Software infrastructure for plasma simulations

Massively parallel PIC codes (from full PIC to hybrid) **+** a in-house developed visualization infrastructure (visXD + servers + mini-portal) **+** software development/versioning tools (e.g. Subversion)

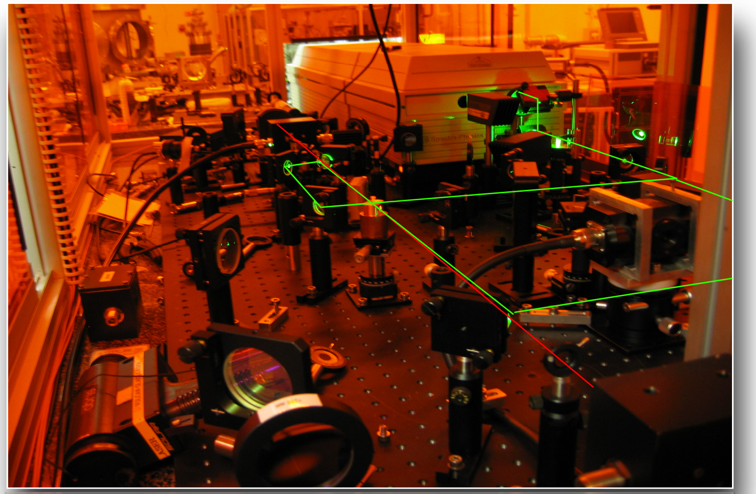

## Access to supercomputers

CPU hours in excess of 30 M CPU hours/year on a wide variety of massively parallel machines, ranging from local clusters (e.g. IST cluster) to supercomputers in Europe and in the US

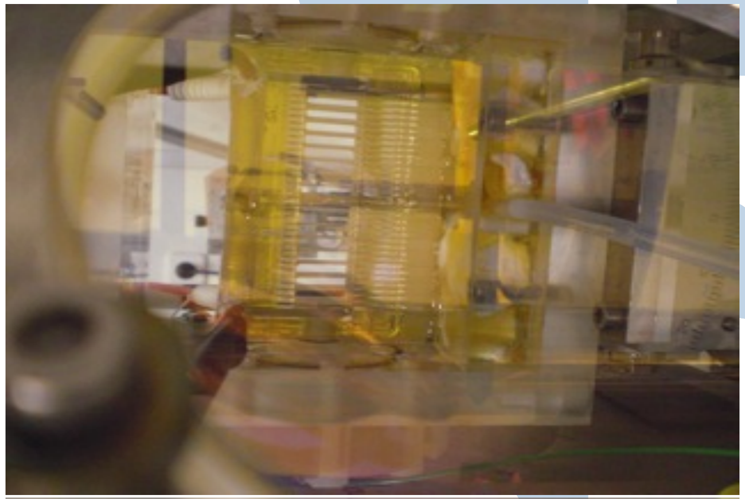
# Focus areas for activities in plasma accelerators

**Key questions to address**

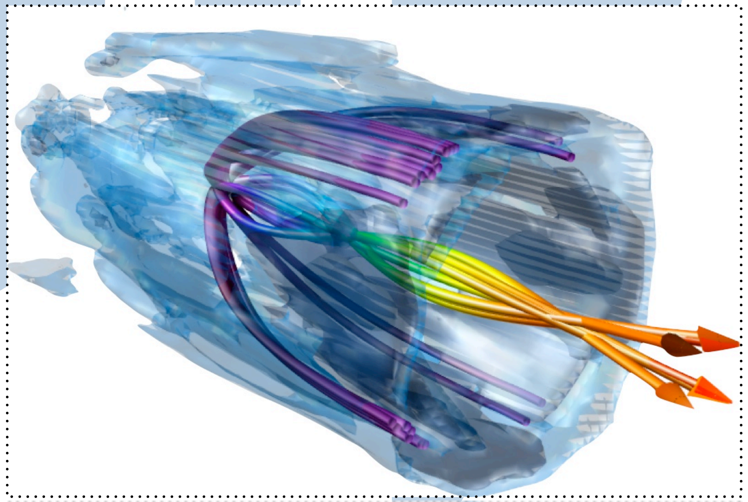
- How to increase the efficiency and rep rate at high intensities?
- What are the plasma sources for + 10 GeV e- in laser wakefield?
- How to optimize the beams from plasma accelerators?



**Photonics**



**Sources for Plasma Accelerators**



**Plasma simulation and theory**

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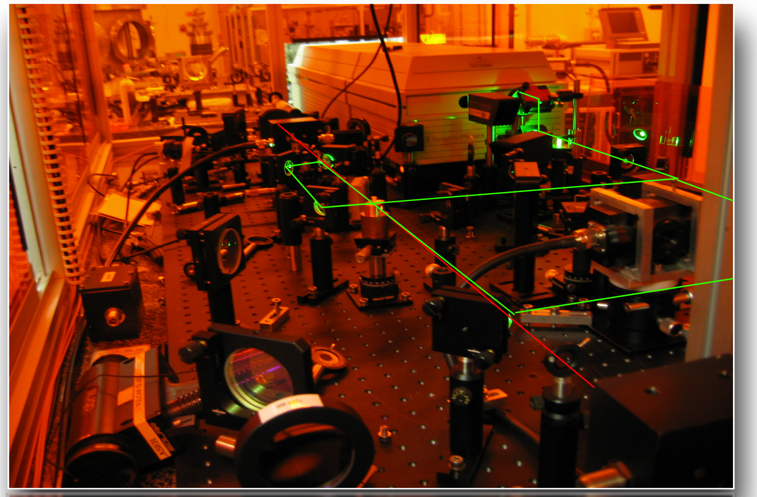

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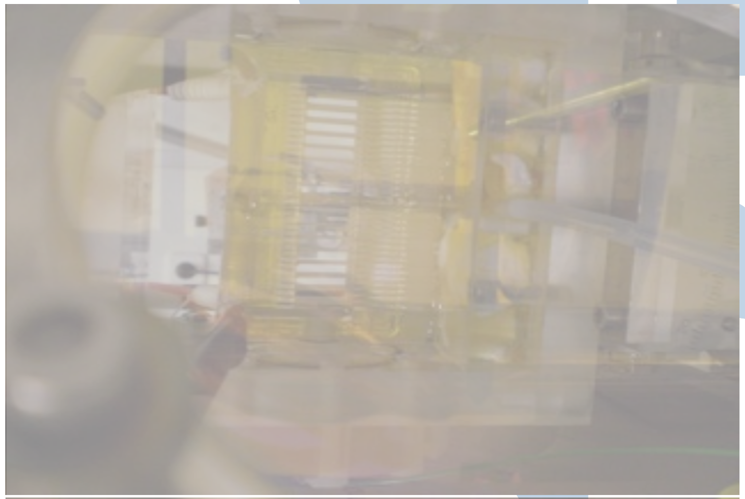

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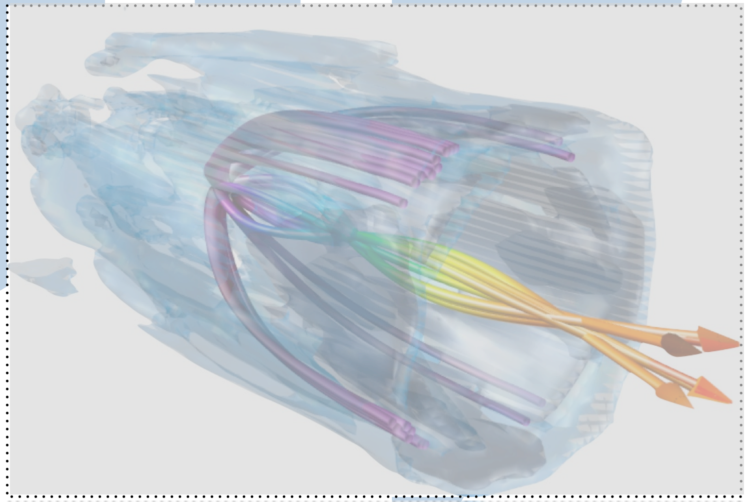
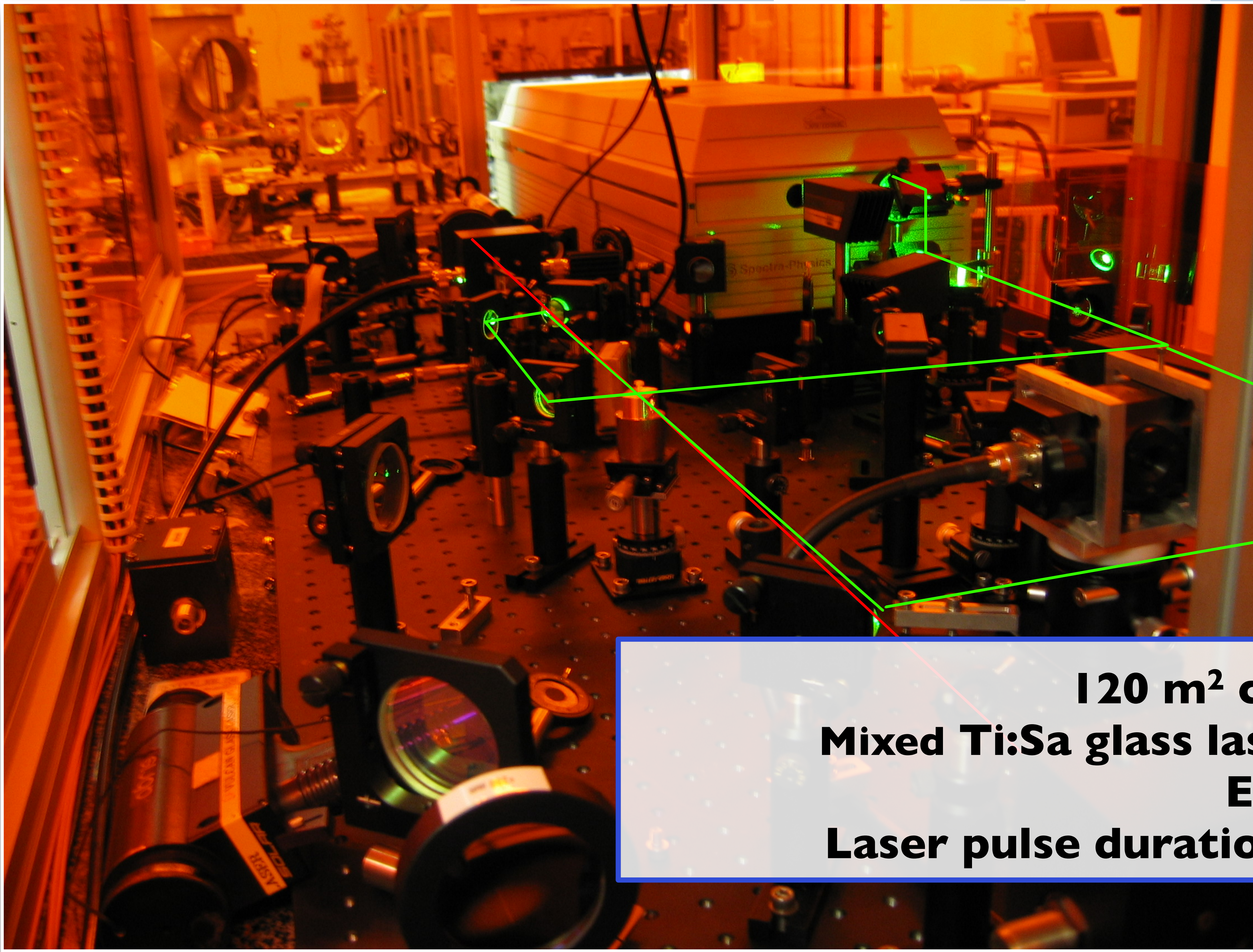


**Plasma simulation and theory**

# Laboratory for Intense Lasers @ IST

**Enabling experimental work/training on plasma sources, high intensity lasers, HHG, and diagnostics**



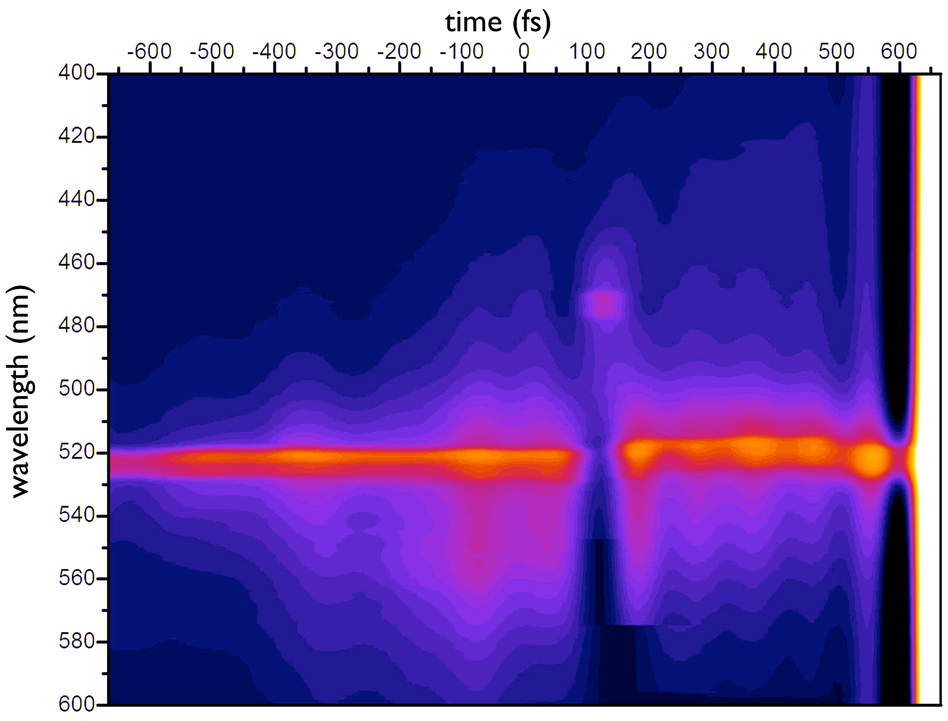
**120 m$^2$ clean room**
**Mixed Ti:Sa glass laser system**
**Elaser ~ 5 J**
**Laser pulse duration ~ 450 fs**

# Laser science & tech: toward ultrabroadband OPCPA

**Parametric amplification and diode pumping: efficient, high repetition rate, high peak and average power laser pulses**

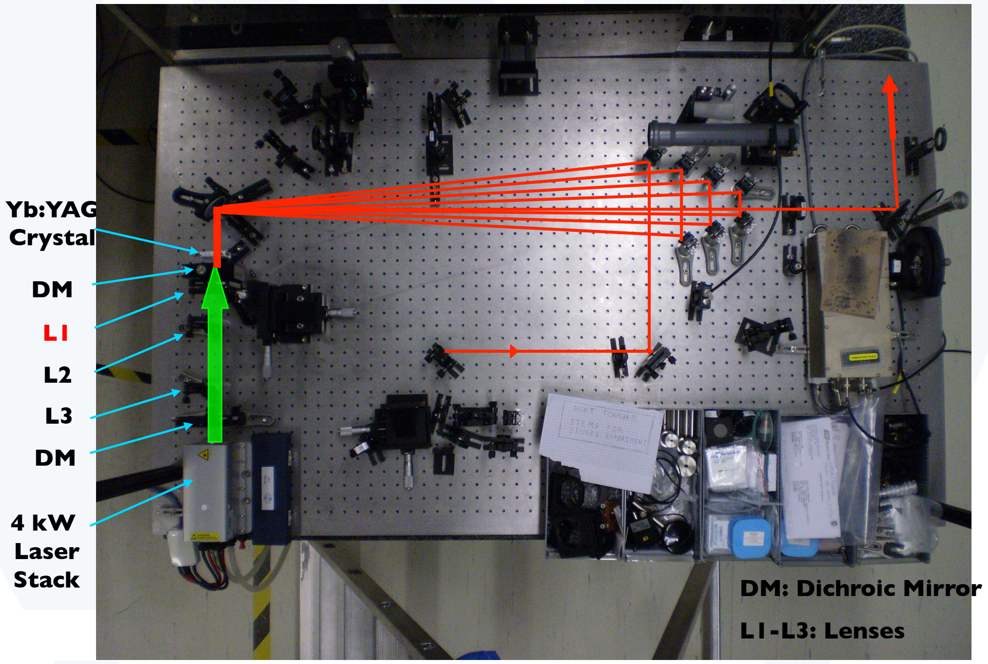
***Demonstration in 2010/2011:***

## X-FROG for supercontinuum




- 700 nm bandwidth through self-phase modulation (using 1mJ , 250 fs, 1053 nm, in bulk media)
- measuring the spectral phase: towards few-fs

## 50 mJ diode-pumped amplifier




- 8-pass diode-pumped amplification in Yb:YAG demonstrated up to 50 mJ, 1 Hz
- For 2011: paralell, fully diode-pumped, regenerative+multipass 100 mJ chain for broadband OPCPA pumping

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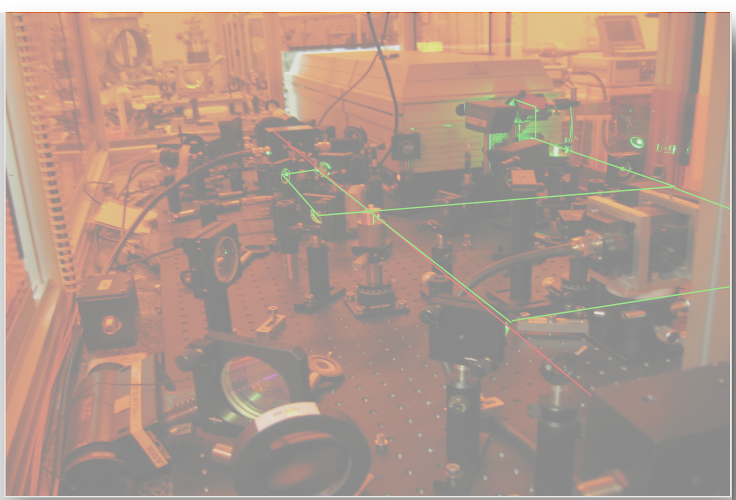

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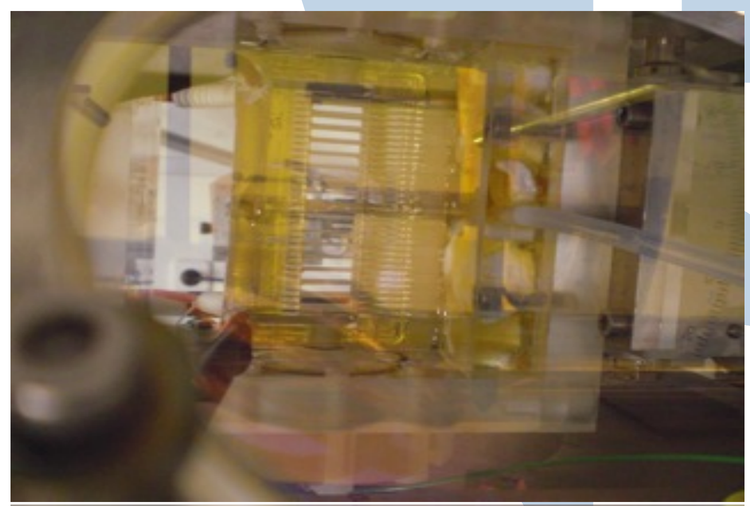
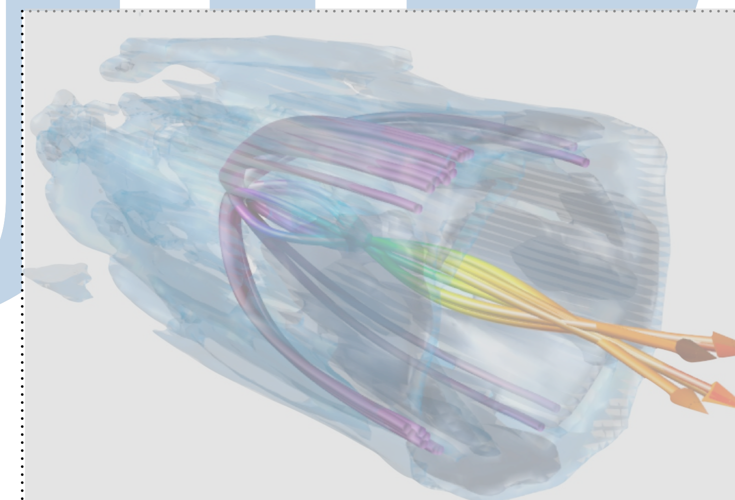


**Sources for Plasma Accelerators**

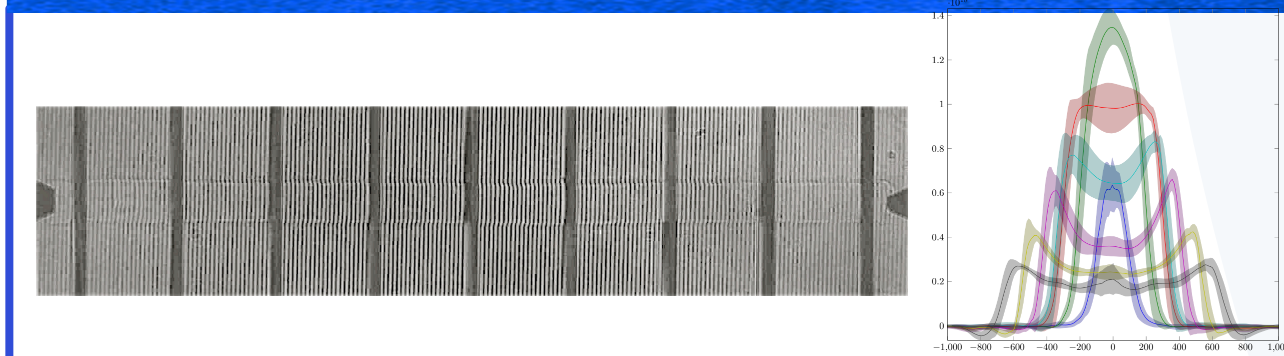


**Plasma simulation and theory**

# Plasma sources: toward 10 GeV electron accelerators

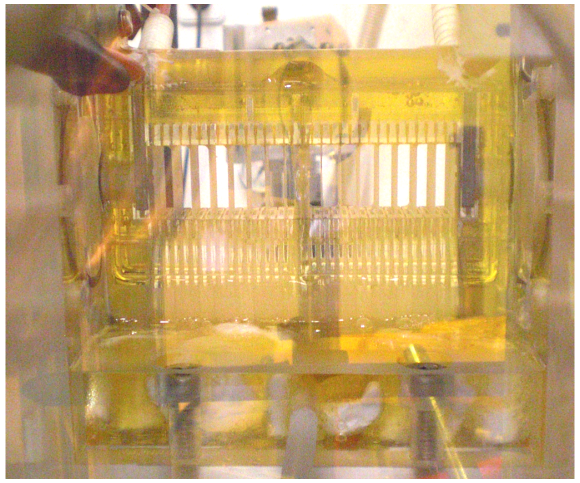
**High quality parabolic plasma channels produced by high voltage discharges**

## 1-5 cm channels in structure gas cells



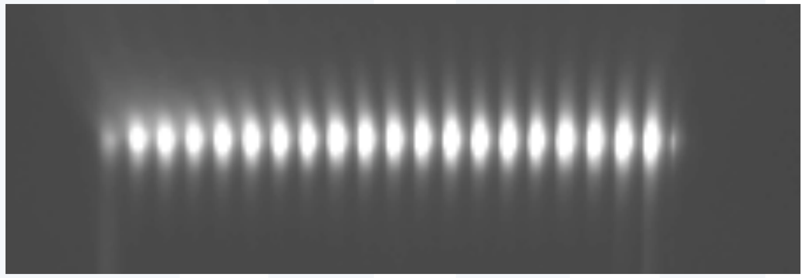
- high-quality channels w/ a pre-discharge
- optimization for 3-10 cm multi-GeV accelerator in 2011

## >10 cm plasma channels for > 10 GeV

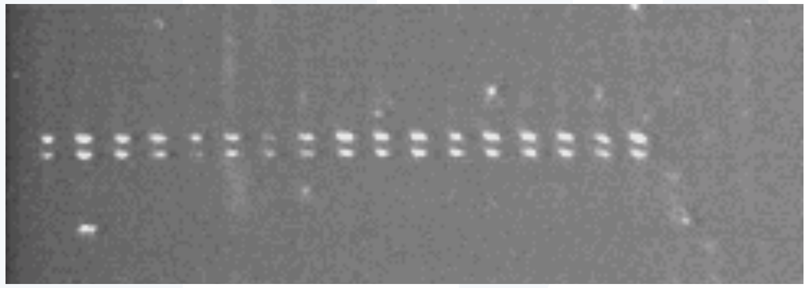


- advanced plasma ignition scheme
- in progress, partial demo in 2011-12

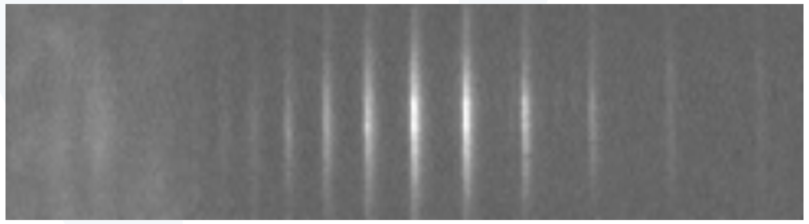
## Corrugated plasma channels for iHHG



**plasma emission**



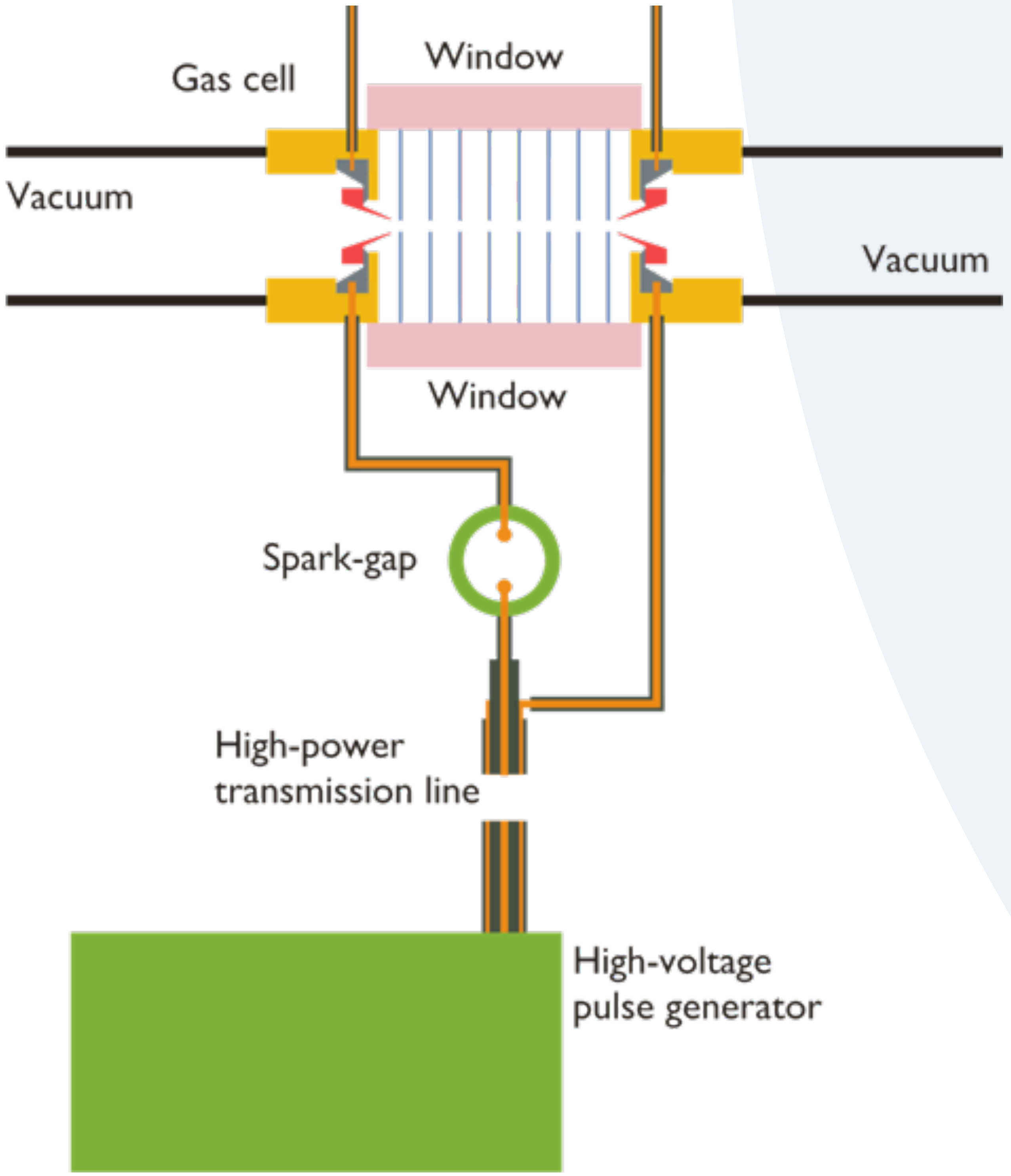
**plasma shadowgraphy**



**HHG spectrum**

- periodic plasma channel modulation for high Z plasmas for quasi-phase-matched HHG on ionic media
- approach spectra to water window for single shot experiments and seeding
- optimization & application in 2010-2011 (in progress)

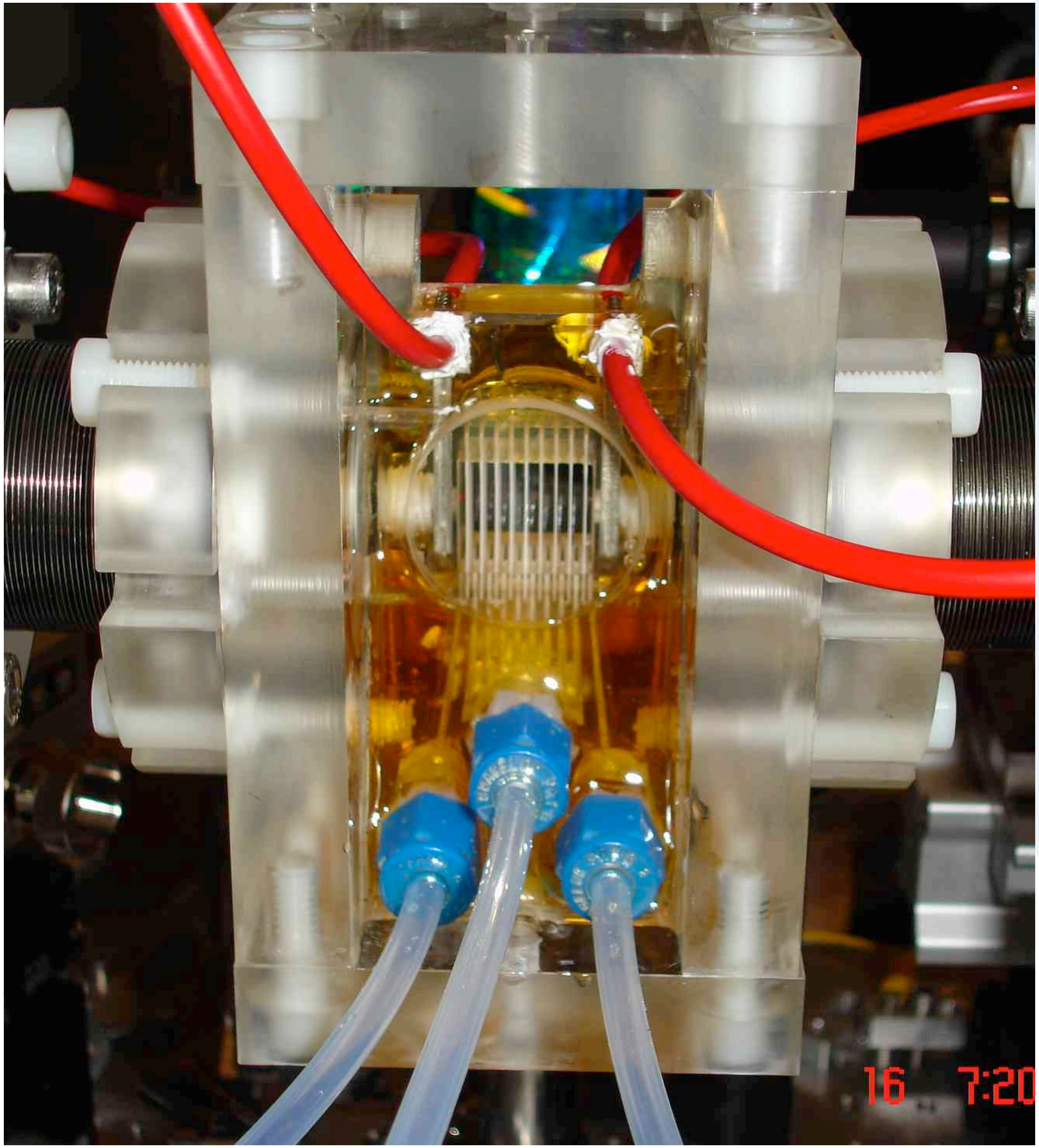
# Structured plasma sources




## structured gas cells

- fast gas injection ( few ms) vs slow gas leak
- plasma produced by discharges between conical hollow electrodes
- internal cell structure sets initial plasma diameter and position
- geometry allows for free radial expansion of the plasma column and formation of parabolic channels
- low current simmer discharge improves the plasma uniformity and reproducibility

# Structured plasma sources

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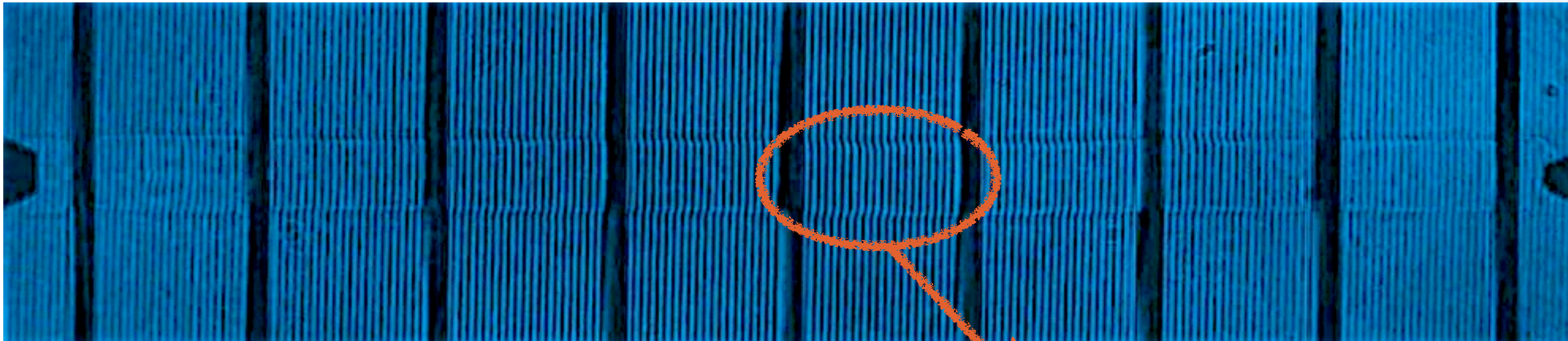
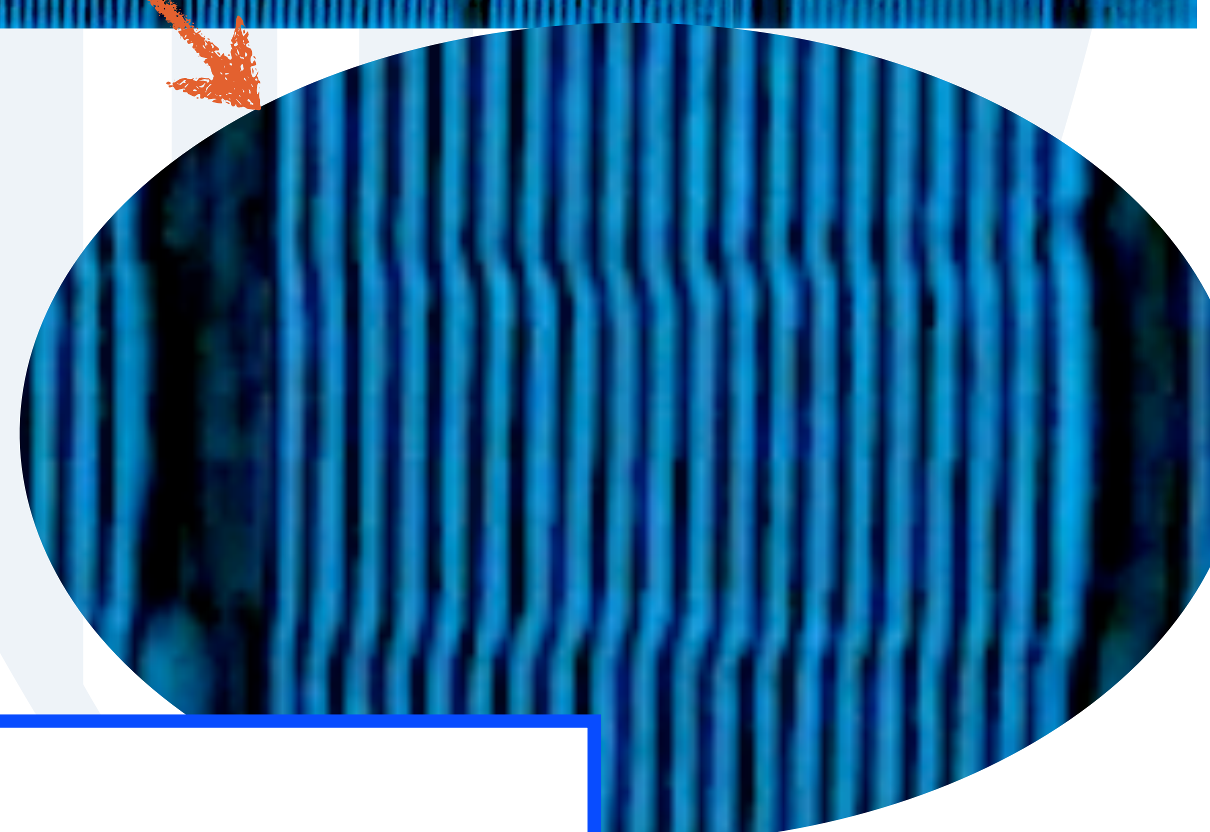
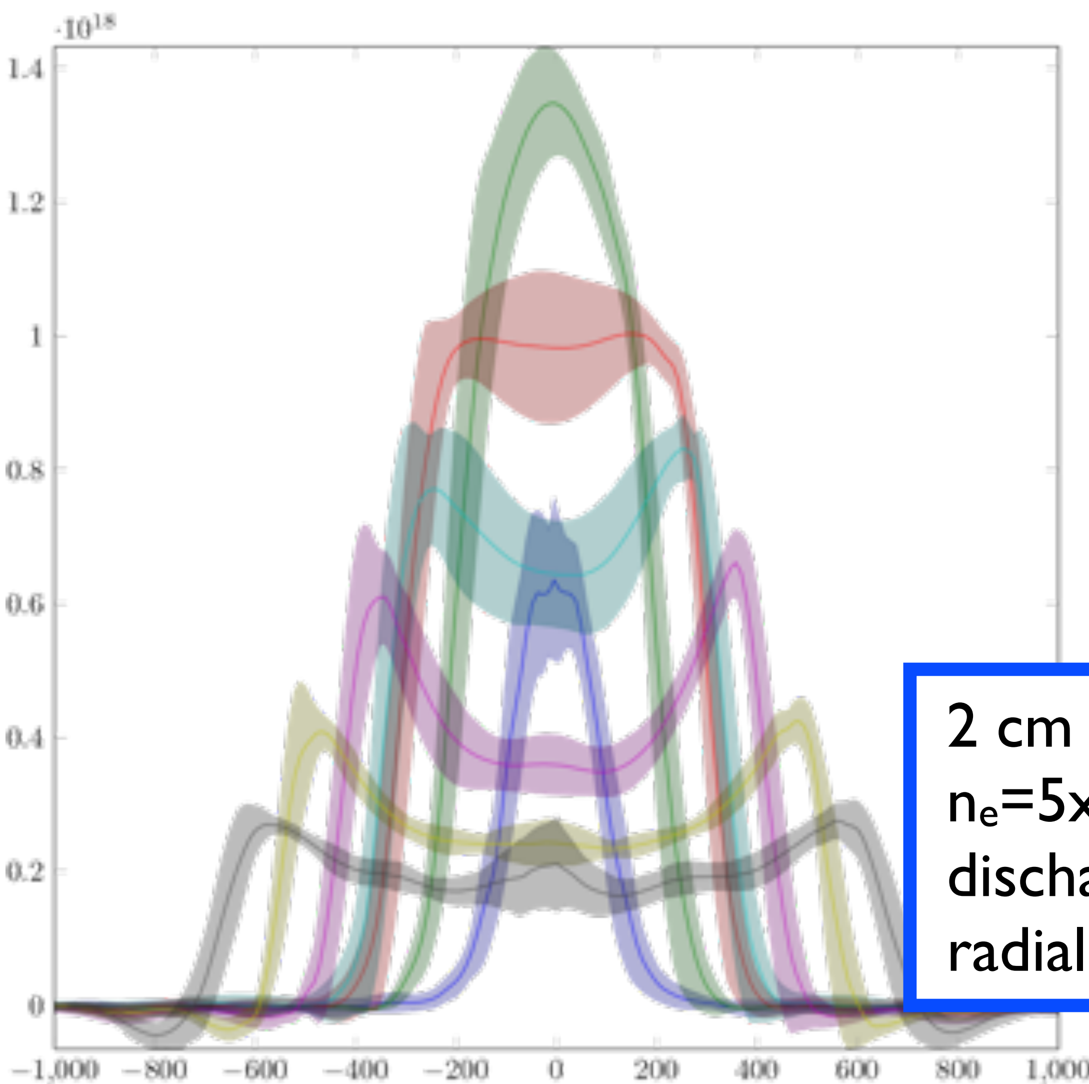
# High quality/control plasma channels

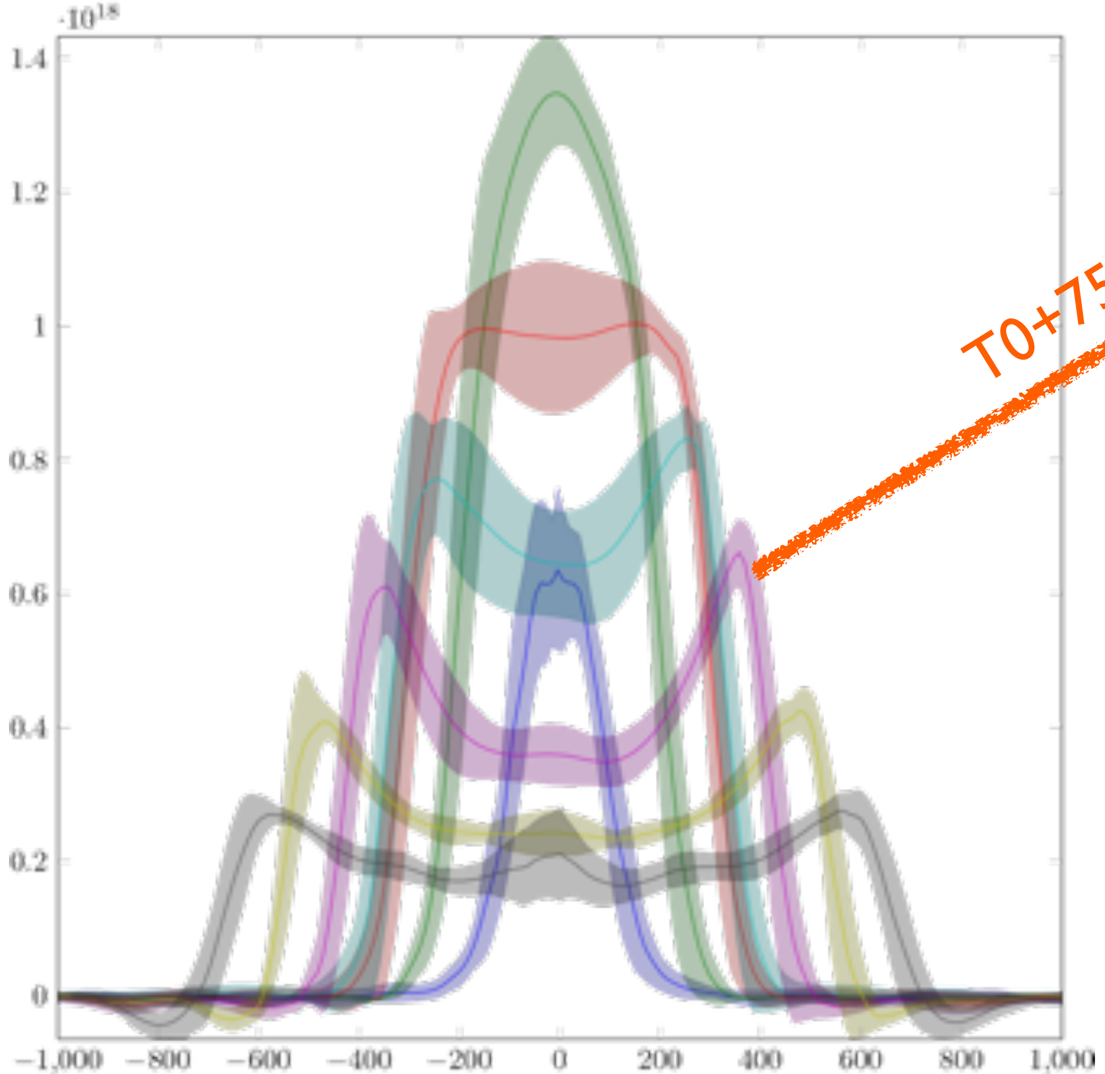


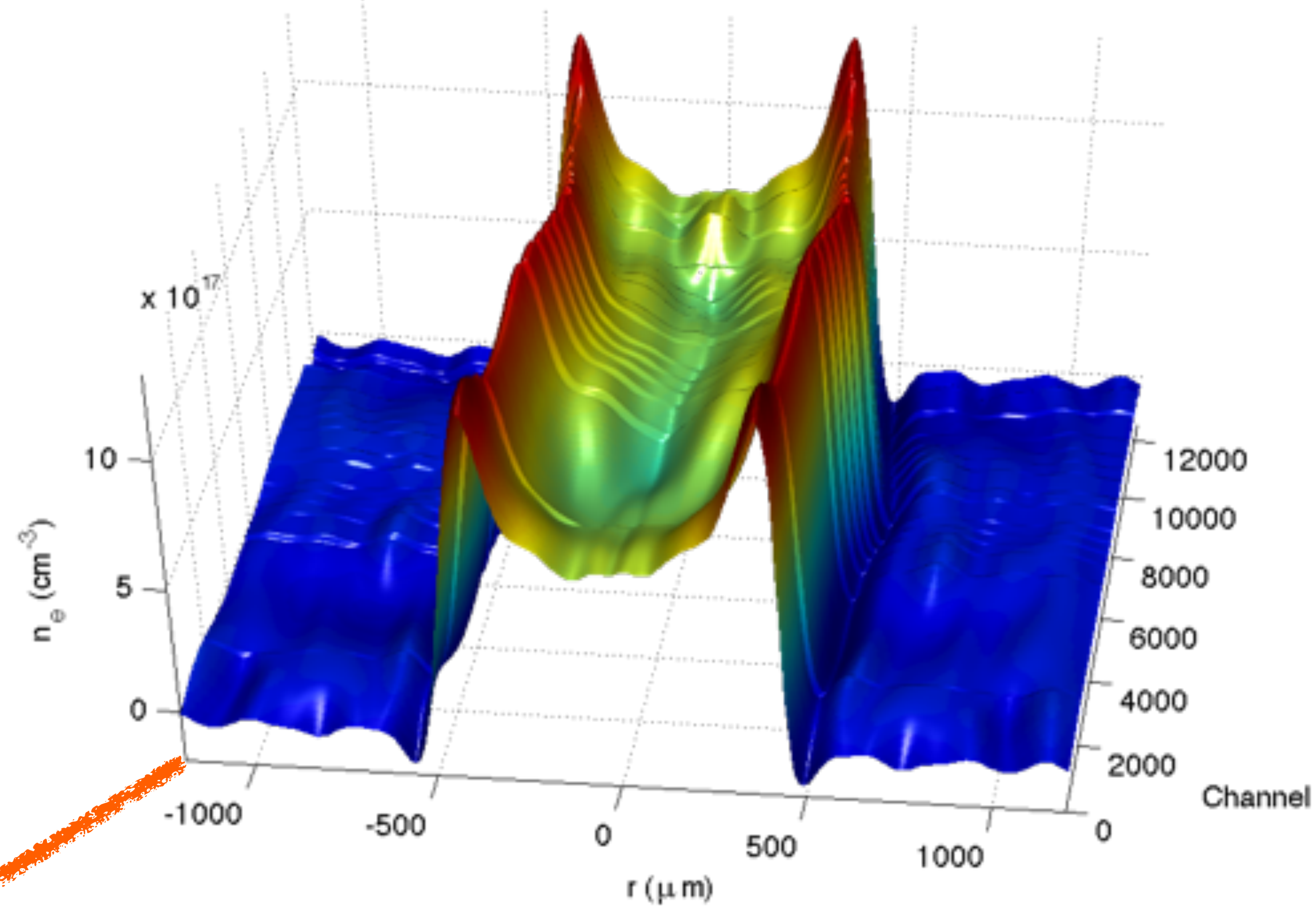


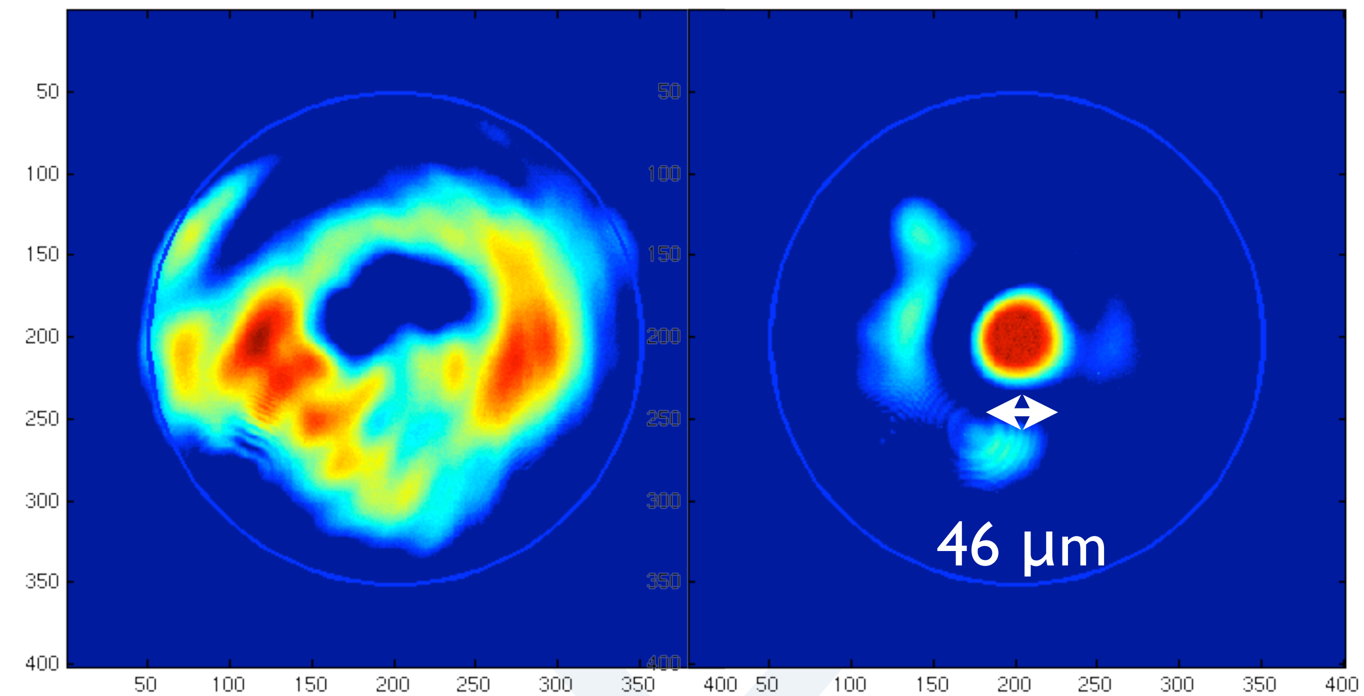



2 cm long discharge
$n_e$=5x10$^{17}$ cm$^{-3}$ in $H_2$
discharge 100 kV, 800 A, 100 ns
radial free expansion for parabolic profile

# High quality/control plasma channels




laser beam without plasma

approx. matched prop. at T0+65 ns

# Focus areas for activities in plasma accelerators

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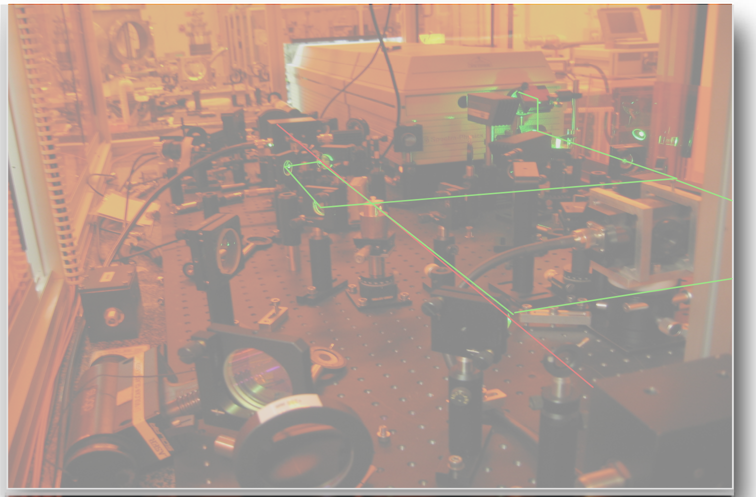
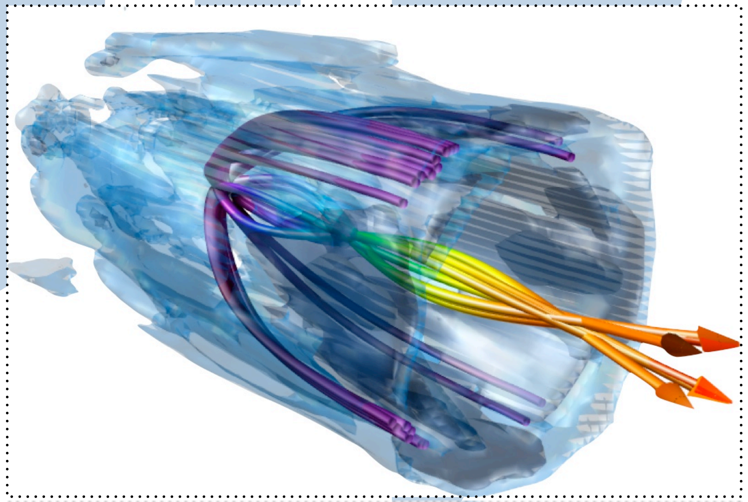


Photonics

Sources for Plasma Accelerators



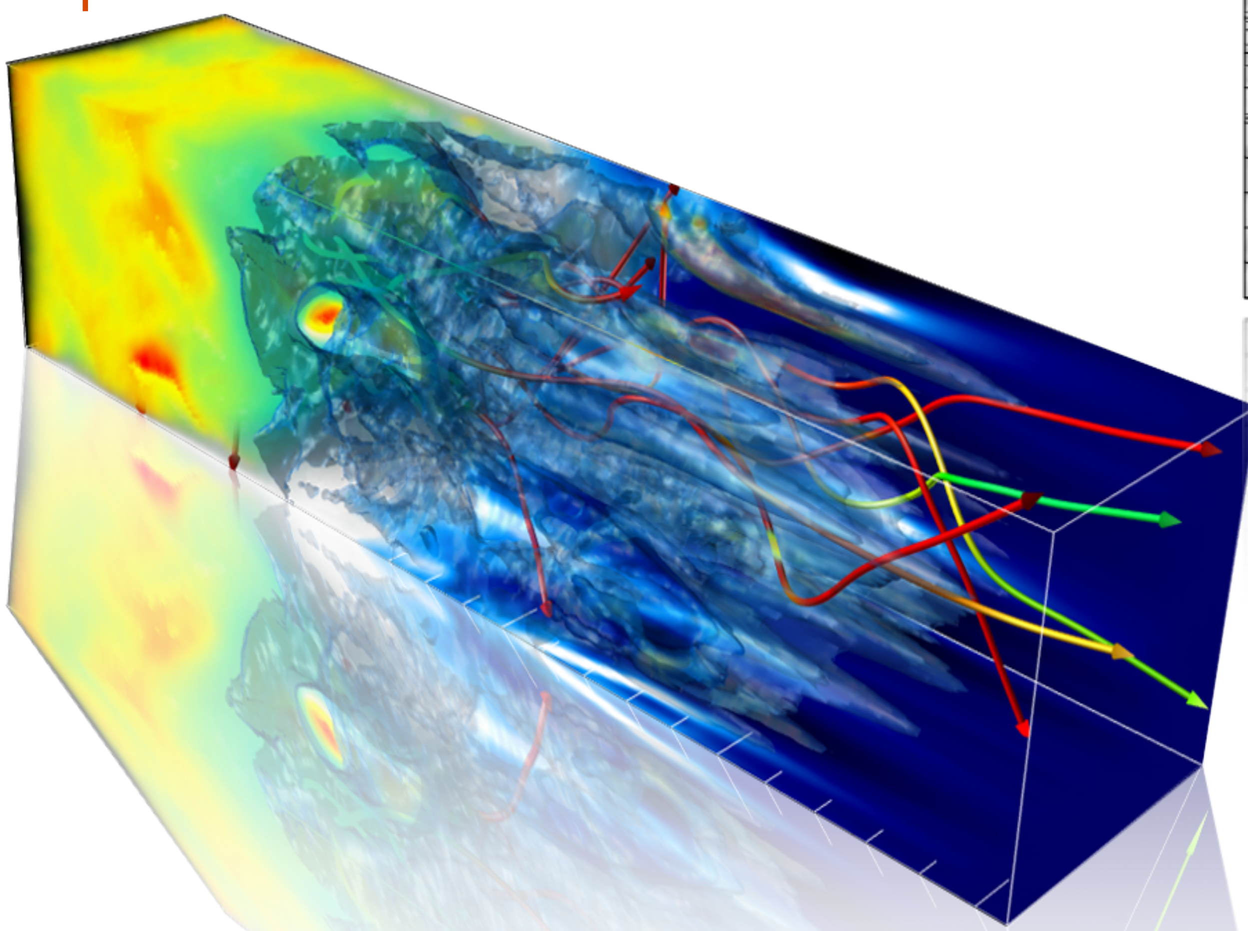
Plasma simulation and theory

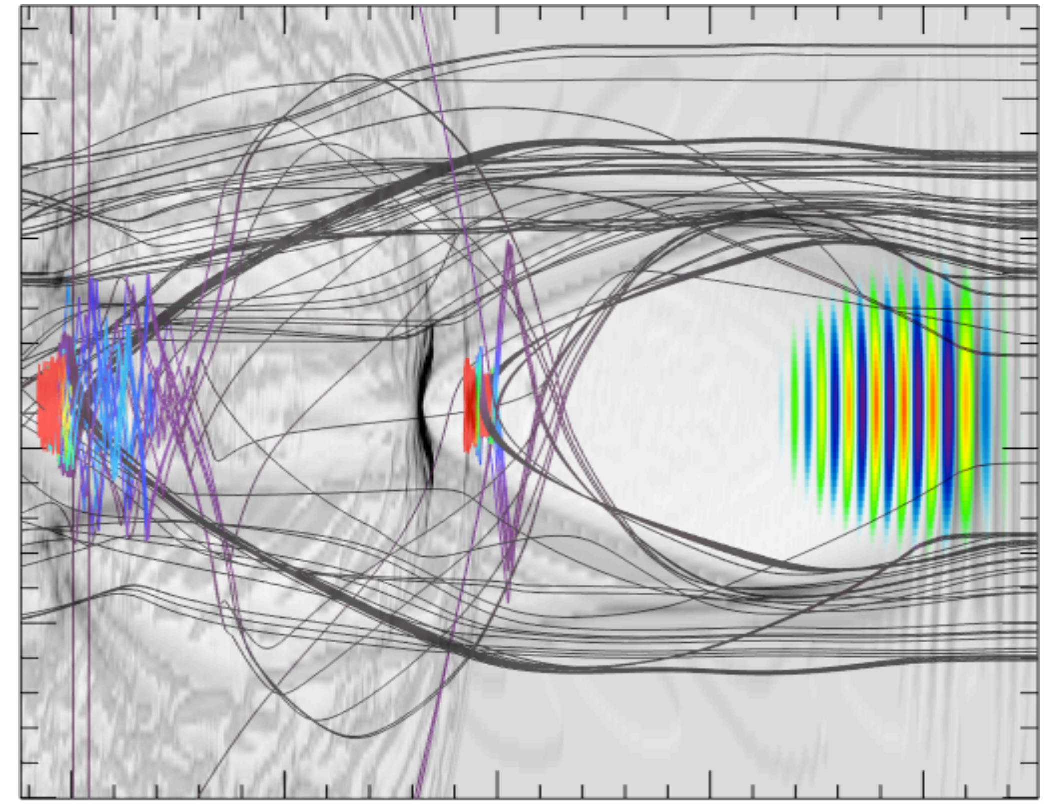
# OSIRIS 2.0

osiris
v2.0

## osiris framework

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





## New Features in v2.0

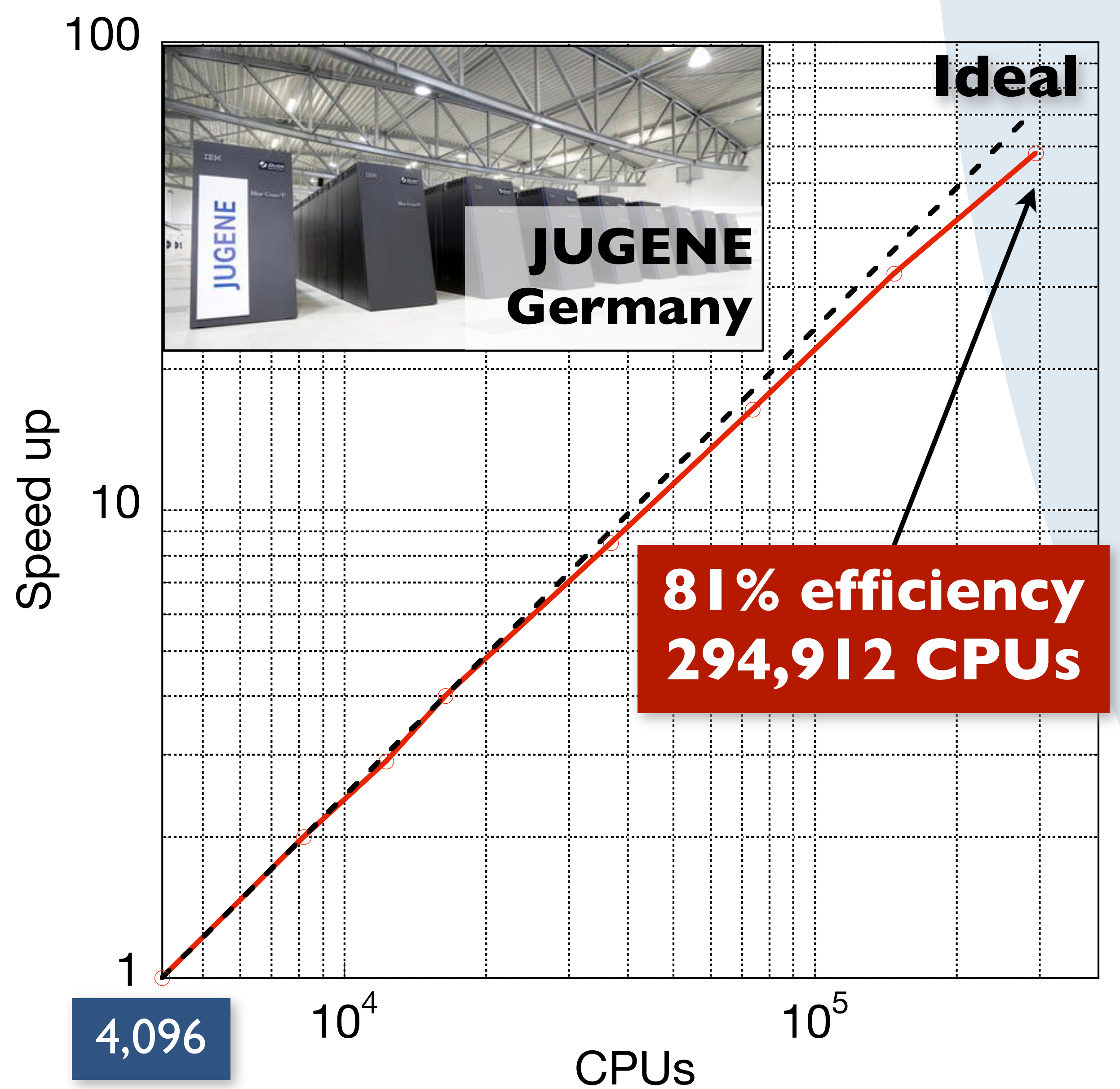
- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

**Ricardo Fonseca:** ricardo.fonseca@ist.utl.pt
**Frank Tsung:** tsung@physics.ucla.edu

http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/

# Massivelly parallel computing and plasma simulations

## OSIRIS strong scaling up to ~300k CPUs




- ✳ Spatial domain decomposition
- ✳ Local field solver
- ✳ Minimal communication
- ✳ Dynamic Load Balancing

## New developments

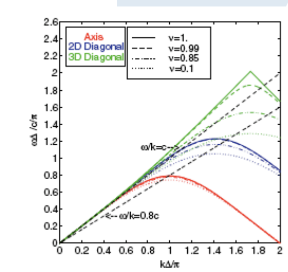
### Performance

SIMD units

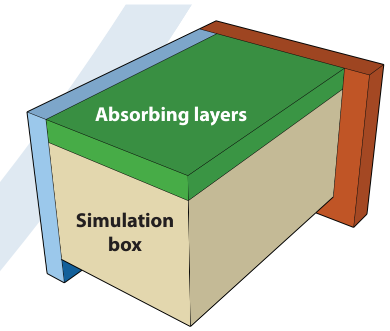
GPUs

### Numerics

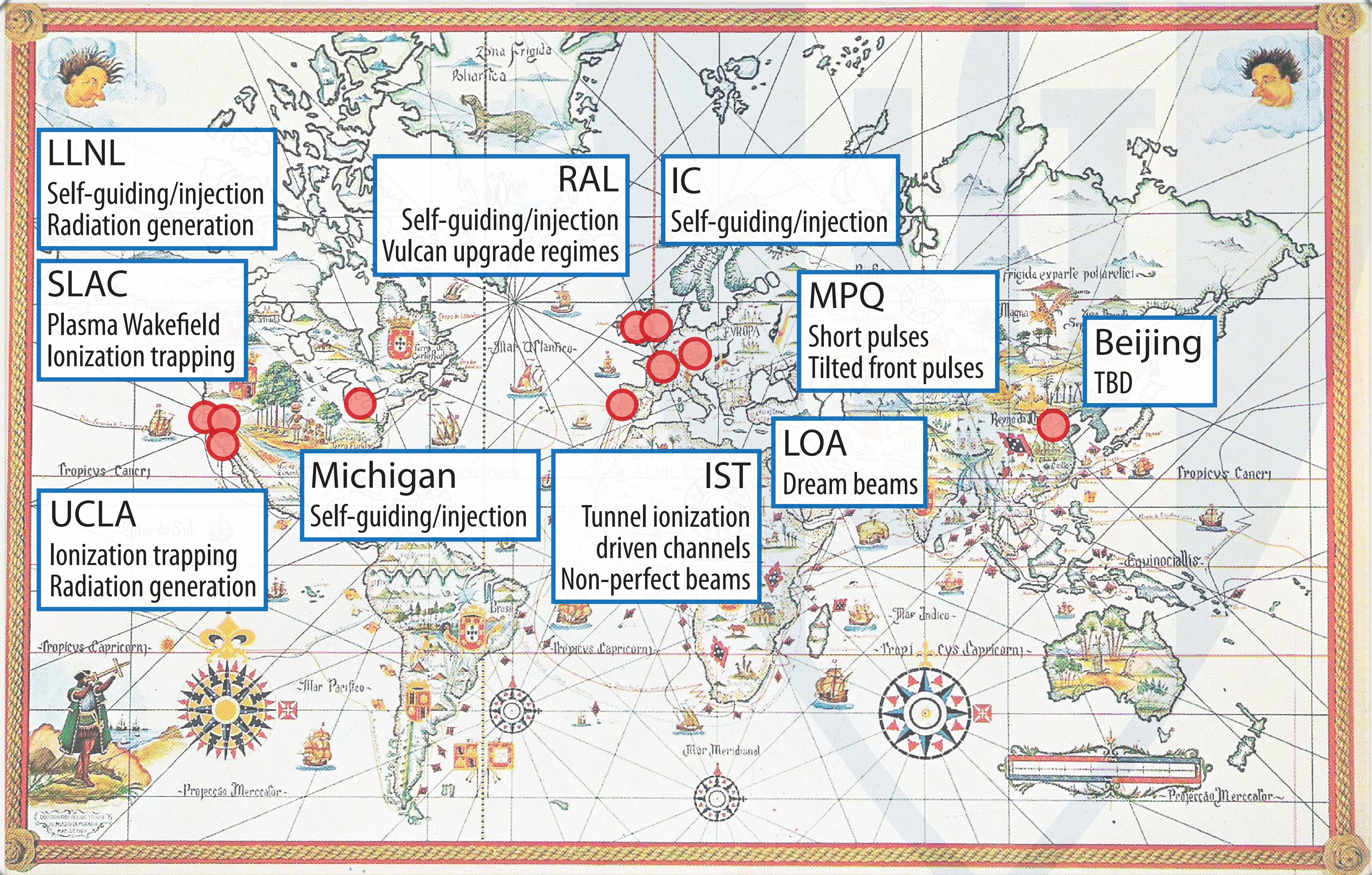
Higher order algorithms



Advanced boundary conditions

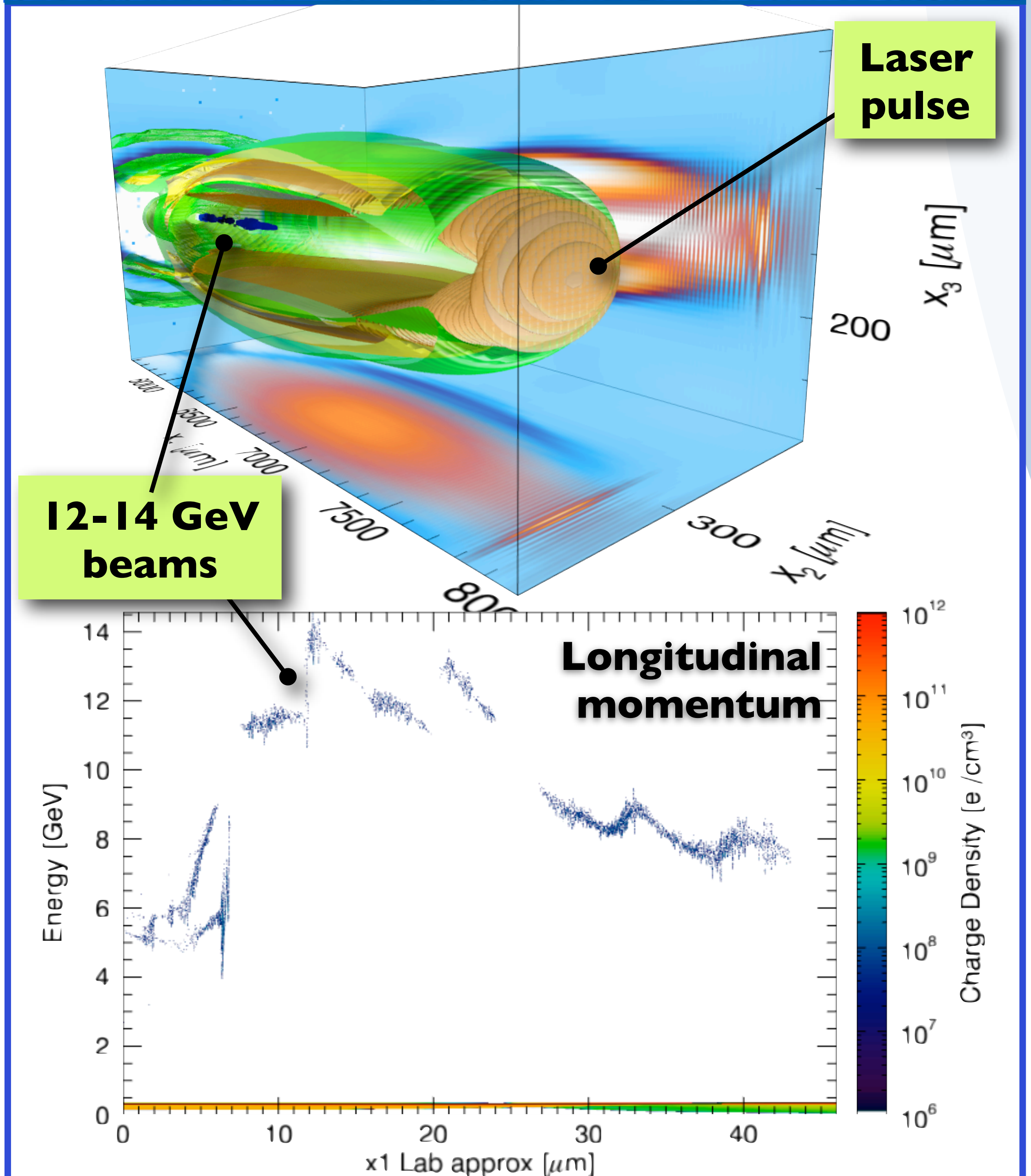


# Supporting experiments with OSIRIS

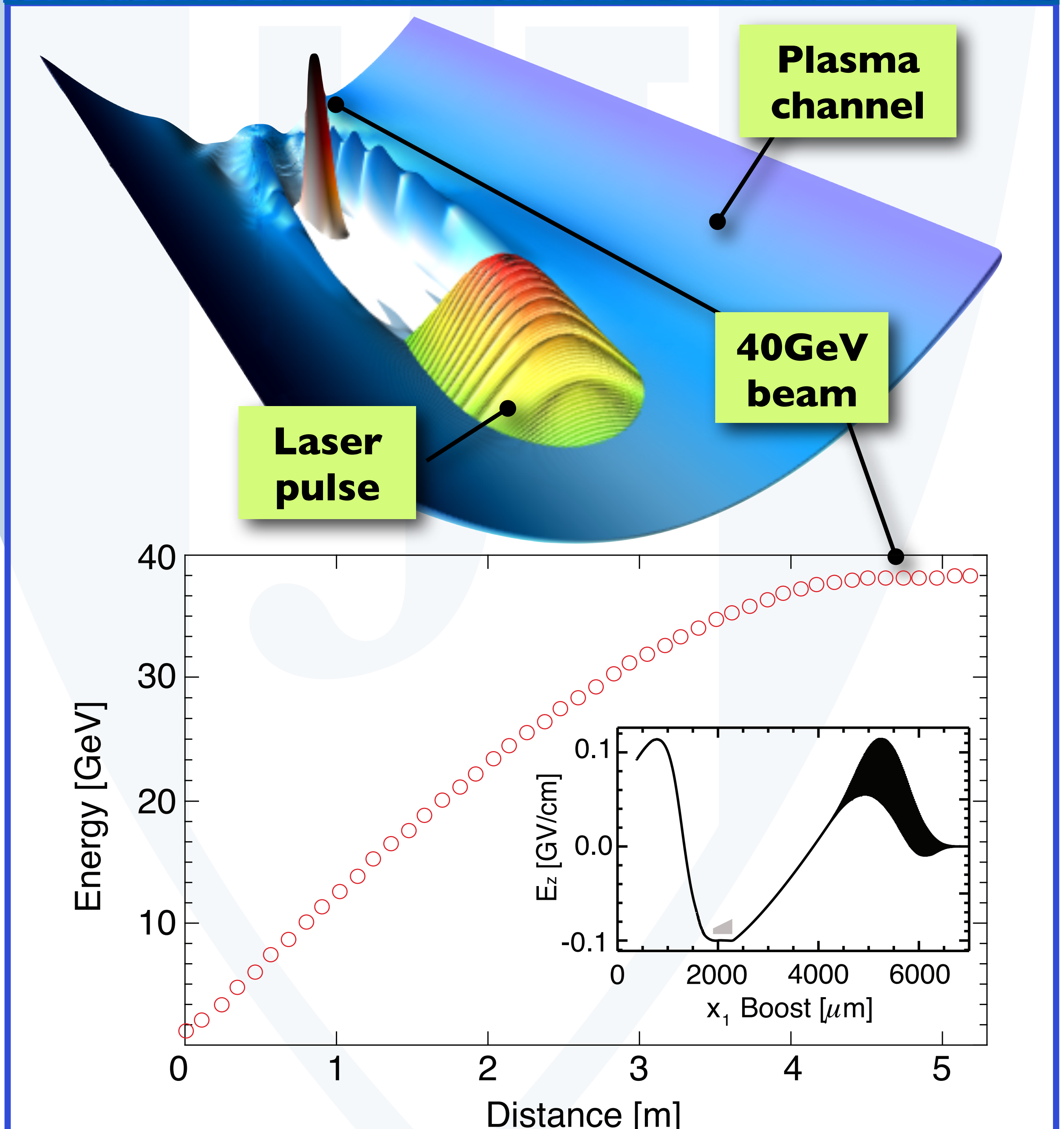


# Boosted frame simulations for long plasma sources

**Self-injection: >10 GeV**




**External-injection w/ beam loading: 40GeV**




*S. F. Martins, et al., Nature Phys., 2010*

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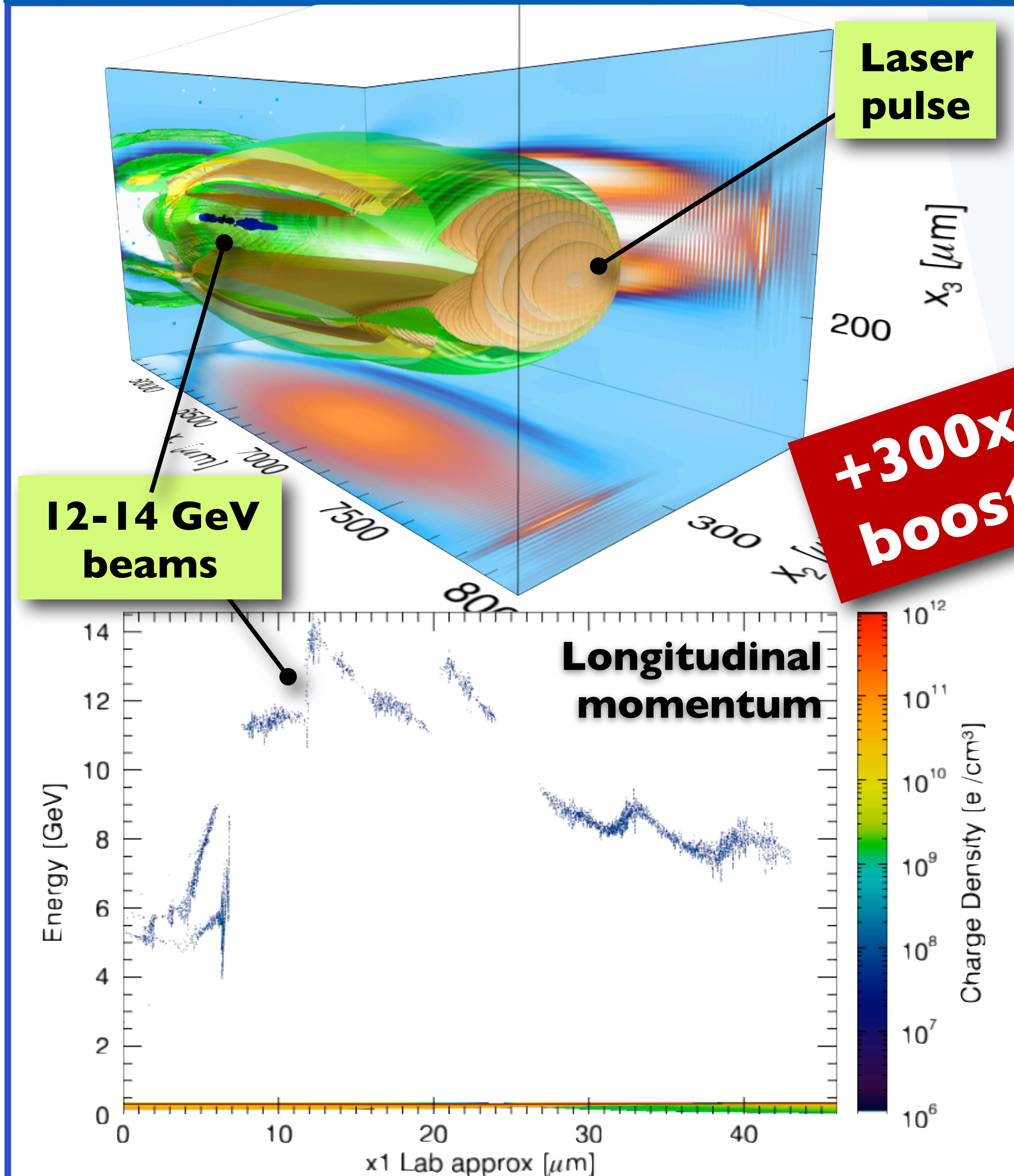


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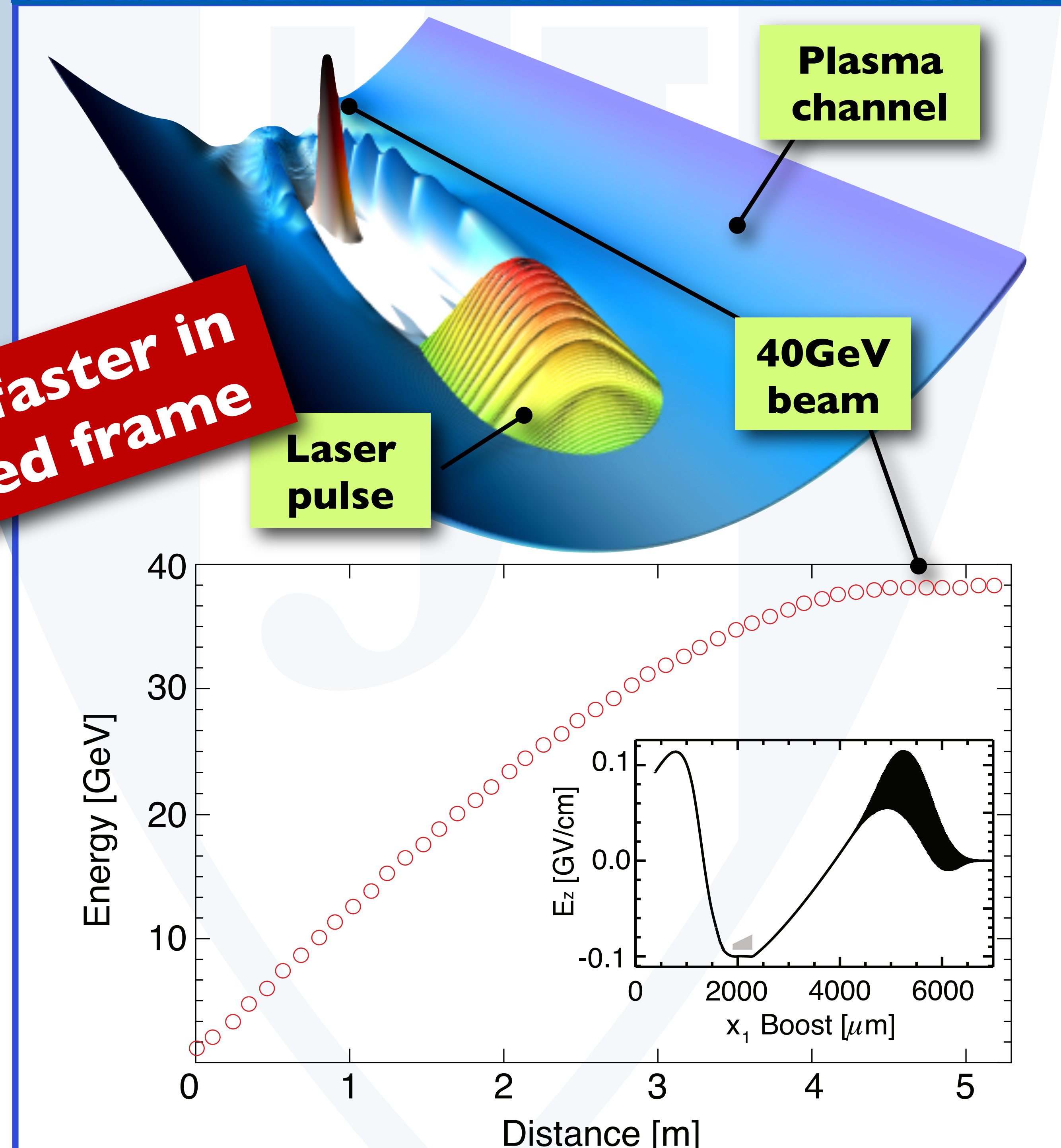
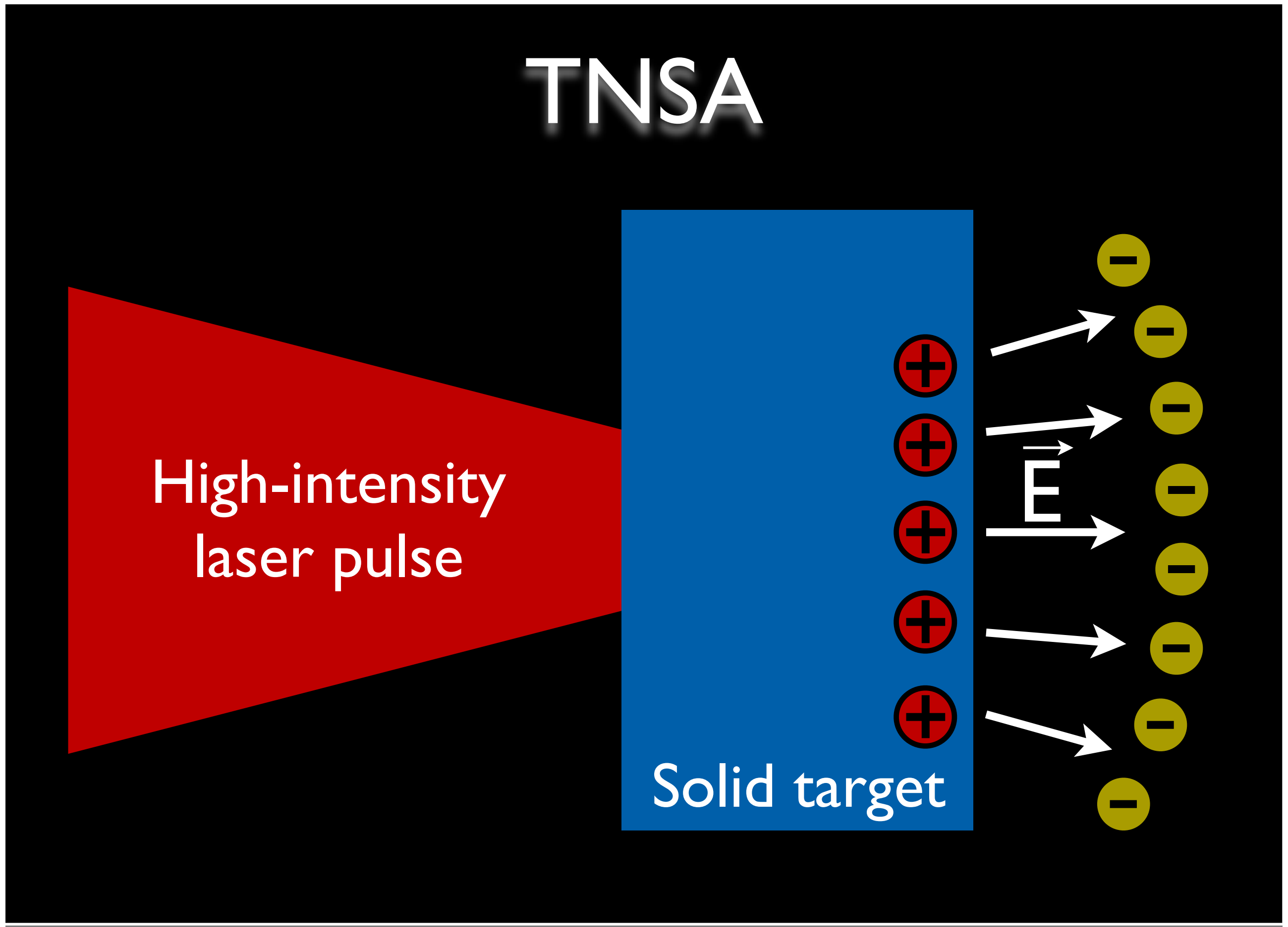



**+300x faster in boosted frame**

*S. F. Martins, et al., Nature Phys., 2010*

# The quest for high-quality monoenergetic proton beams

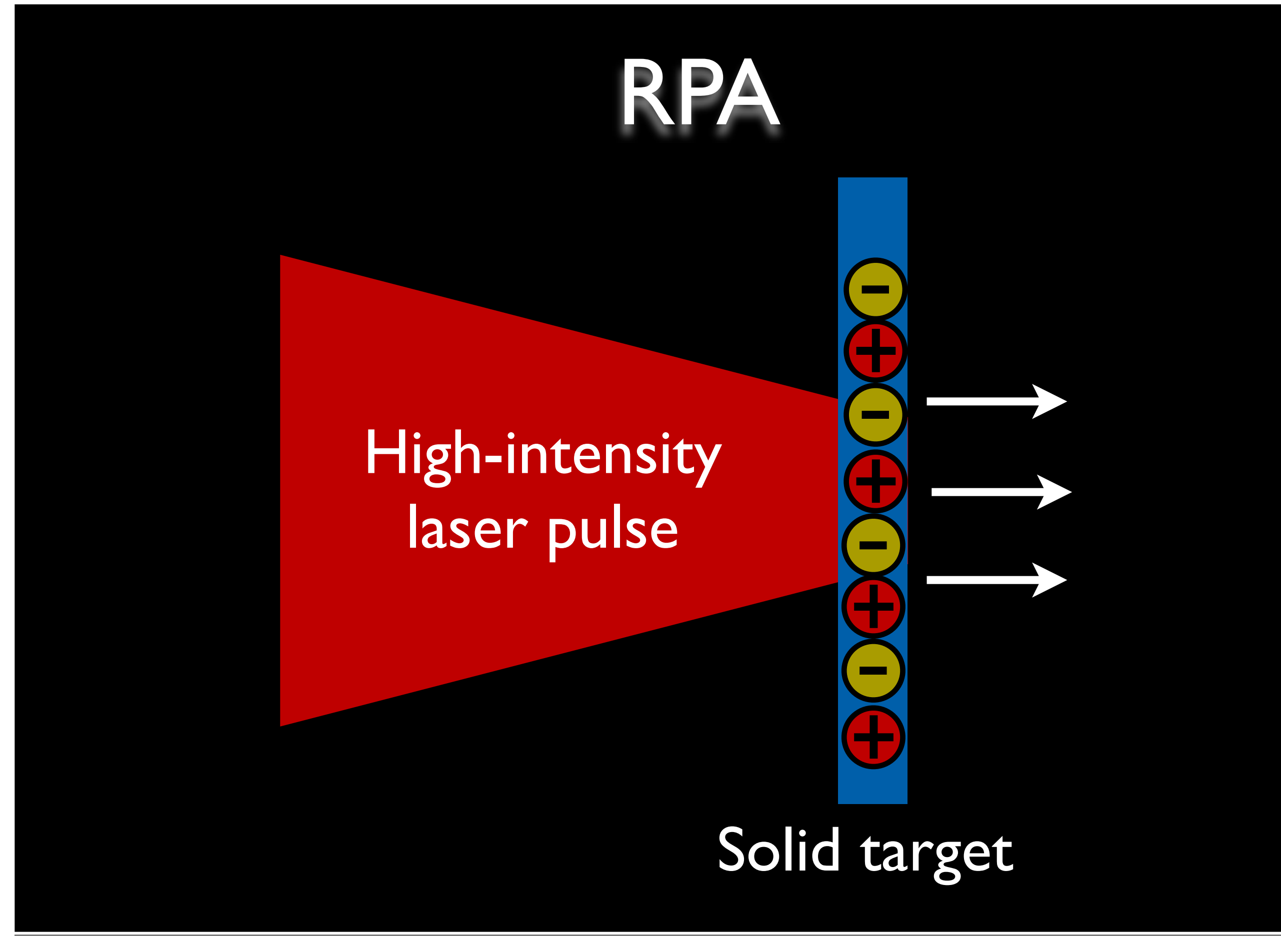



Cold solid target

Linear polarization

Continuum spectrum

Max. proton energy ~ 60 MeV



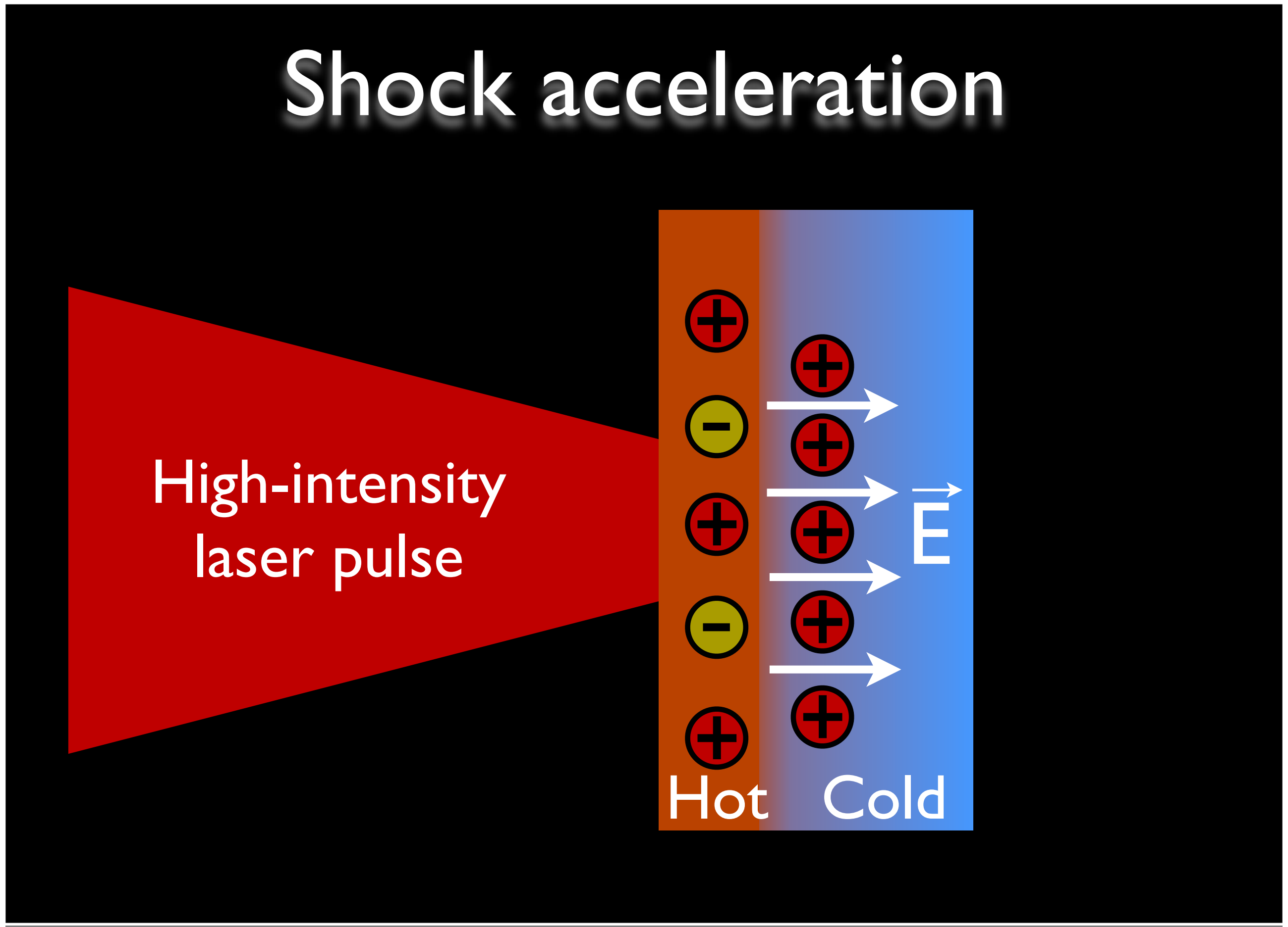

Cold solid target

Circular polarization

High contrast ratio

Mono-energetic spectrum

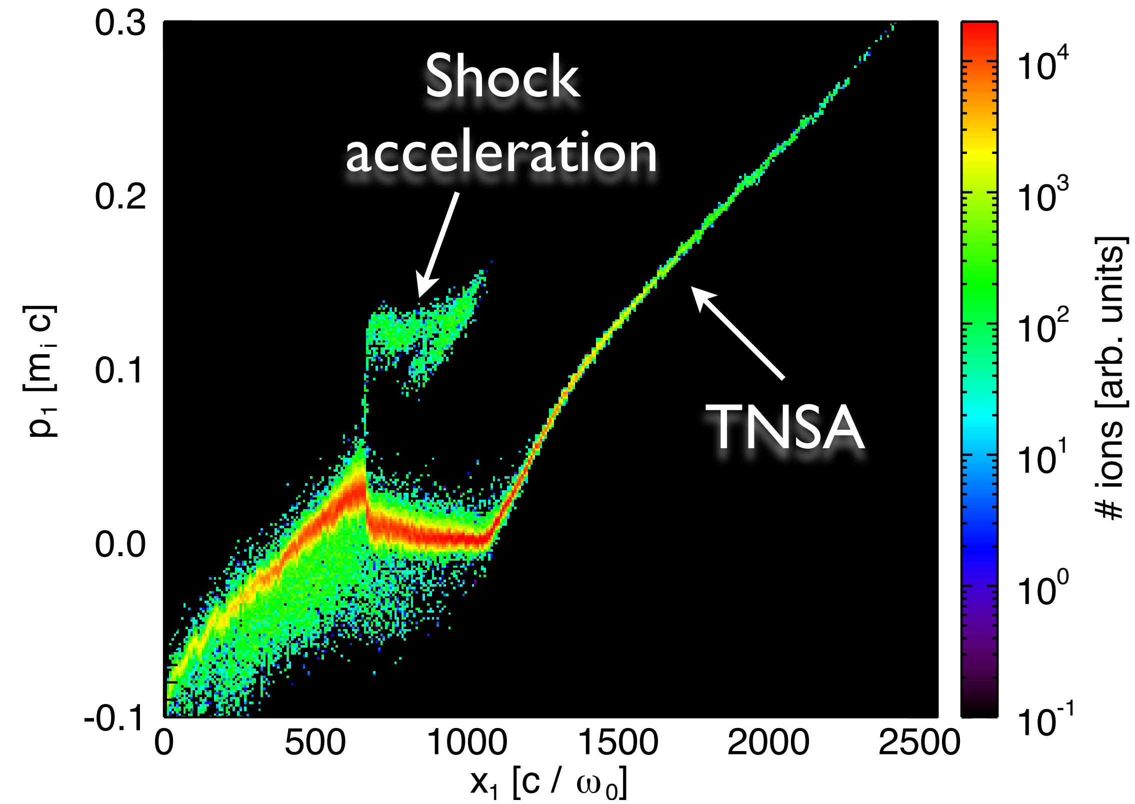
# Shock acceleration can lead to monoenergetic proton beams

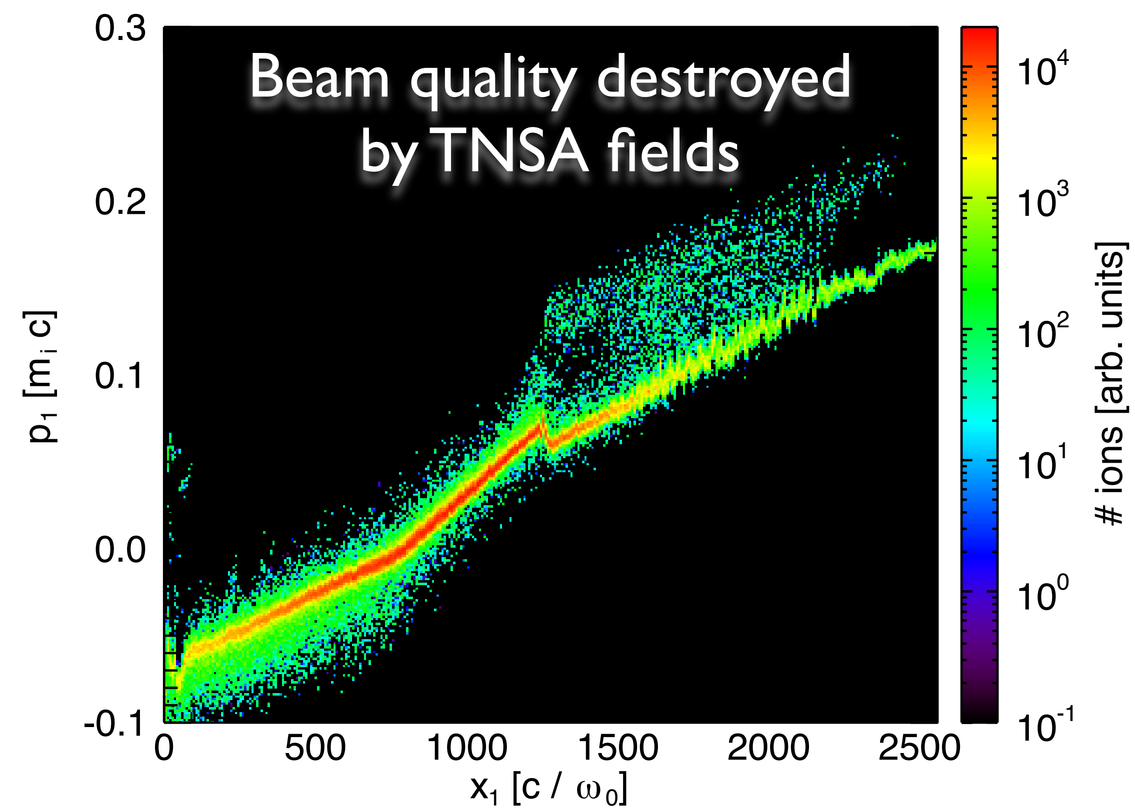



Linear polarization

Strong heating

Monoenergetic spectrum?



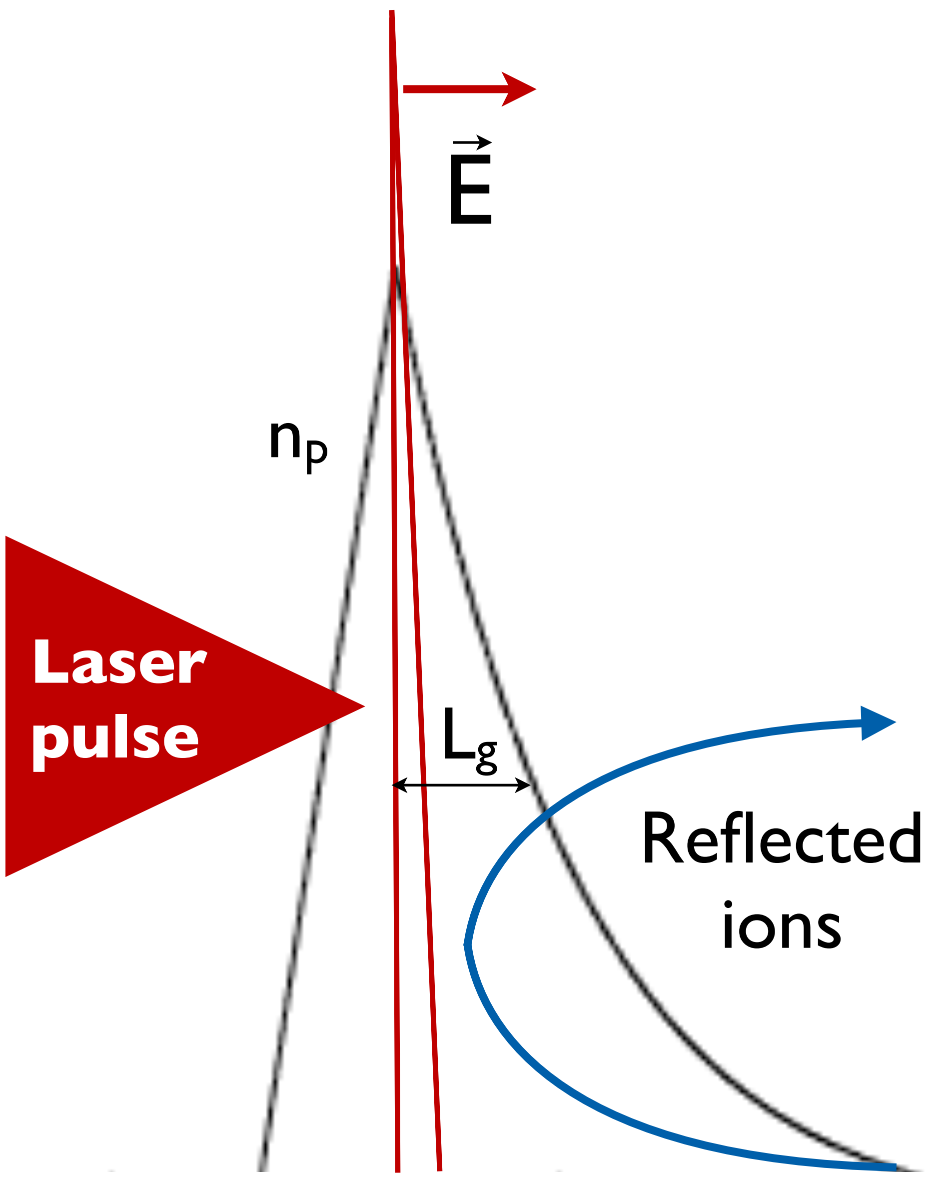


J. Denavit, PRL 69, 3052 (1992)
L. O. Silva et al., PRL 102, 015002 (2004)

# Gas jet targets allow for high-quality shock accelerated beams

UCLA

## Interaction at densities close to $n_c$ is critical




Plasma profile

### Requirements for high-quality shock acceleration

- High Mach number shocks in different density/temperature plasmas*
- Shock acceleration must dominate over TNSA fields**
- When shock is formed:***

$$v_{sh} > v_{ions} \Rightarrow \quad L_g > \frac{20\pi}{\omega_{pi}} \frac{C_{s0}^2}{v_{sh}}$$

- When shock crosses back of target:

$$v_{sh} > v_{ions} \Rightarrow \quad L_g \ll \frac{v_{sh}}{\omega_{pi}} \left( e^{\frac{v_{sh}}{2C_{s0}}} - 20\pi \right)$$

- For optimal absorption ($n_p \sim n_c$), optimal thickness $L_g \sim 20\ l_0$

**$CO_2$ lasers allow for the use of mm scale gas jet targets ($n_c$) at high repetition rates**

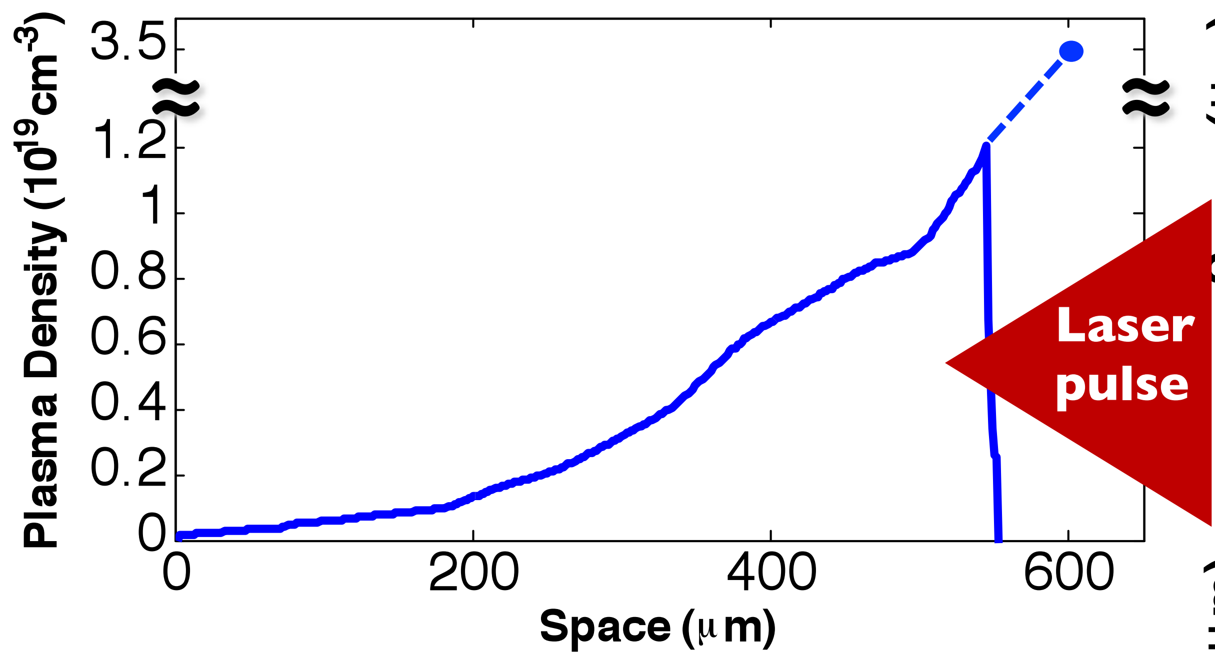
* G. Sorasio et al. PRL 2006

** T. Grismayer & P. Mora Phys. Plasmas 2006

*** shock formation time ~ 20p $w_{pi}^{-1}$ (D.W. Forslund & C. R. Shonk PRL 1970)

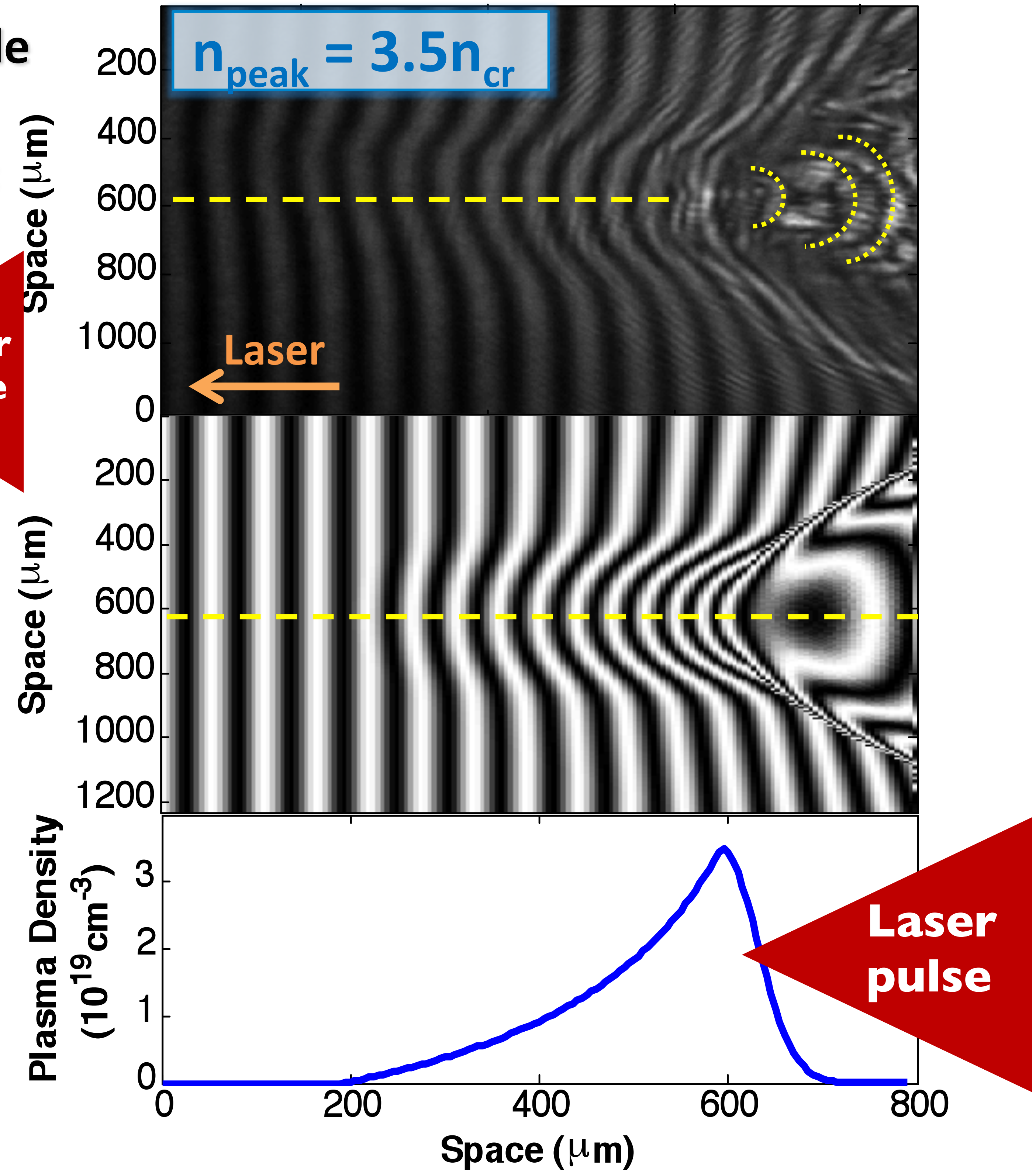
# mm scale plasmas can be formed by using structured $CO_2$ lasers

**Abel inverted back side plasma profile**

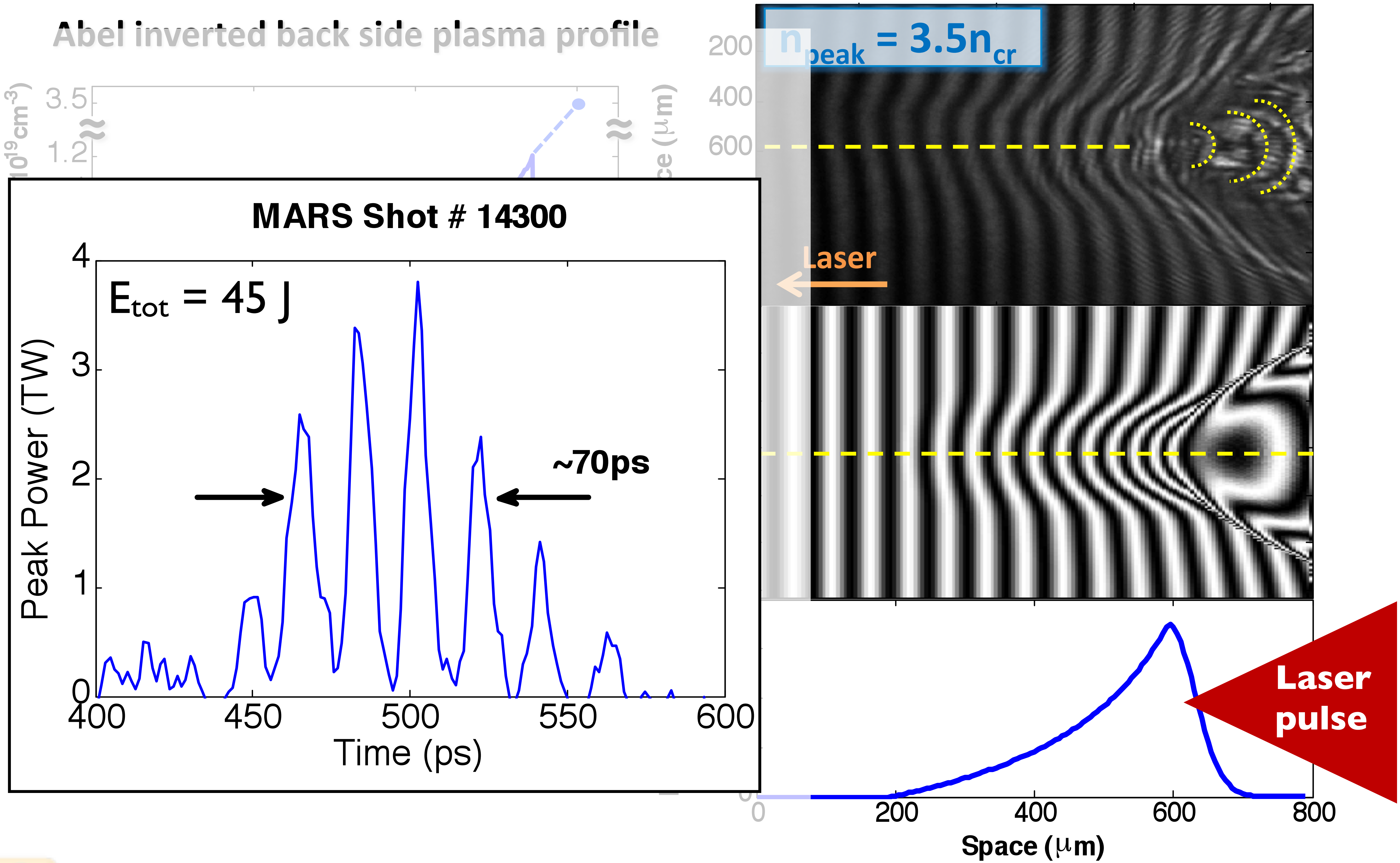



**Simulated interferogram to model sharp front side of plasma**

**Plasma density profile used to create simulated interferogram**

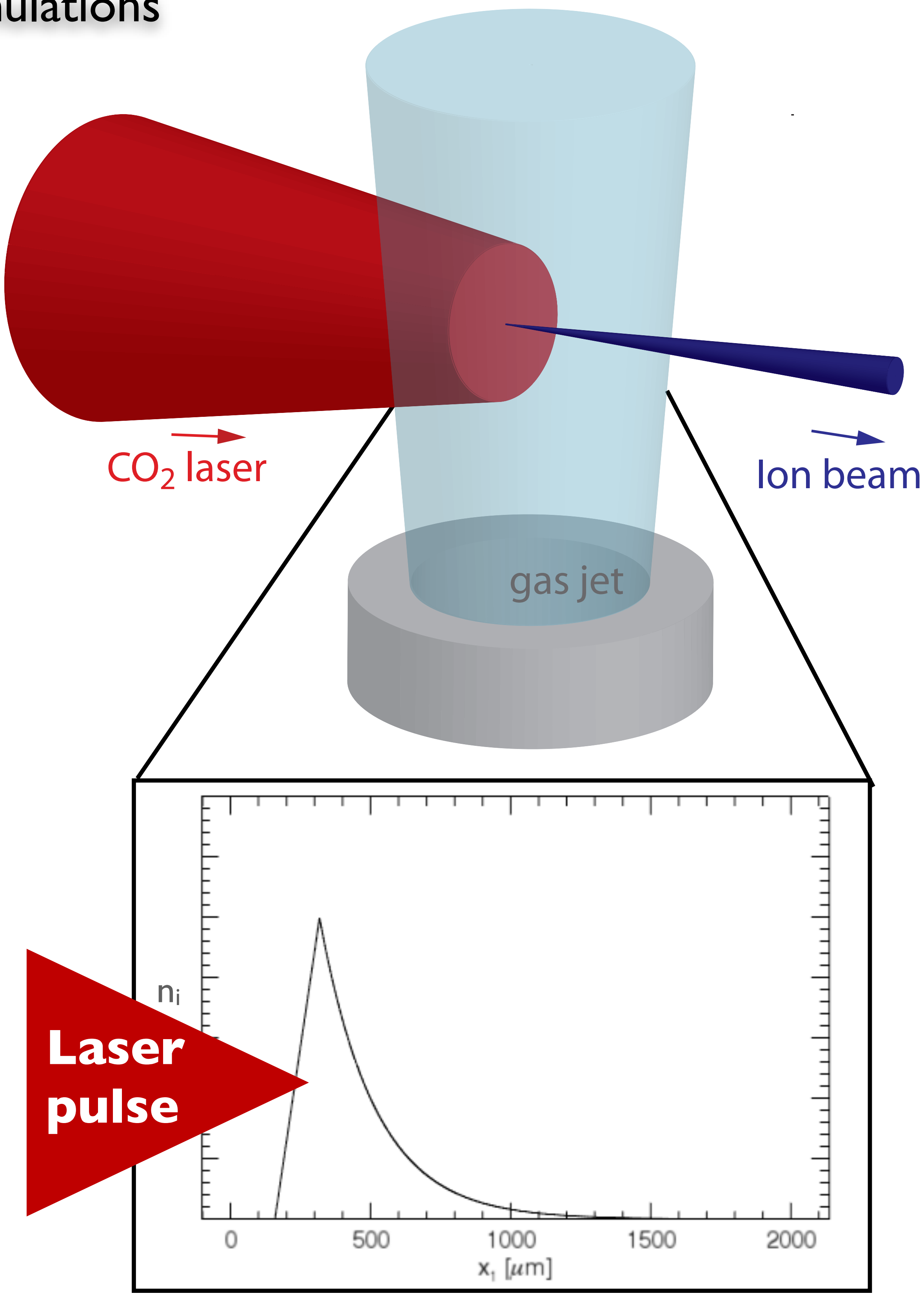


# mm scale plasmas can be formed by using structured $CO_2$ lasers



# OSIRIS simulation setup

2D simulations




## Physical Parameters

**Laser**

- $\lambda_0$ = 10 mm
- $I_0 = 10^{16} - 10^{18}$ $Wcm^{-2}$
- $\tau_0$ = 3 - 10 ps
- $W_0$ = 50 μm - ∞

**Plasma**

- Box = 6000 x 400 $\mu m^2$
- $L_g$ = 20 μm
- $n_{e0} = 10^{19}$ ($n_c$) - $10^{20}$ $cm^{-3}$ (10 $n_c$)
- $m_i/m_e$ = 1836

## Numerical Parameters

- $\Delta x = \Delta y = 0.5\ c/\omega_p$
- Part. per cell = 16
- cubic interpolation

# Mono-energetic proton beams driven by $CO_2$ laser

Ion density

Longitudinal E-field

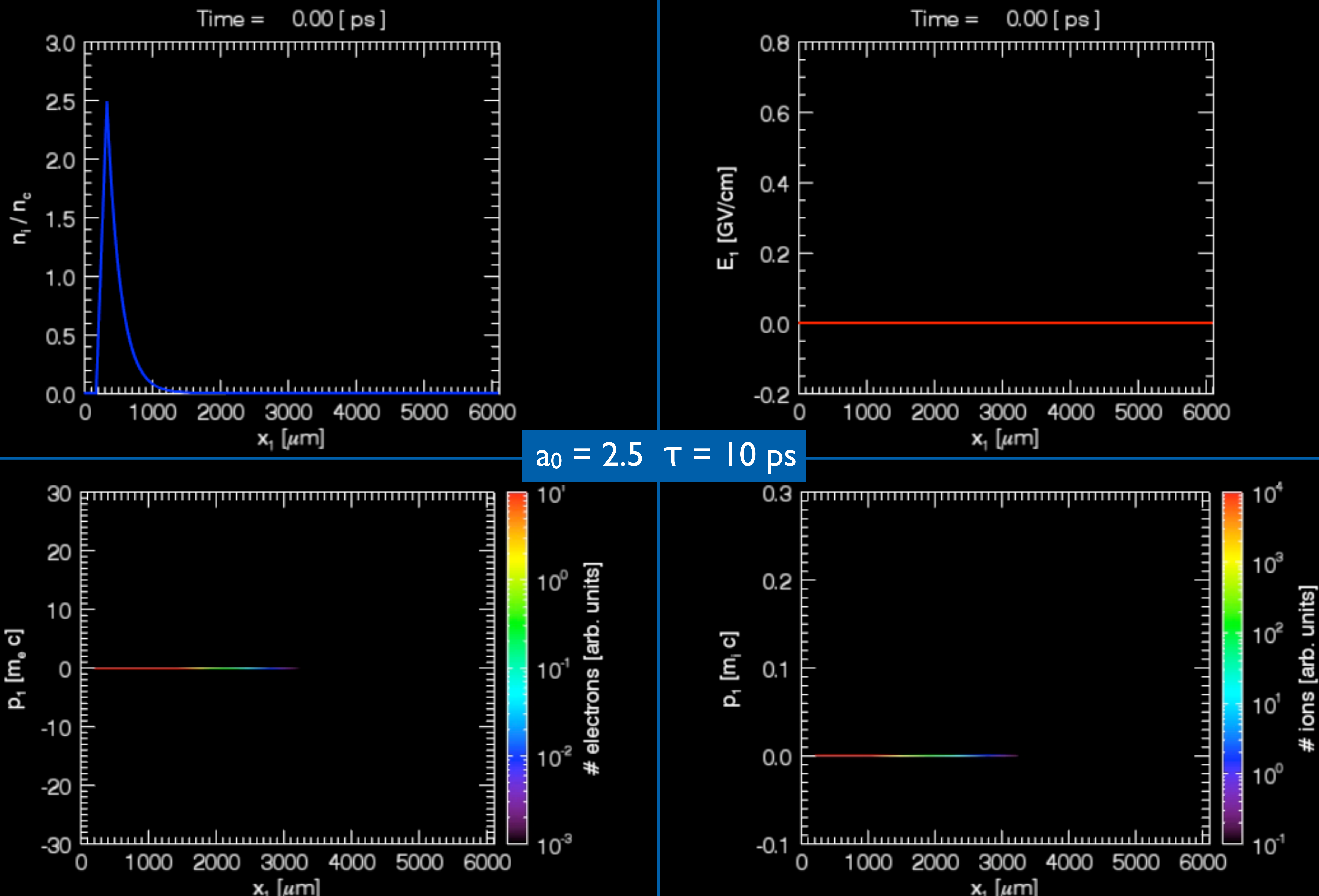
$a_0 = 2.5 \quad \tau = 10$ ps

Electron phase-space

Ion phase-space

2D simulation

# Mono-energetic proton beams driven by $CO_2$ laser




$a_0 = 2.5$ $\tau = 10$ ps

2D simulation

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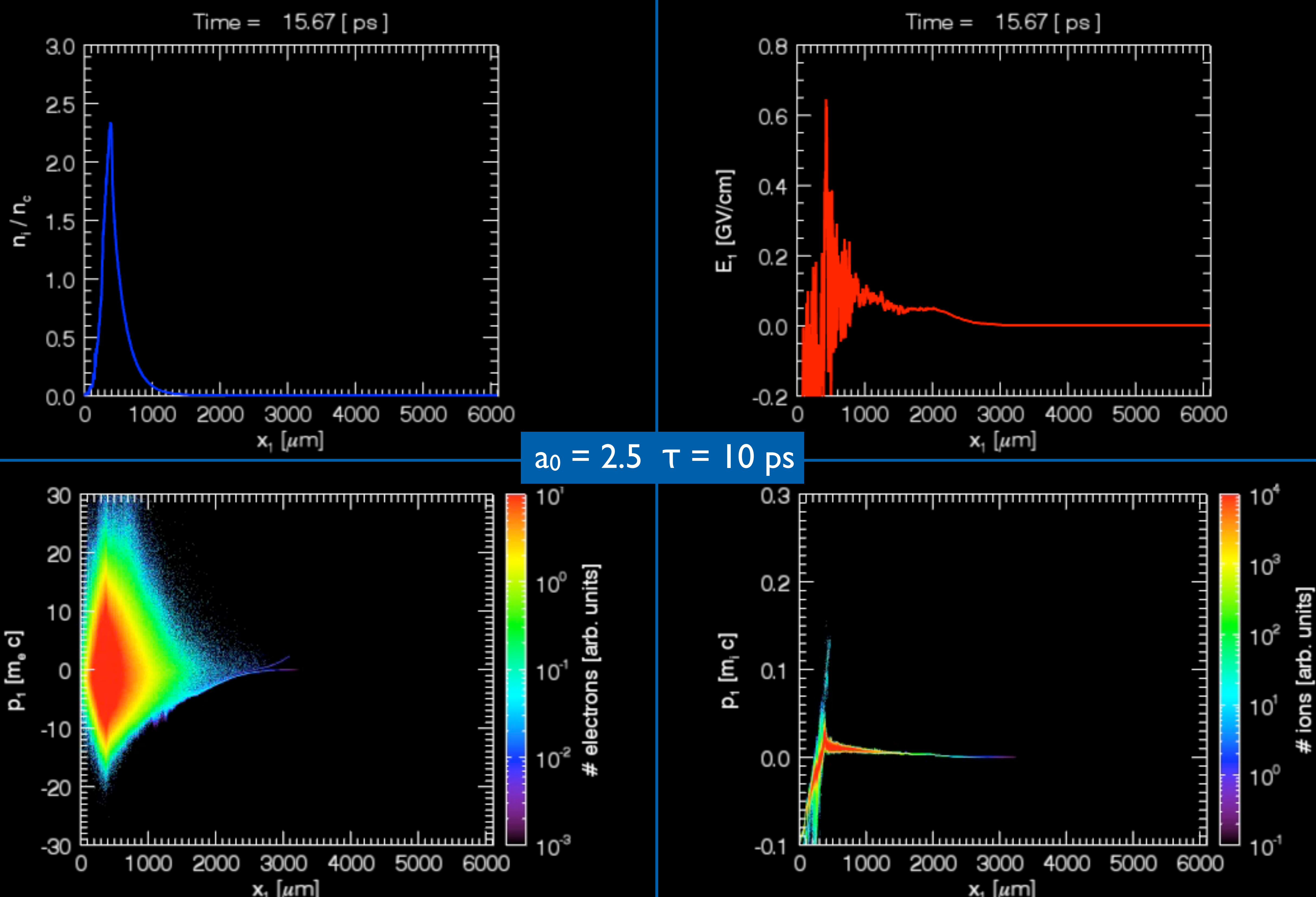
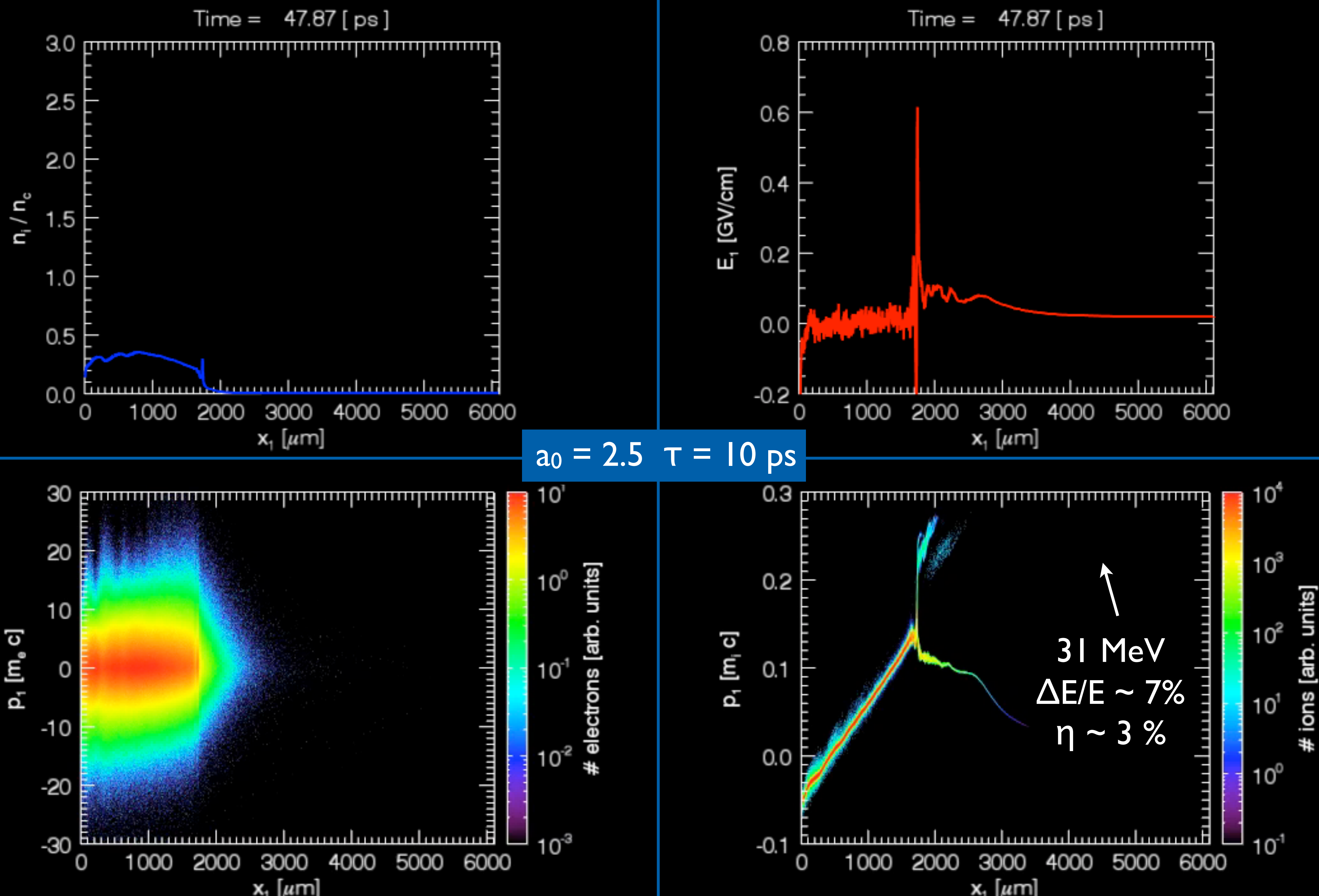



2D simulation

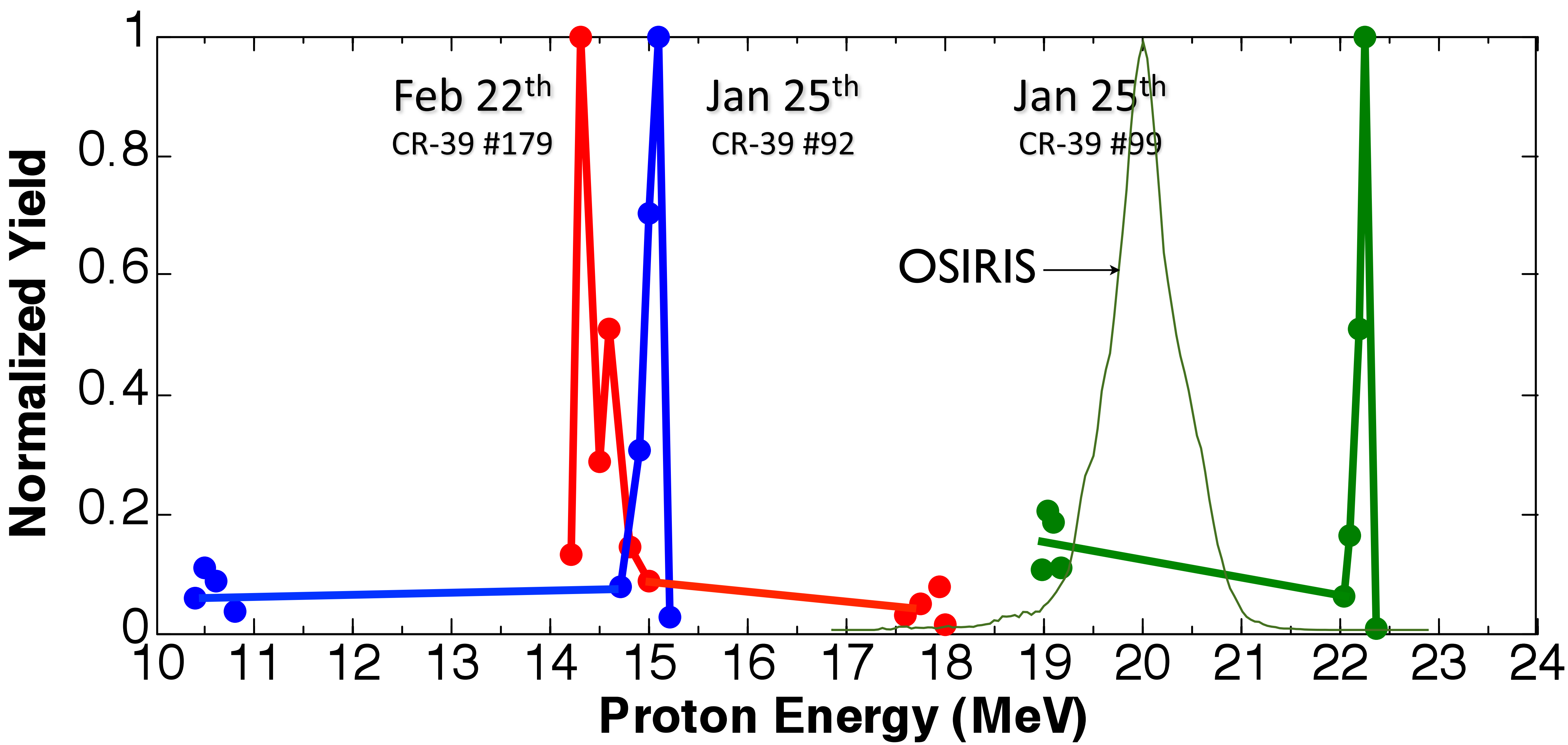
# Mono-energetic proton beams driven by $CO_2$ laser




2D simulation

# Monoenergetic proton beams with unprecedented energies

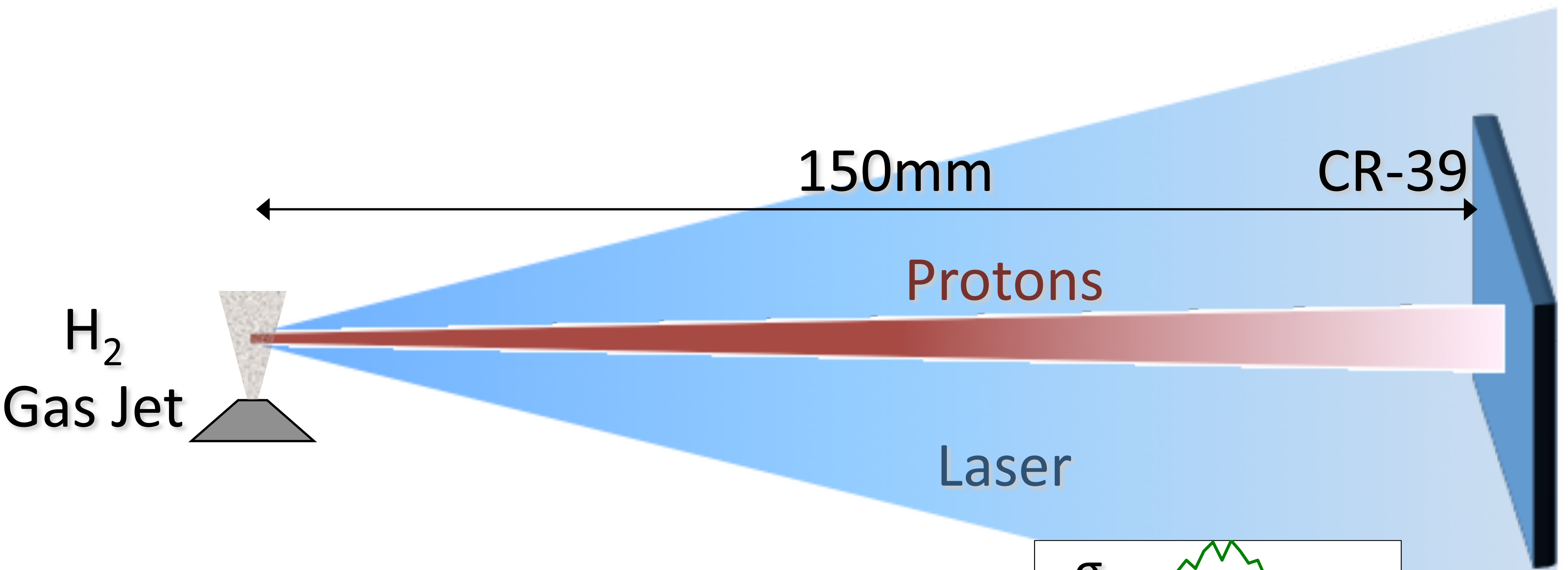
Energy spreads measured to be FWHM ΔE/E ~1%

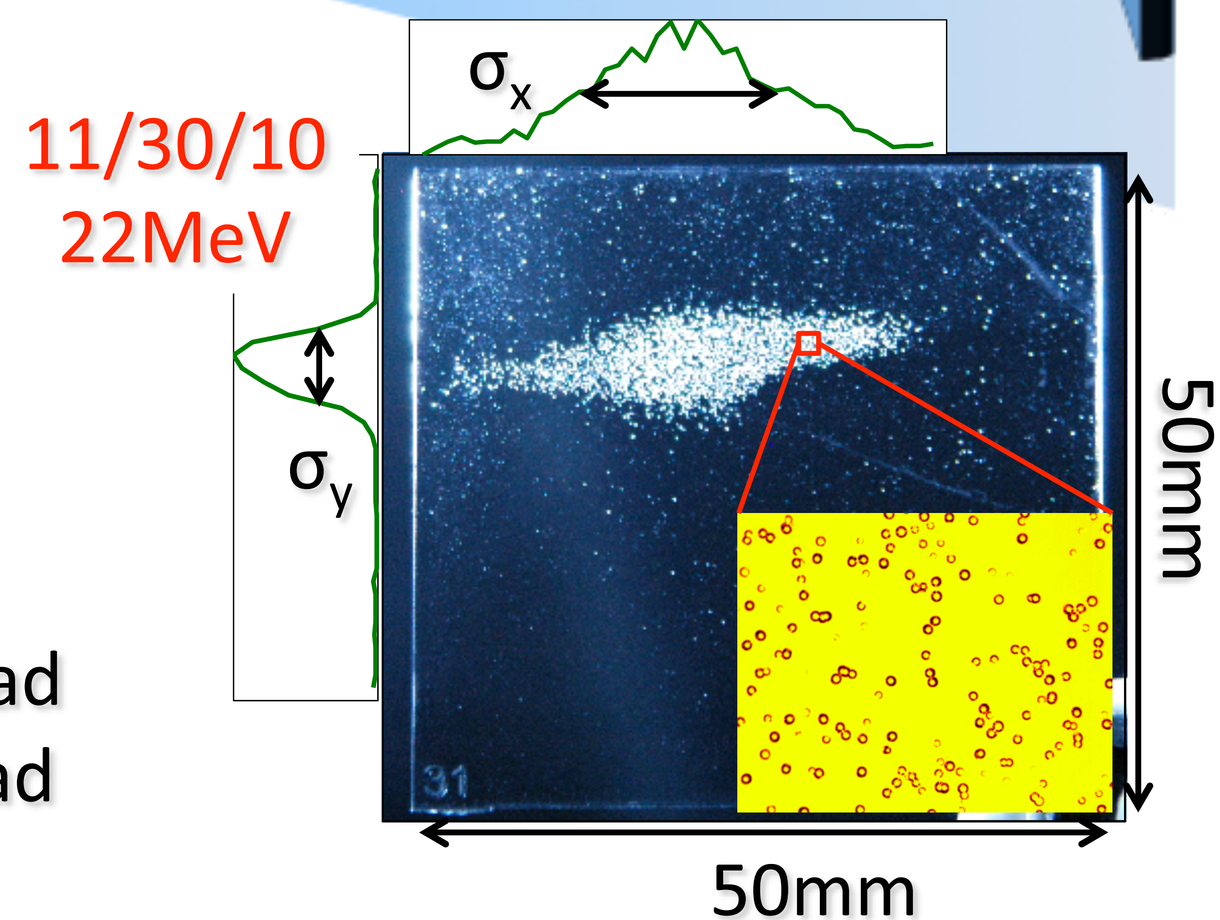



Previously 1 MeV, rms ΔE/E ~ 4% had been measured (C. Palmer et al., PRL 2011)

Neptune Laboratory

# Low beam emittance has been measured




Source Size : d = 120μm

Beam Size (RMS) : $\sigma_x$ ~ 5.7mm

$\sigma_y$ ~ 2.2mm

Divergence : $\theta_x$ ~ 37mrad

$\theta_y$ ~ 14mrad

Emittance : $\varepsilon_x = d \cdot \theta_x$ = 4.6mm·mrad

$\varepsilon_y = d \cdot \theta_y$ = 1.7mm·mrad

# Summary

- **R&D in plasma based accelerators in Portugal is based at IST,** with experimental activities launched in 1991 by Tito Mendonça, in close collaboration with EU and US partners

- **Focus at IST** is on **PIC simulations** and **plasma sources** as key technologies for plasma accelerators

- **Theory and simulations** grounded on **massivelly parallel simulations** (OSIRIS, QUICKPIC, JRad, dHybrid, visXD)

- **Experimental activities** take advantage of **Laboratory for Intense Lasers at IST + laser team** and **gas electronics expertise**