Laser-Accelerated Protons as a Probe of Laser Acceleration of Protons: Electromagnetic Dynamics of Space-Charge Fields

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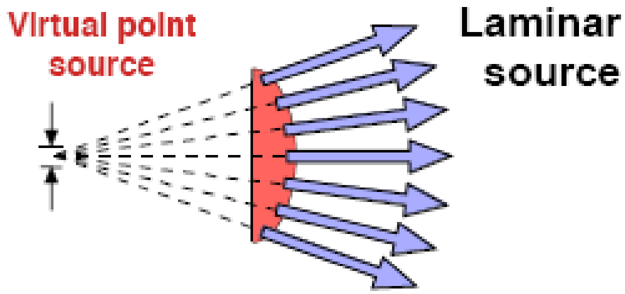
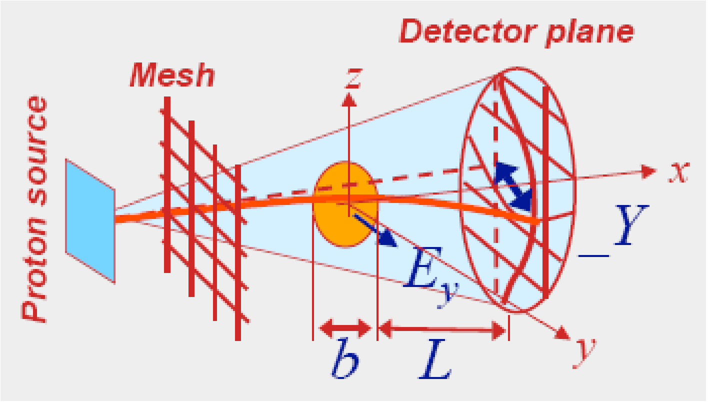
Outline

- Laser-Accelerated Protons as a probe of Laser-Plasma interactions
- Proton probing-based investigations
  - ➔ Plasma expansion and sheath acceleration
  - ➔ Pulse self-channeling in the charge-displacement regime
  - ➔ Ultrafast charging dynamics

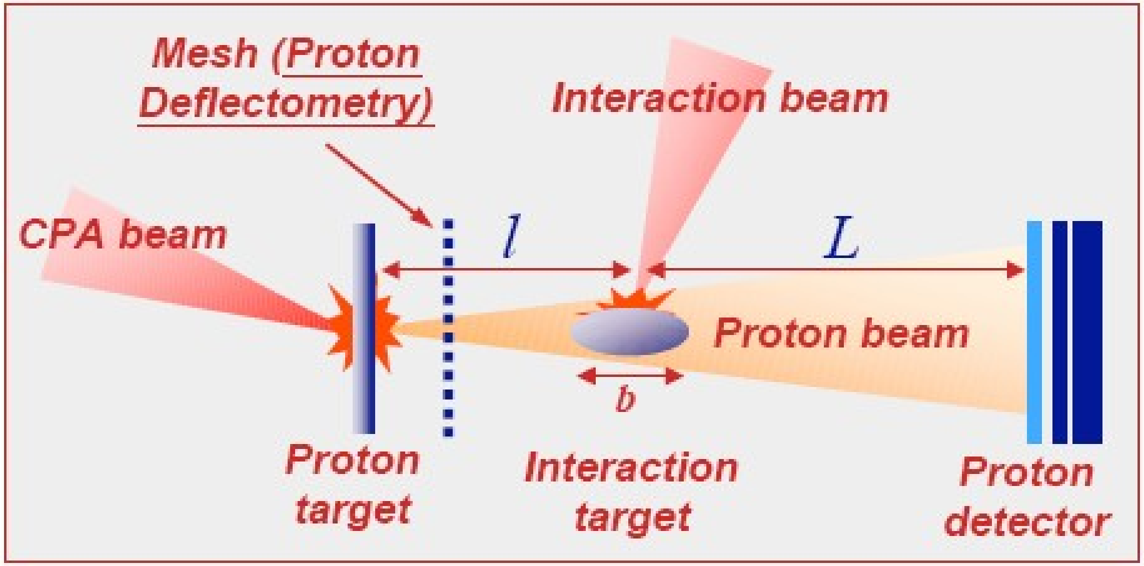
Use of laser-accelerated protons as a probe of EM fields in laser-plasma interactions





Due to high laminarity the proton beam has **imaging properties**

The short duration of the proton burst allows **picosecond temporal resolution**



Borghesi et al, Phys.Plasmas **9** (2002) 2214
Borghesi et al, Phys.Rev.Lett. **92** (2004) 055003
Cowan et al, Phys.Rev.Lett. **92** (2004) 204851

Protons of a given energy will cross the probed object at a particular time.
An energy-resolving detector (e.g. Radiochromic Film) thus provides **multiframe capability**

In a laser-plasma experiment the proton probe is easily **synchronized with the interaction**

Modeling of "proton probing experiments"

The proton probing techinque (PPT) is unique in providing space- and time-resolved measurement of probe proton deflection which can be traced back to the effect of electric and magnetic fields.

Interpretation of proton diagnostic data usually occurs through three steps:

1. Find a model (analytical and/or numerical) for the electric field $\mathbf{E}(x,t)$ [and/or the magnetic field $\mathbf{B}(x,t)$]

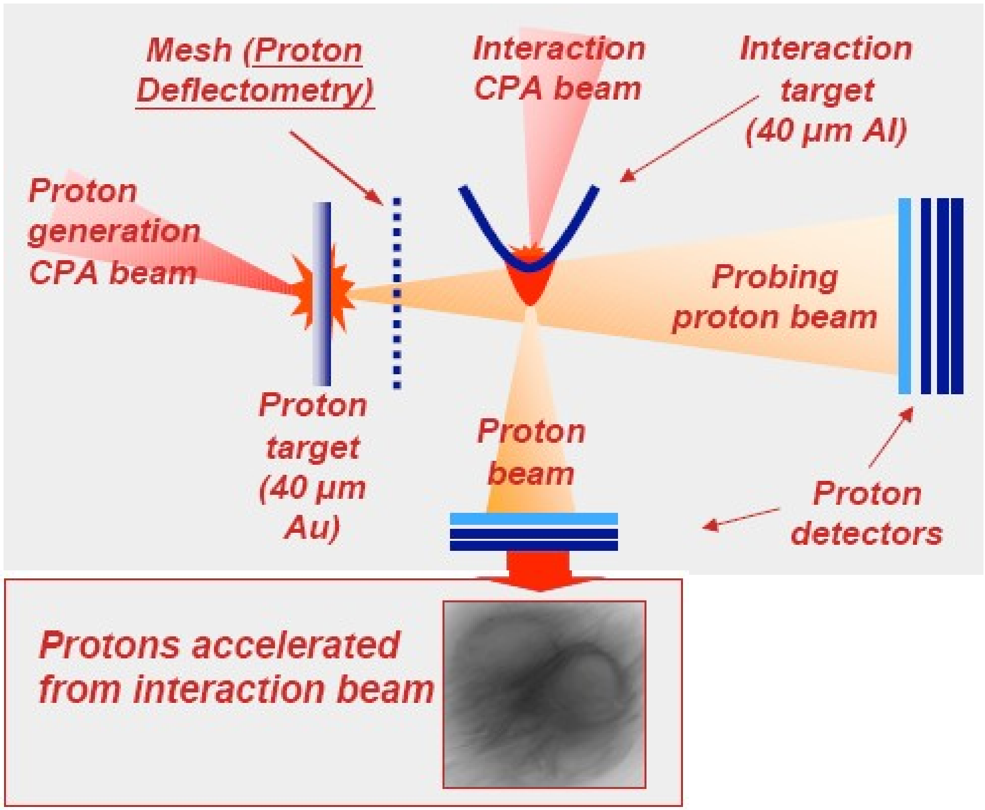
   - frequent need to bridge the gap between temporal scales or dimensionality of laser-plasma "ab initio" simulations (particle-in-cell method) and those of the experiment:

   fs ➡ ps , 2D ➡ 3D

2. Simulate the proton diagnostic via particle tracing simulations with $\mathbf{E}(x,t)$ [and/or $\mathbf{B}(x,t)$] as input

3. Compare simulated proton images with experimental ones

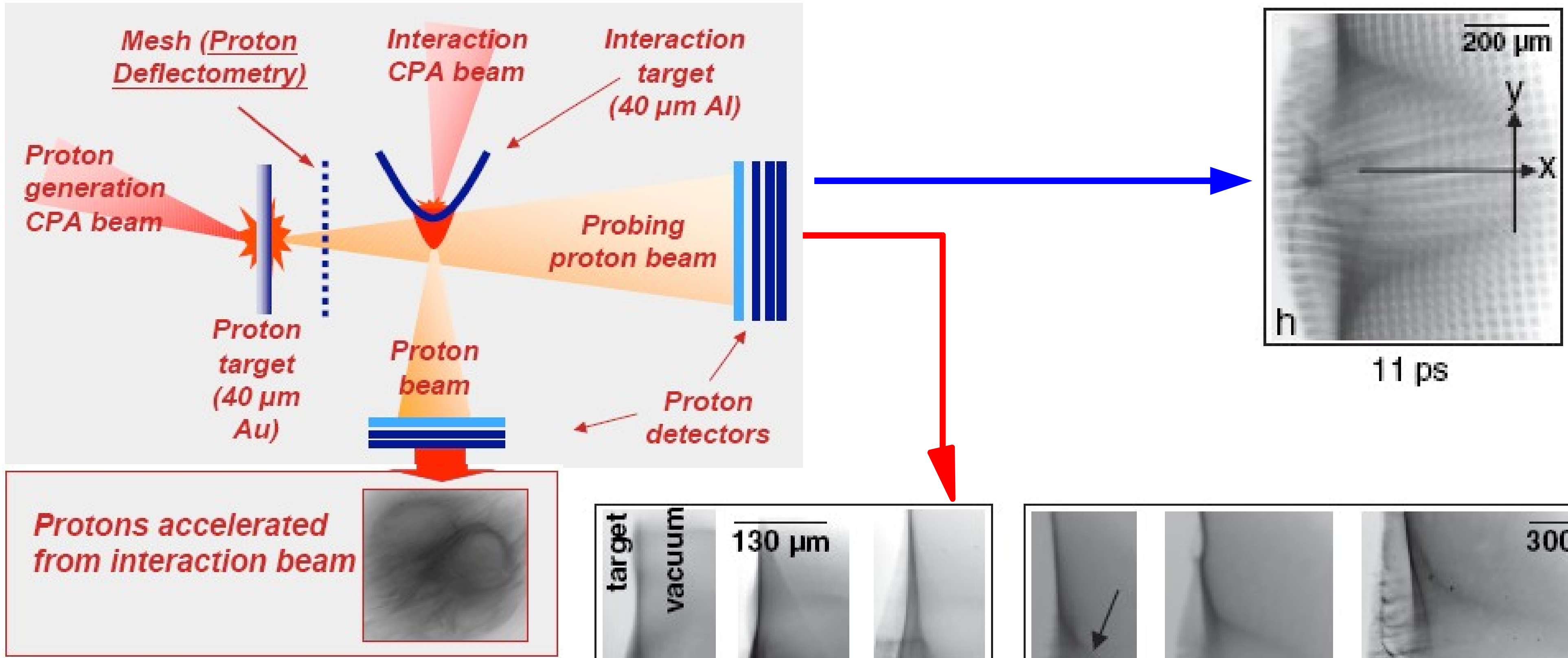
Detection of Proton-Accelerating Sheath Fields

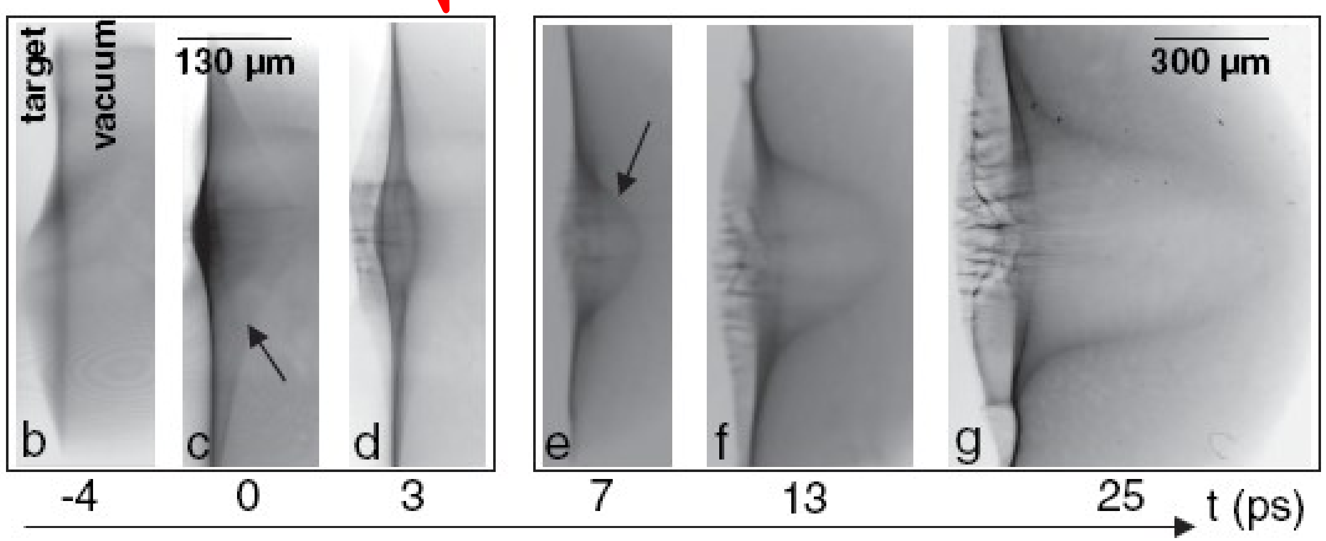


Goal: study of TNSA mechanism for ion acceleration
by the direct detection of related space-charge electric field

Technique: use a second proton beam as a transverse probe

Detection of Proton-Accelerating Sheath Fields



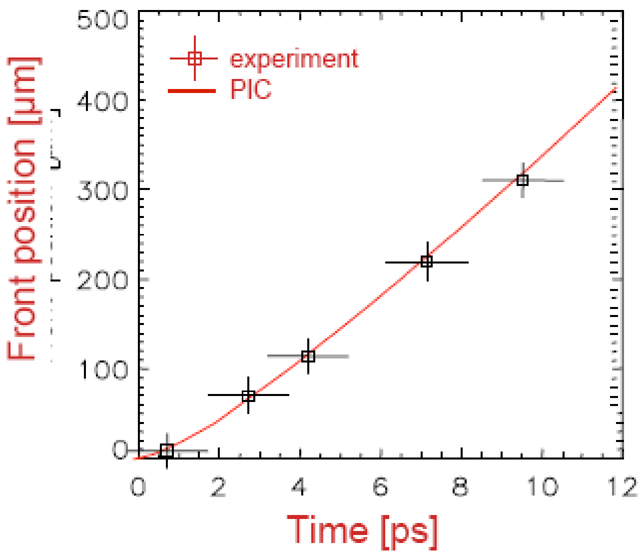


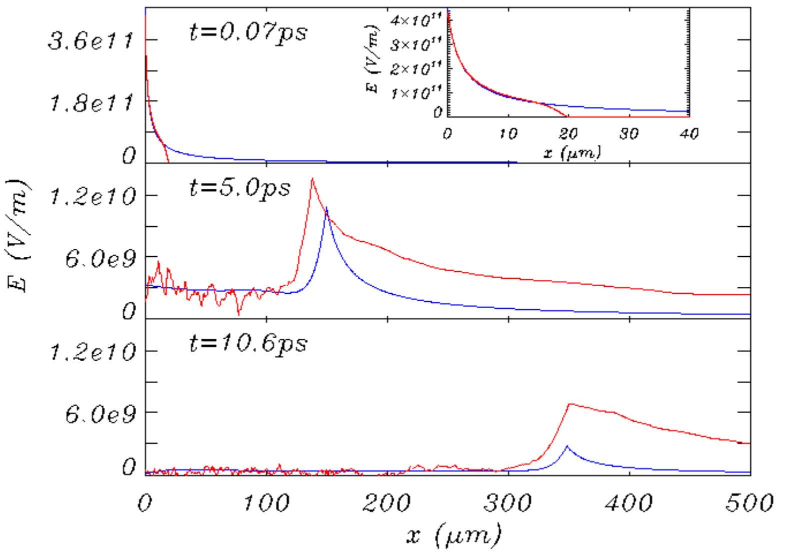
Expanding, bell-shaped front observed in proton images and deflectograms

L. Romagnani, J. Fuchs, M. Borghesi, P. Antici, P. Audebert, F. Ceccherini, T. Cowan, T. Grismayer, S. Kar, A. Macchi, P. Mora, G. Pretzler, A. Schiavi, T. Toncian, O. Willi, Phys. Rev. Lett. **95** (2005) 195001

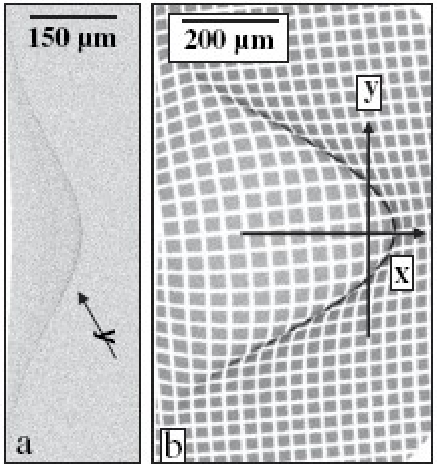
Experimental detection of sheath fields using the proton diagnostic

Experimental results have been compared with PIC simulations using the plasma expansion model.





Particle tracing simulations of proton deflection in the PIC fields (plus an "heuristic" modeling of the 2D expansion) fit well experimental images and deflectrograms

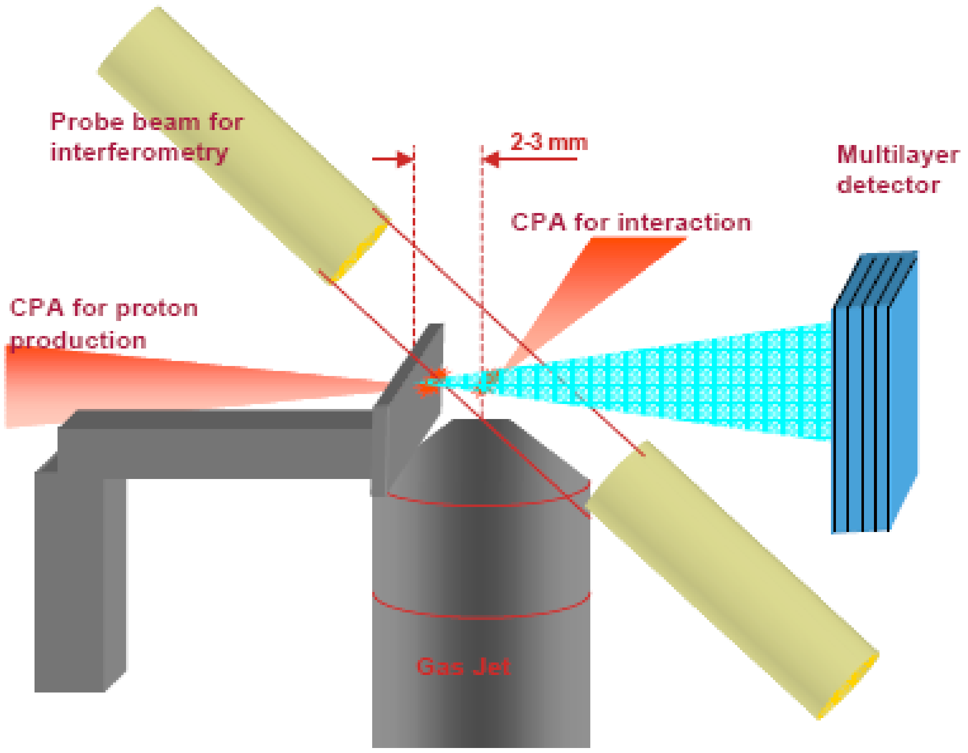


Comparison of fluid and kinetic (PIC) results show the importance of **non-**equilibrium, **kinetic** and **non-Maxwellian** effects in the plasma expansion

L. Romagnani, J. Fuchs, M. Borghesi, P. Antici, P. Audebert, F. Ceccherini, T. Cowan, T. Grismayer, S. Kar, A. Macchi, P. Mora, G. Pretzler, A. Schiavi, T. Toncian, O. Willi, Phys. Rev. Lett. **95** (2005) 195001

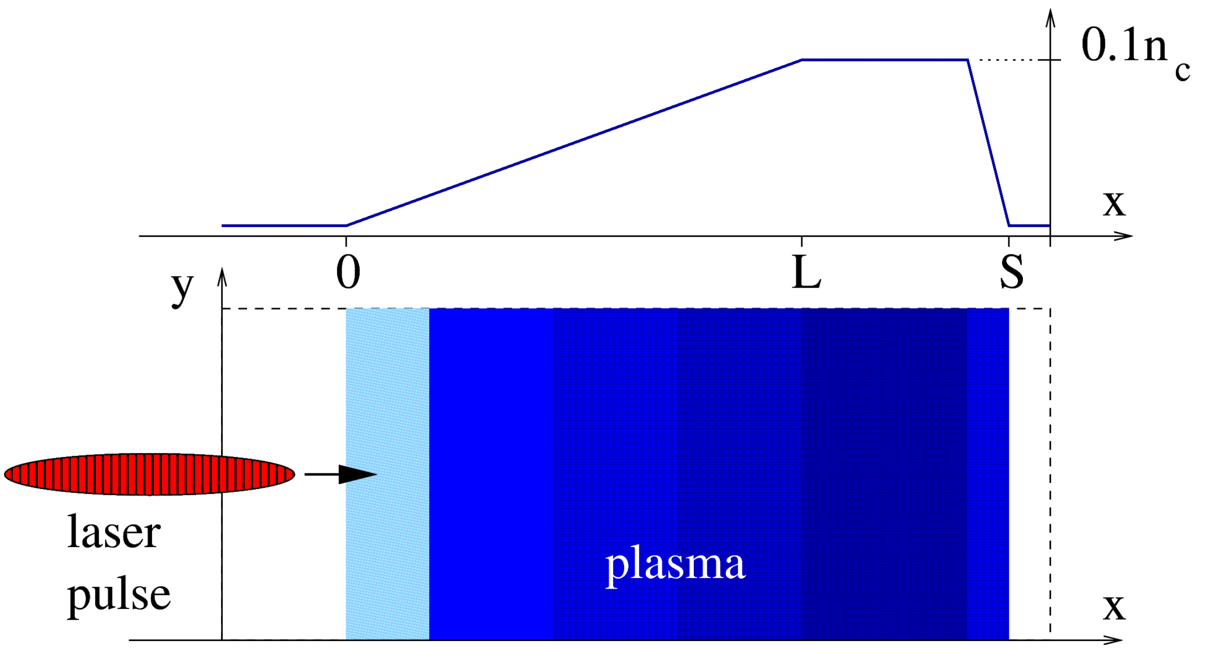
Study of charge-displacement self-channeling

A superintense laser pulse propagating in a low-density plasma (produced in a gas jet) undergoes self-focusing and channeling due to both relativistic effects and radial plasma expulsion by radiation pressure.

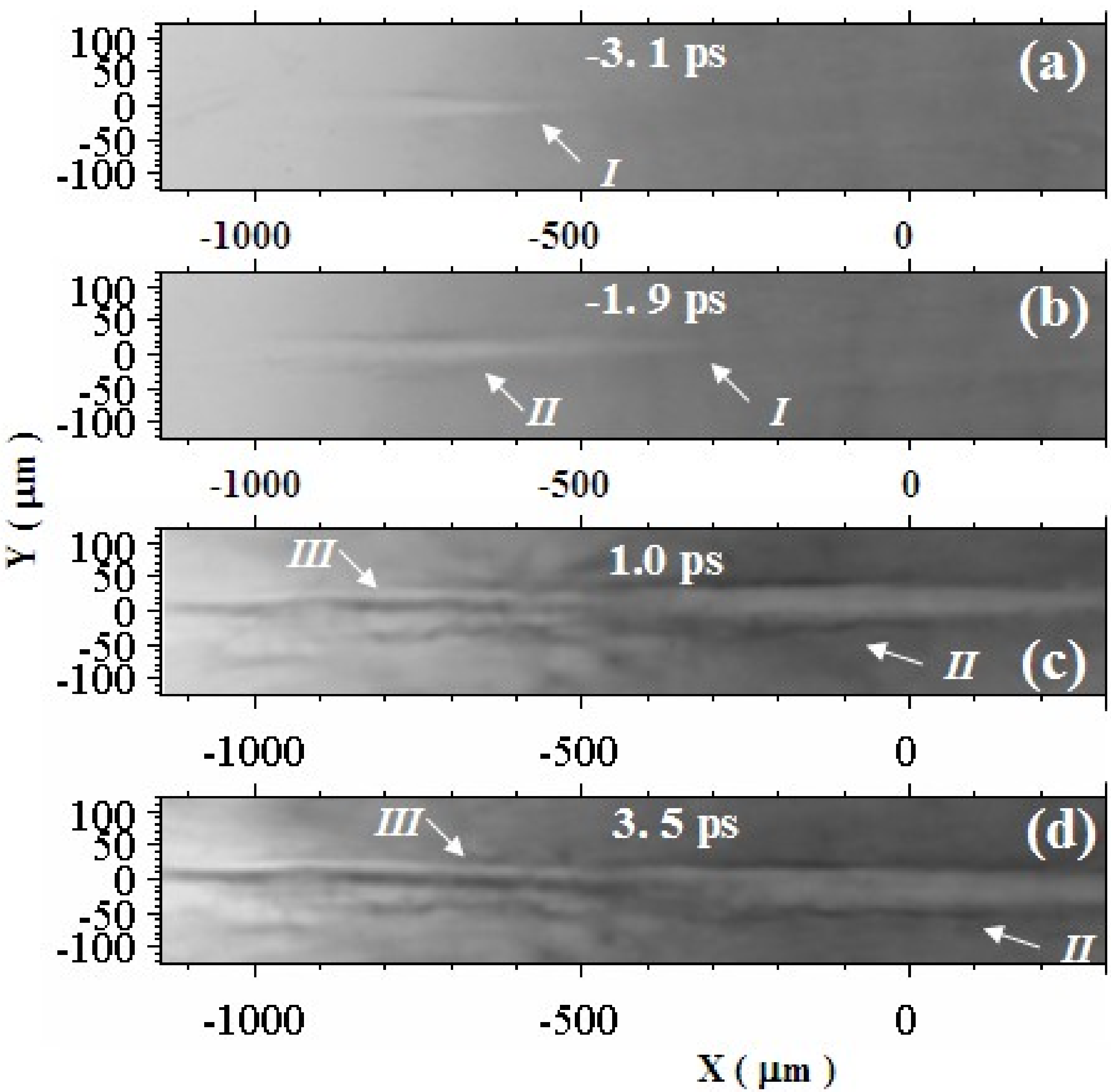


For a transient stage the channel is charged since electrons are expelled first.

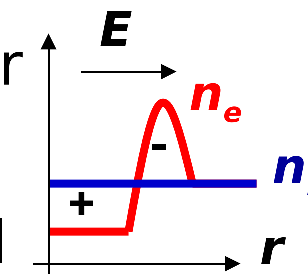
Proton probing along the direction perpendicular to propagation has been used to study this effect



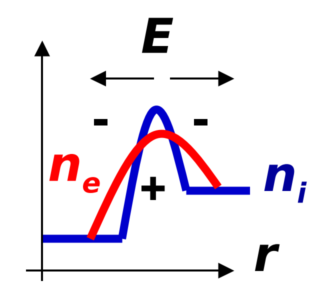
Proton images of charged channel evolution



Early times (during the laser pulse) propagating "white" channel front indicates electron expulsion from the axis

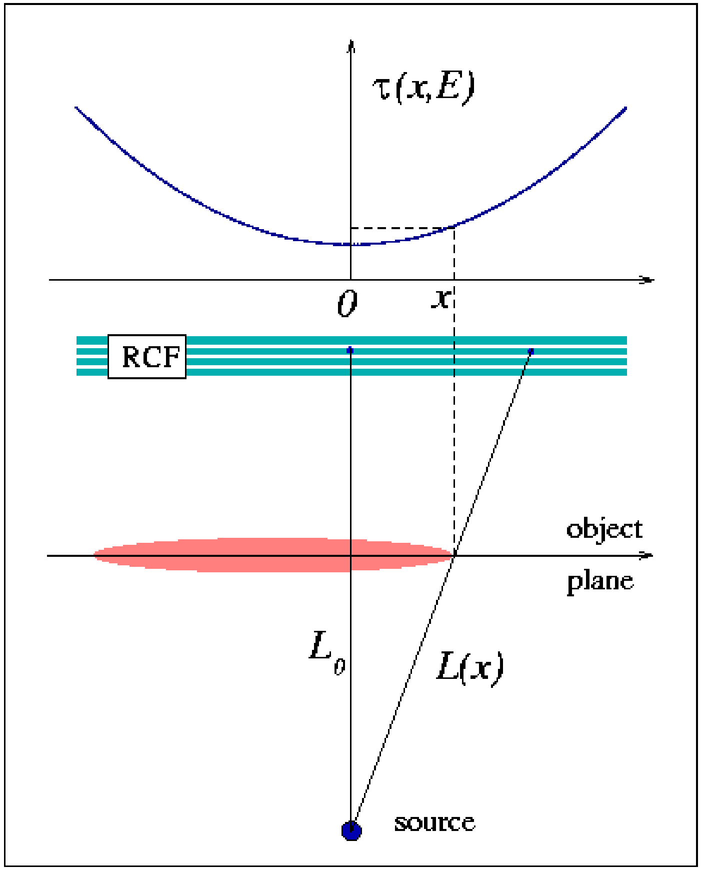


Late times (after the laser pulse) "black" line on axis indicates field inversion at some location



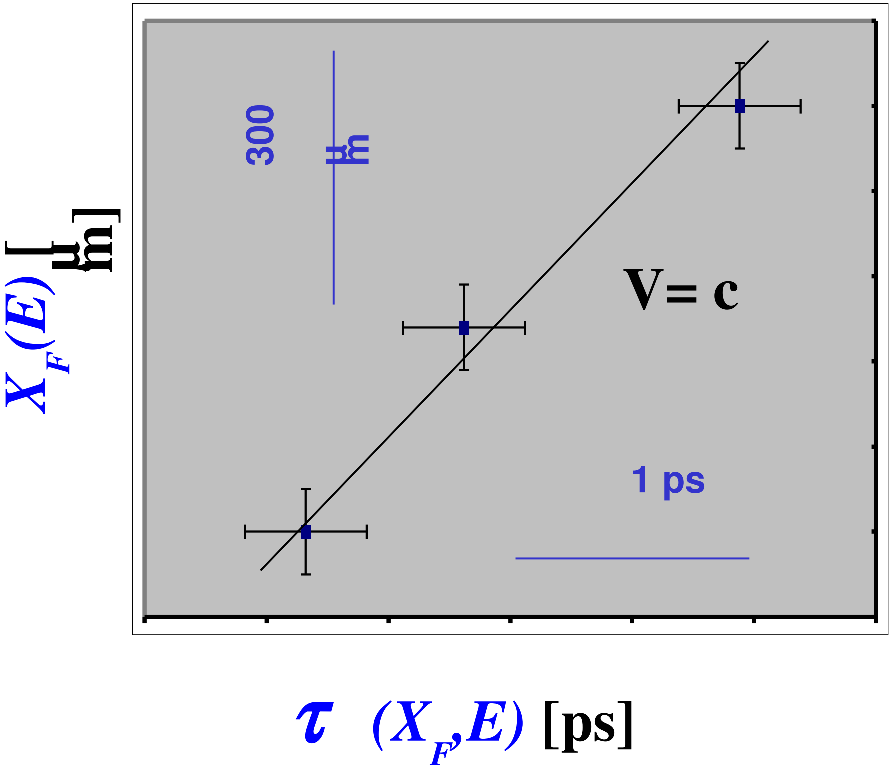
S.Kar, M.Borghesi, C.A.Cecchetti, L.Romagnani, F.Ceccherini, T.V.Lyseikina, A. Macchi, R.Jung, J.Osterholz, O.Willi, M.Galimberti, L.A.Gizzi, A.Schiavi, R.Heathcote, New J. Physics **9**, 402 (2007)

Channel front propagation speed



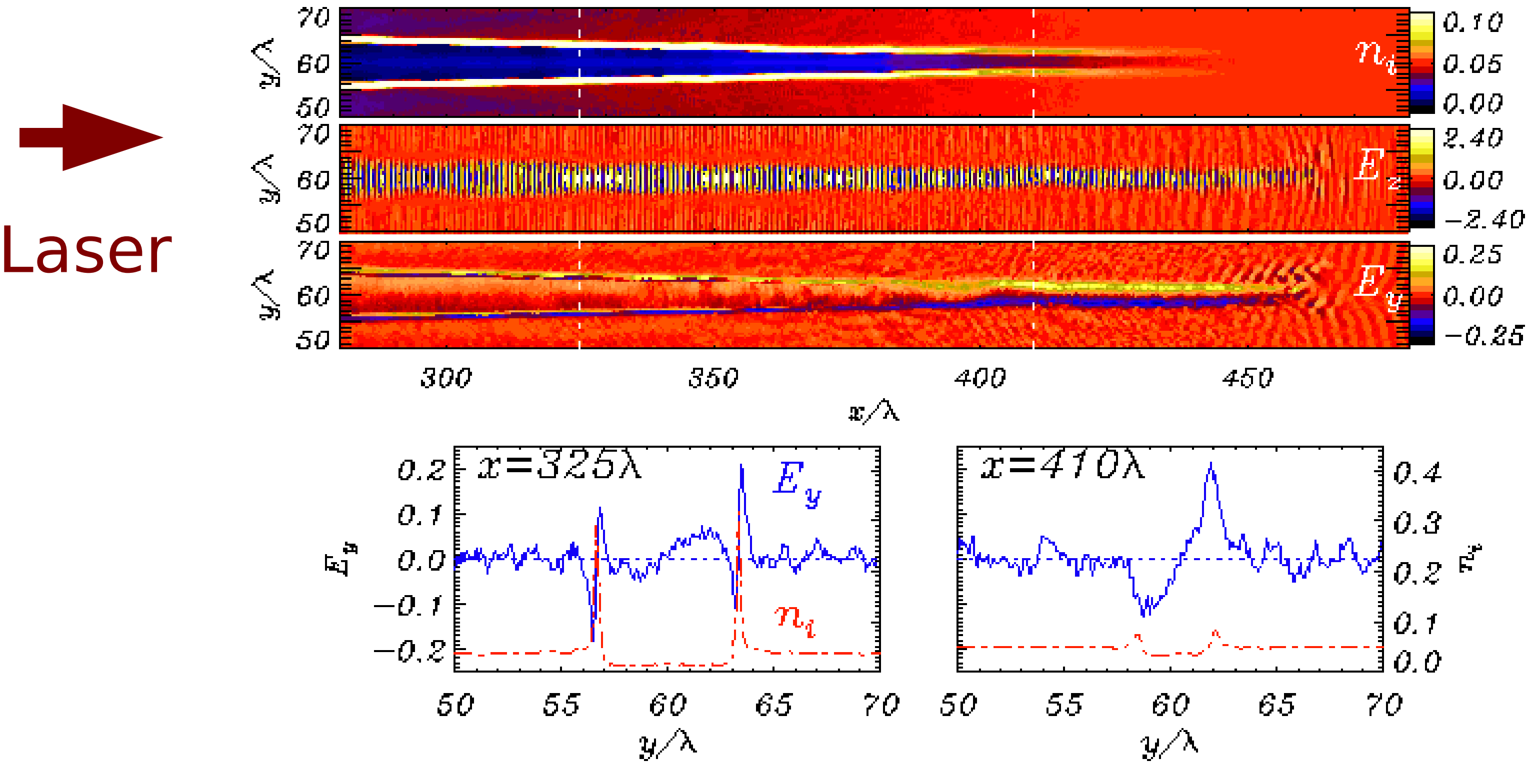
Due to the divergence of the proton beam the "probing time" depends on angle (i.e. on the position on the object plane)

$$\tau(x, E) = t_0(E) + \frac{L_0}{\sqrt{2E/m_p}}\left(\sqrt{1 + x^2/L_0^2} - 1\right)$$



Plotting the channel front displacement $X_F(E)$ vs. the probing time τ (X_F,E) we obtain the front propagation speed $V \sim c$

2D PIC simulations show “radial” field dynamics



Two ambipolar fronts of E_y appear in the trailing edge of the channel; “negative” part can produce “black line” in proton images

Outward-directed radial field E_y due to electron expulsion from axis

EM component E_z reveals self-focusing

S.Kar, M.Borghesi, C.A.Cecchetti, L.Romagnani, F.Ceccherini, T.V.Lyseikina, A. Macchi, R.Jung, J.Osterholz, O.Willi, M.Galimberti, L.A.Gizzi, A.Schiavi, R.Heathcote, New J. Physics **9**, 402 (2007)

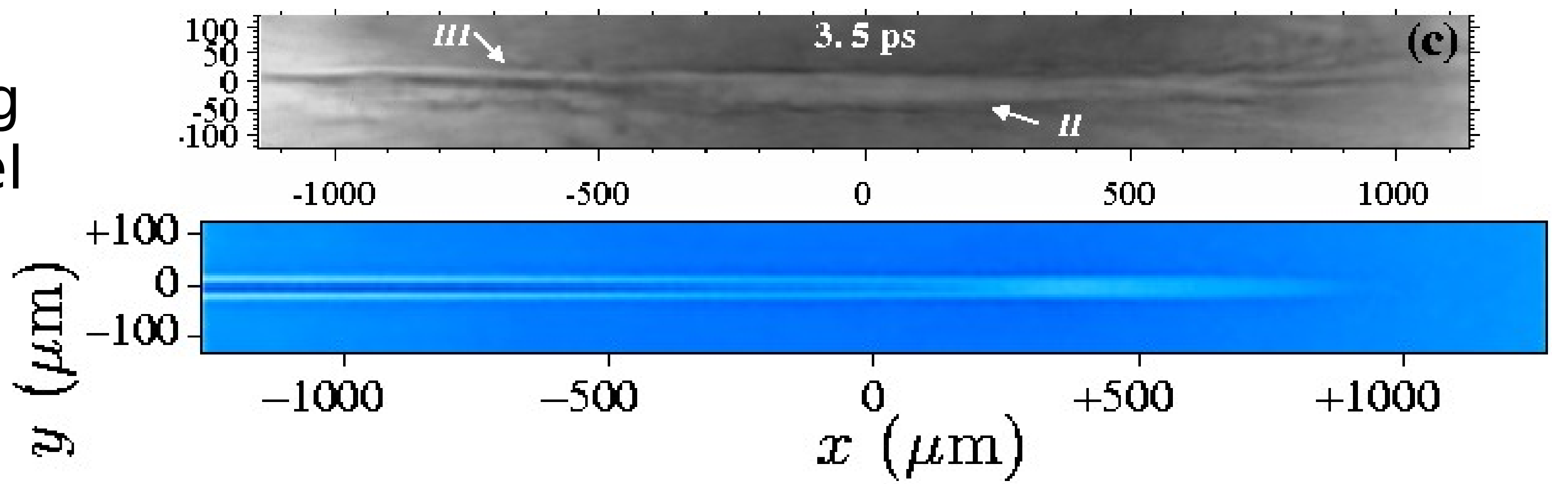
Ponderomotive model of self-channeling

Assumptions:
- cylindrical symmetry
- non-evolving laser pulse
- electrostatic approximation

$$\begin{aligned} m_e dv_e/dt &= -eE_r - m_e c^2 \partial_r \sqrt{1+a^2} \\ a = a(x,r,t) &= a_0 e^{-r^2/r_0^2-(x-ct)^2/c^2\tau^2} \\ m_i dv_i/dt &= ZeE_r \\ \frac{1}{r}\partial_r(r \cdot E_r) &= 4\pi e(Zn_i - n_e) \end{aligned}$$

Solution based on kinetic PIC model

Particle tracing simulations using $\mathbf{E}$ from PIC model well reproduce experimental features



S.Kar, M.Borghesi, C.A.Cecchetti, L.Romagnani, F.Ceccherini, T.V.Lyseikina, A. Macchi, R.Jung, J.Osterholz, O.Willi, M.Galimberti, L.A.Gizzi, A.Schiavi, R.Heathcote, New J. Physics **9**, 402 (2007)

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$$m_e dv_e/dt = -eE_r - m_e c^2 \partial_r \sqrt{1+a^2}$$

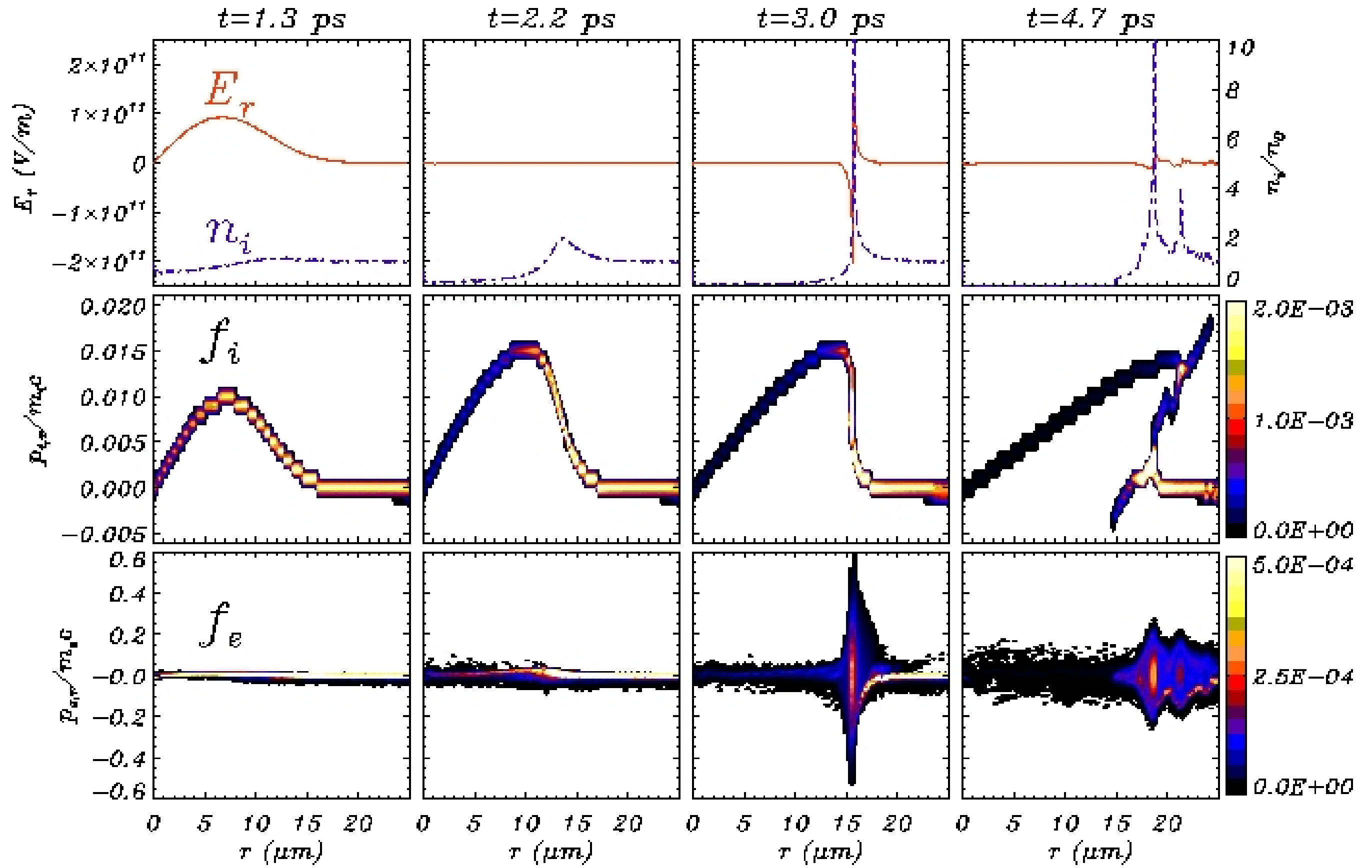
$$a = a(x,r,t) = a_0 e^{-r^2/r_0^2-(x-ct)^2/c^2\tau^2}$$

$$m_i dv_i/dt = ZeE_r$$

$$\frac{1}{r}\partial_r(r \cdot E_r) = 4\pi e(Zn_i - n_e)$$

Solution based on kinetic PIC model

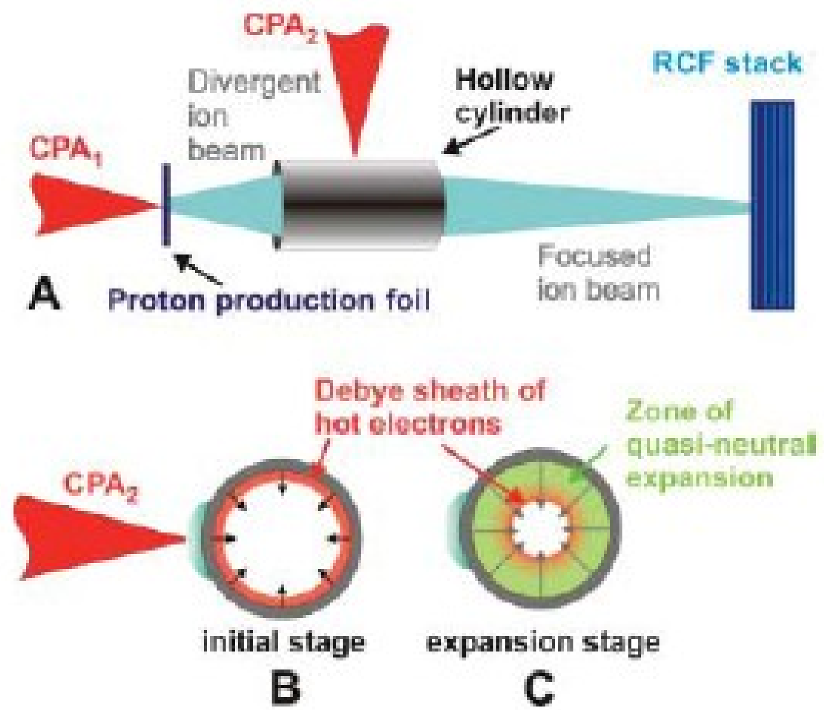
The late ambipolar field appears after the vanishing of the early field ("echo effect") due to hydrodynamical breaking of "X-type" in the ion density profile causing strong electron heating



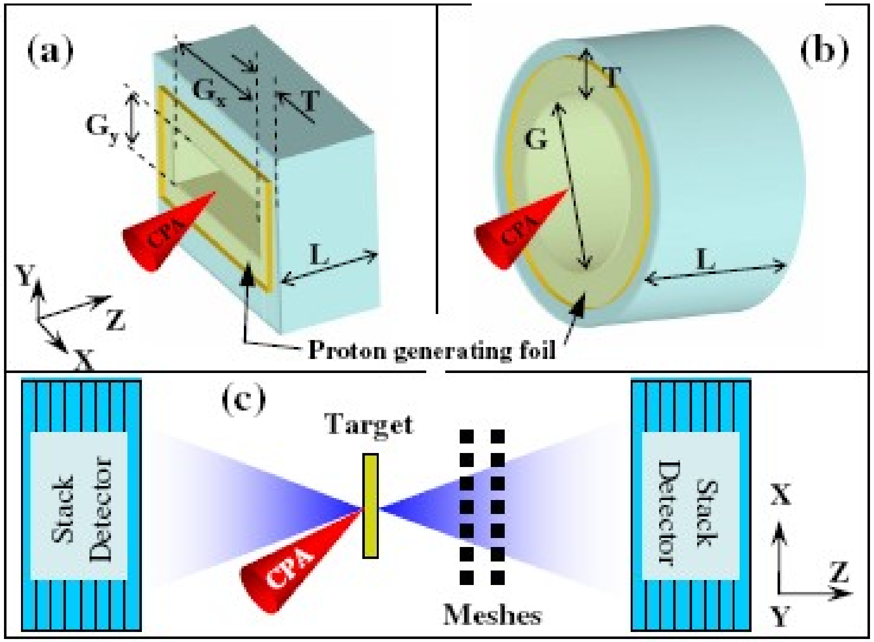
A. Macchi, F.Ceccherini, F. Cornolti, S.Kar, M.Borghesi, PPCF **51** (2009) 024005

Dynamic control of proton beam properties

Concept: achieve **focusing** and **energy selection** of the proton beam by “external” devices or by “target engineering”



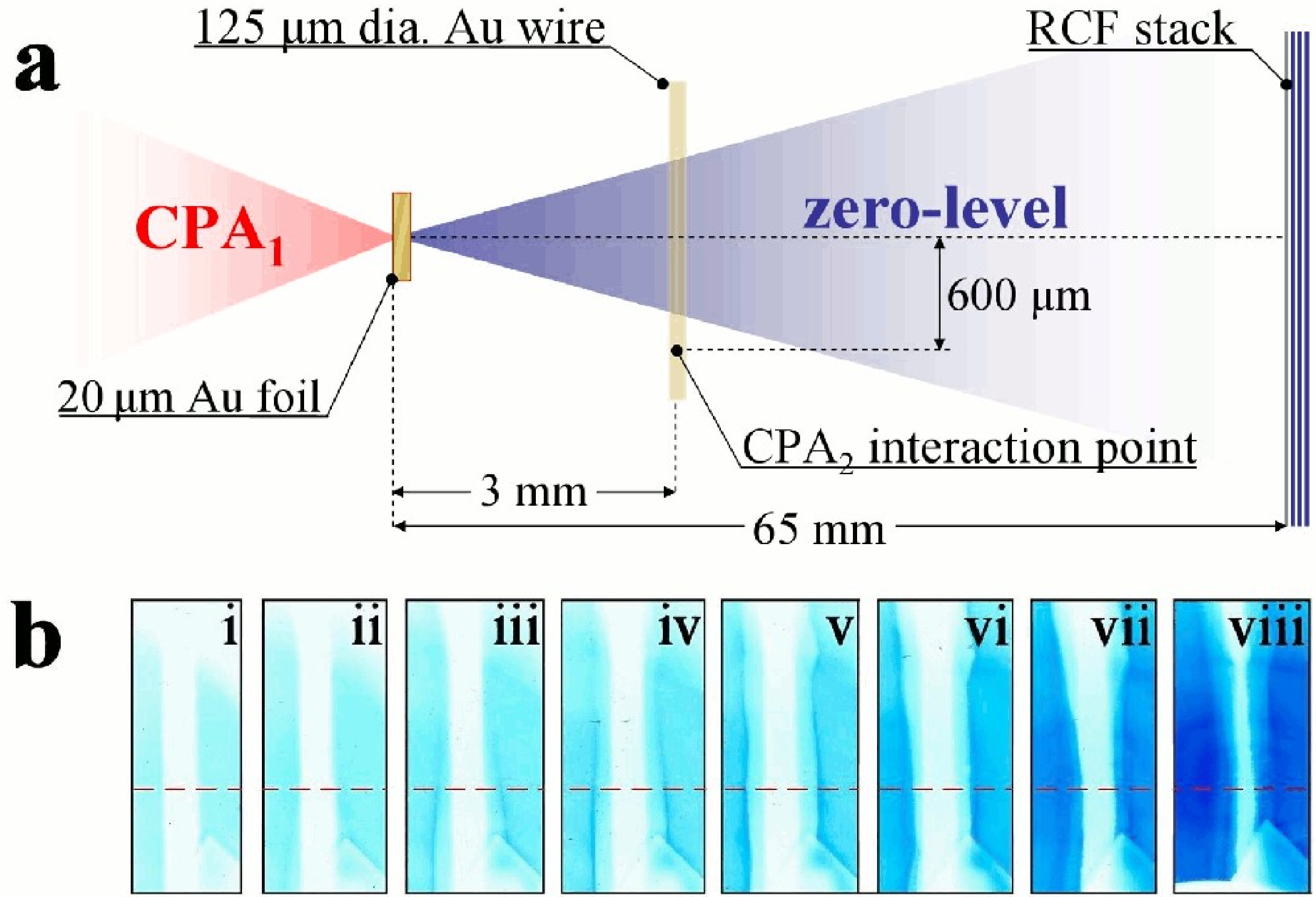
Laser-driven cylindrical microlens
Toncian et al., Science **312** (2006) 410



Shaped targets designed as **electrostatic (?) lenses**
Kar et al., PRL **100** (2008) 105004

Both approaches pose the question on **how rapidly** the electric field created by escaping electrons propagates on the surface of the target

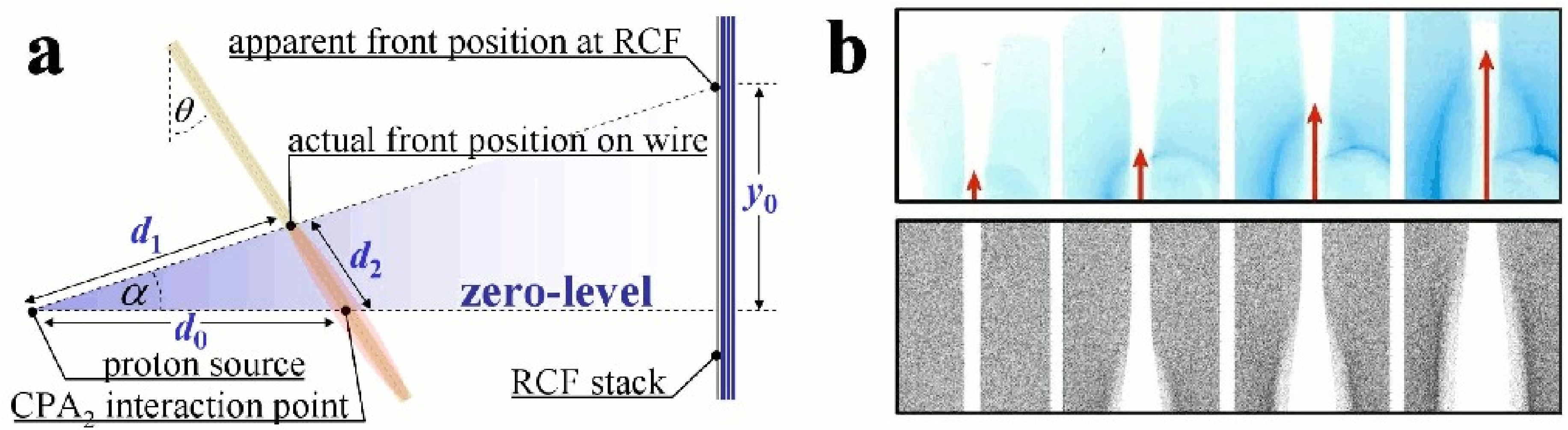
Electrical charging of a laser-irradiated solid wire



- In the interaction with a wire target a fast positive charging followed by later discharging is observed: escape of fast electrons and return neutralizing current?
- The propagation of the field out of the interaction region is not resolved with a "vertical" wire

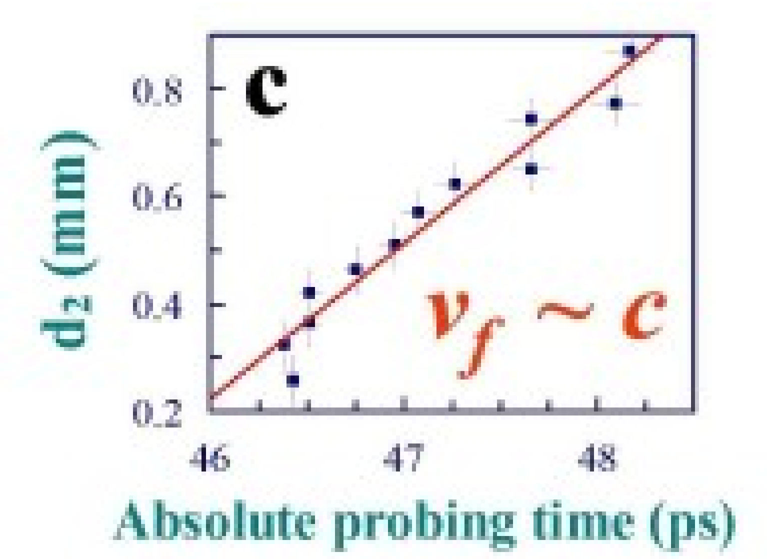
K. E. Quinn et al, accepted on PRL

Propagation velocity of the charging wave



By inclining the wire to an angle θ
with respect to the vertical axis
the propagation of the field is resolved now ;

the speed v_f=0.96±0.04c

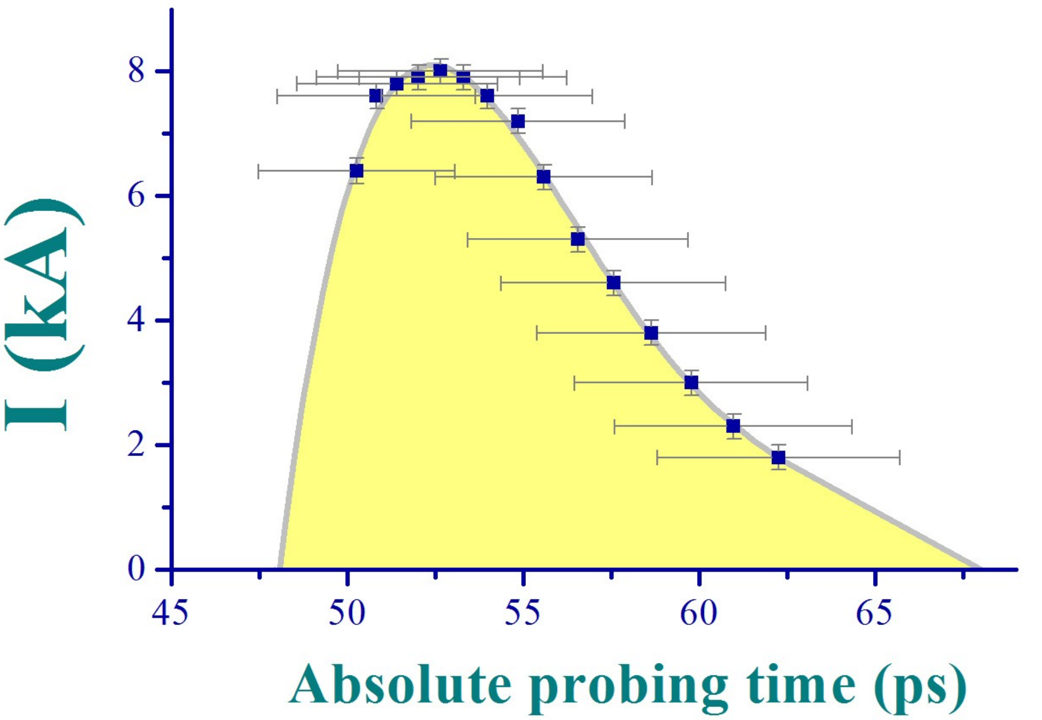


K. E. Quinn et al, submitted to PRL

Flowing current and loss of electrons from the wire

From the measurement of the radial field E_r and the propagation velocity v_f it is possible to reconstruct the history of the total current I flowing trough the wire

$$J(t) = \frac{1}{2} r_{\mathrm{w}} v_f E_s(t)$$



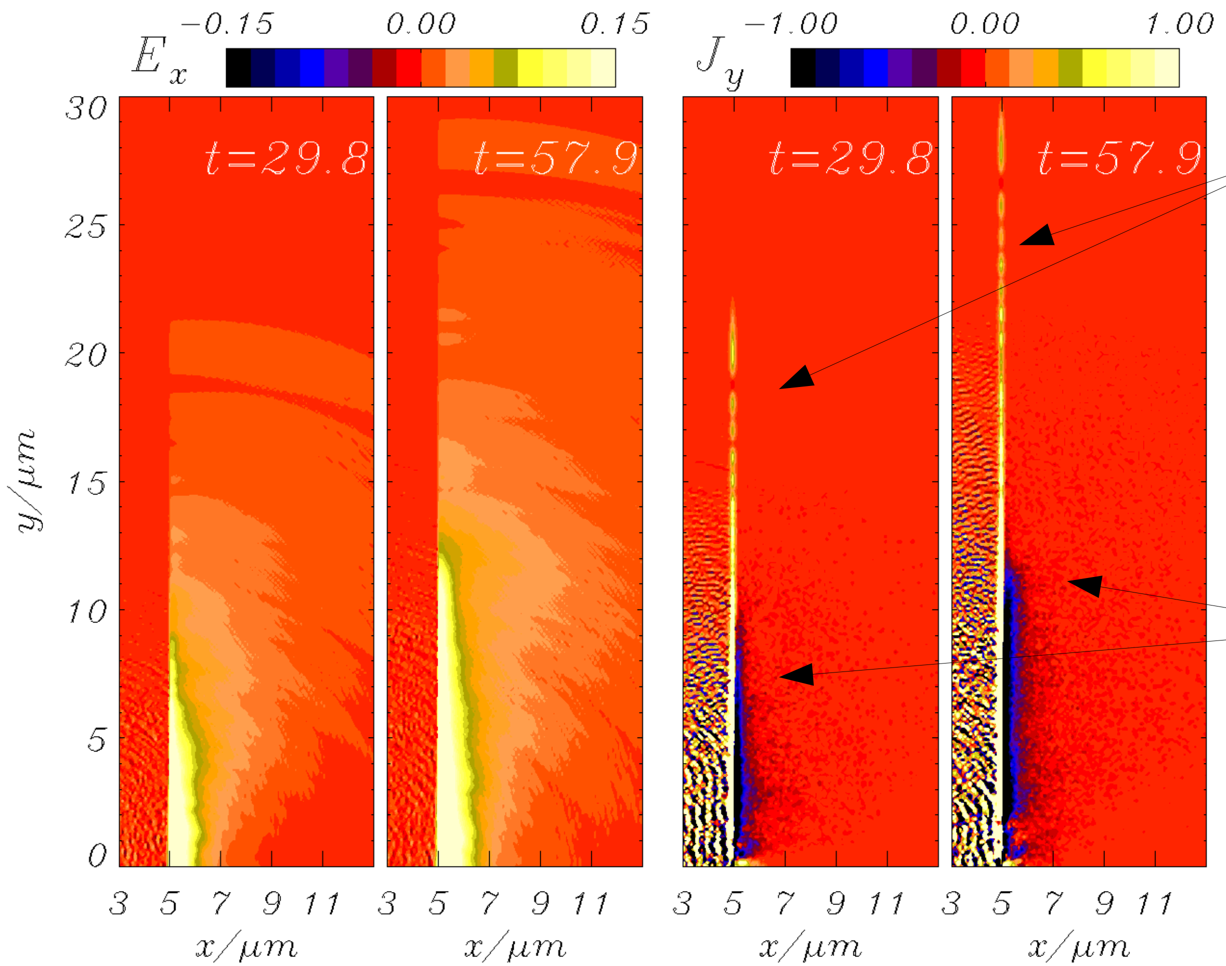
The estimate of the fraction of electrons escaped in vacuum f_{esc} thus obtained is roughly consistent with a simple estimate based on the charging of an “hot” plasma sphere or radius r_0 with N_e electrons in Boltzmann equilibrium

$$\frac{\ln f_{\mathrm{esc}}}{f_{\mathrm{esc}}} = -\frac{r_c}{r_0}\frac{m_e c^2}{k_B T_e} N_e$$

K. E. Quinn et al, accepted on PRL

Simulation of field propagation on the rear surface

PIC simulations of a “model problem” show a “double front” structure of the current at the rear surface:

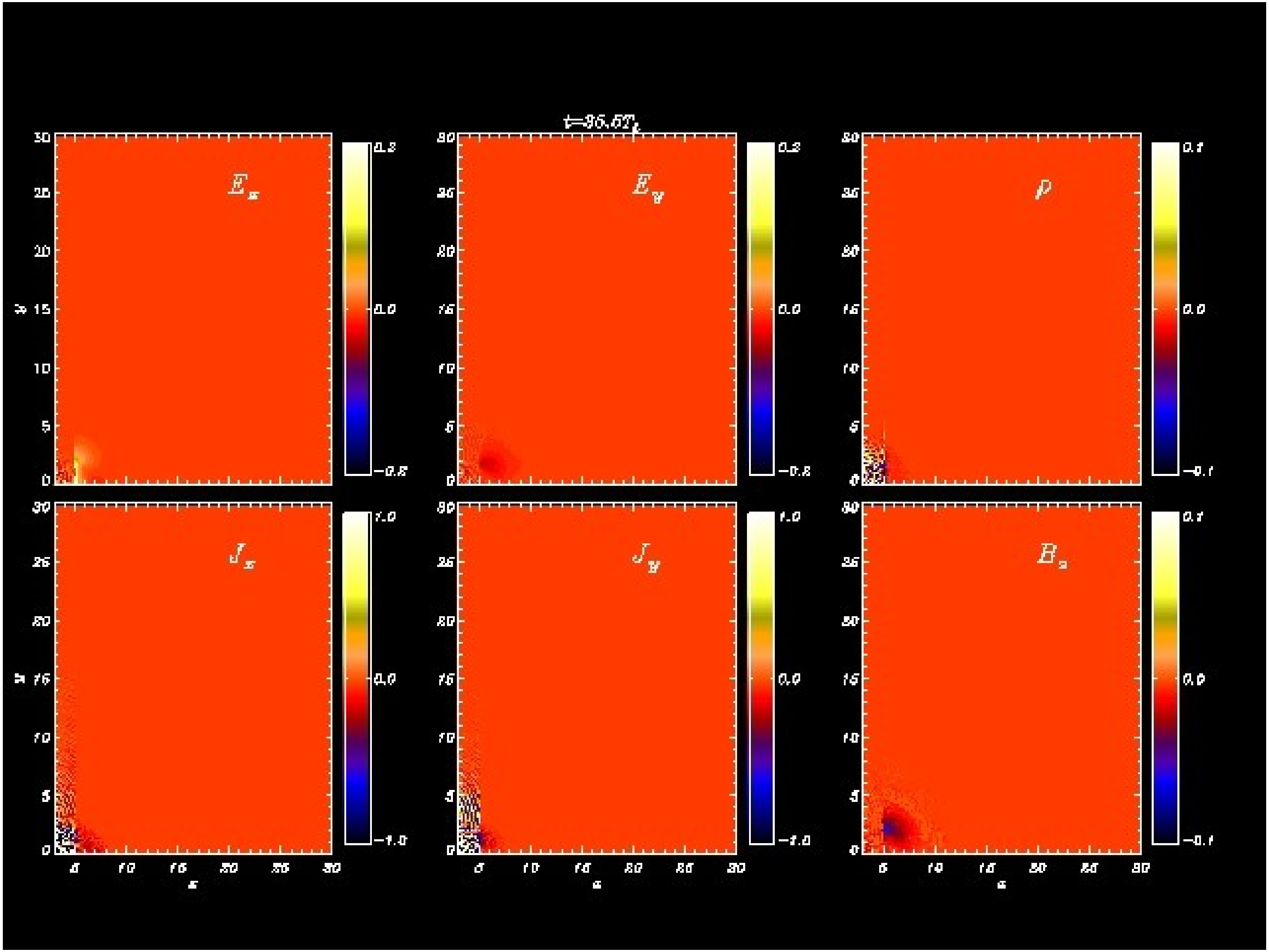


- thin current layer on the surface, propagating at speed c
-> driven by EM fields by the transient “antenna” created by escaping electrons

- bulk current of “fast” electrons, propagating slower than c
-> due to the spread of “fast” electrons in the transverse direction

K. E. Quinn et al, accepted on PRL

Field propagation on the rear surface of solid targets



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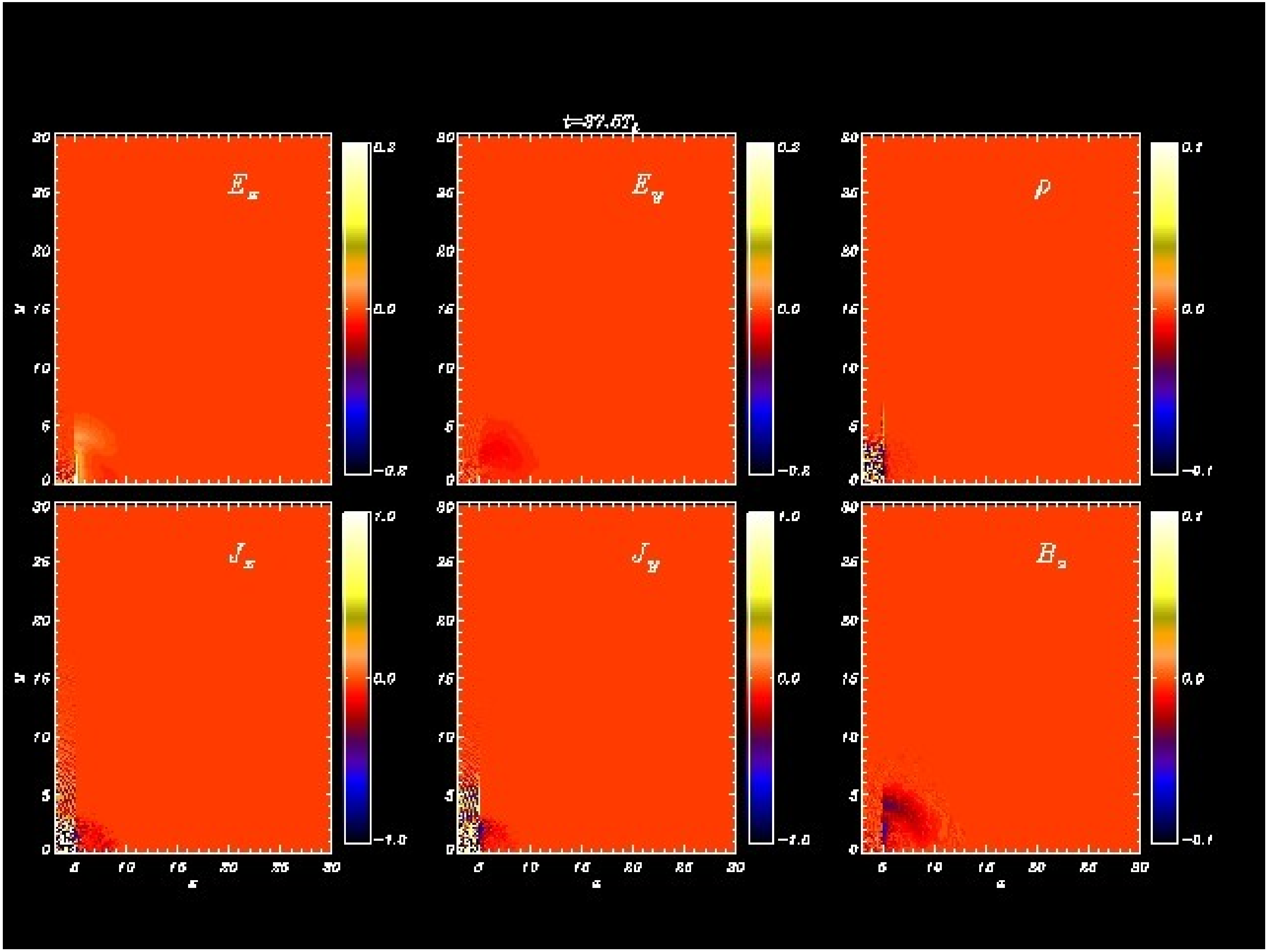

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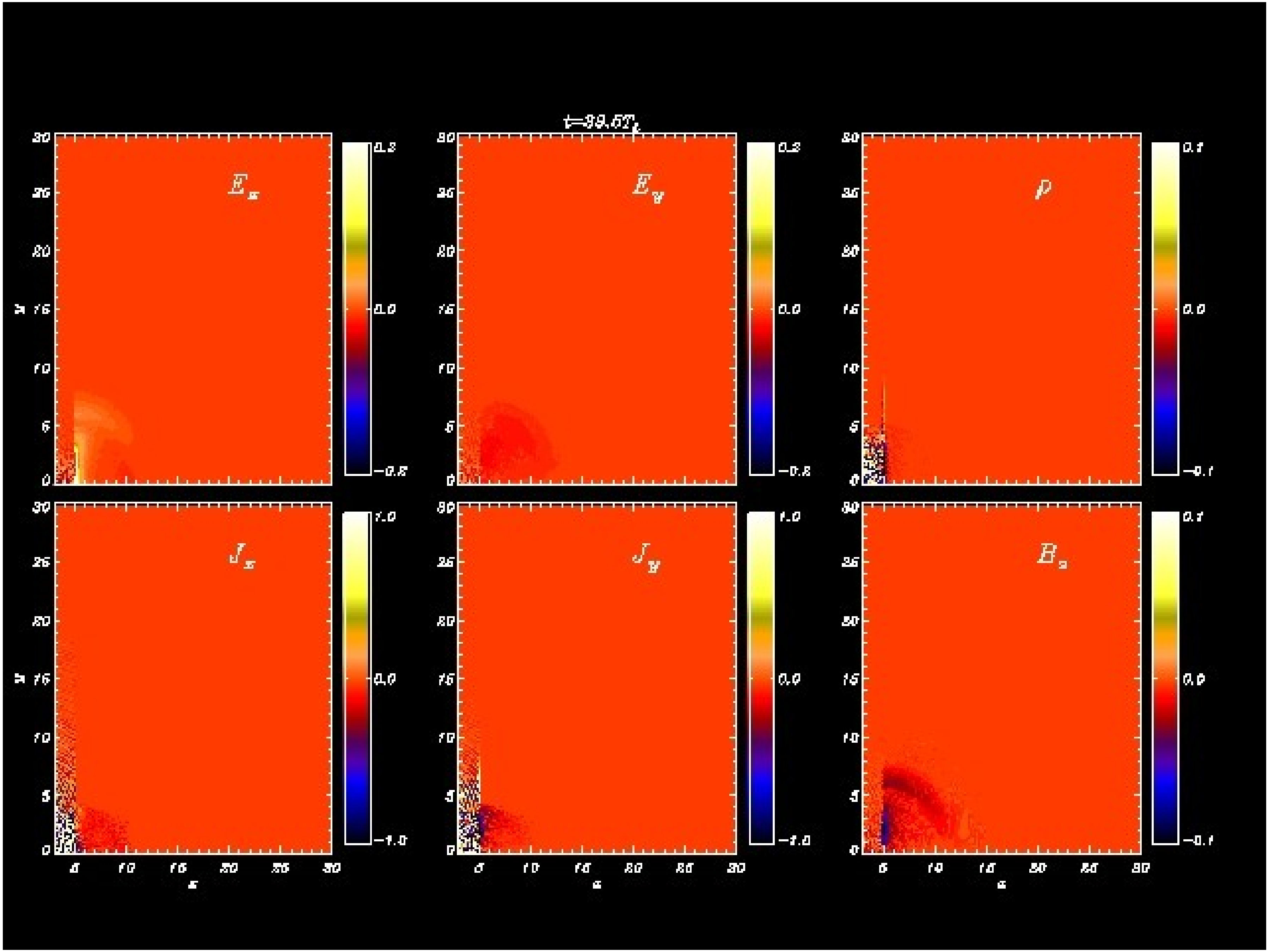

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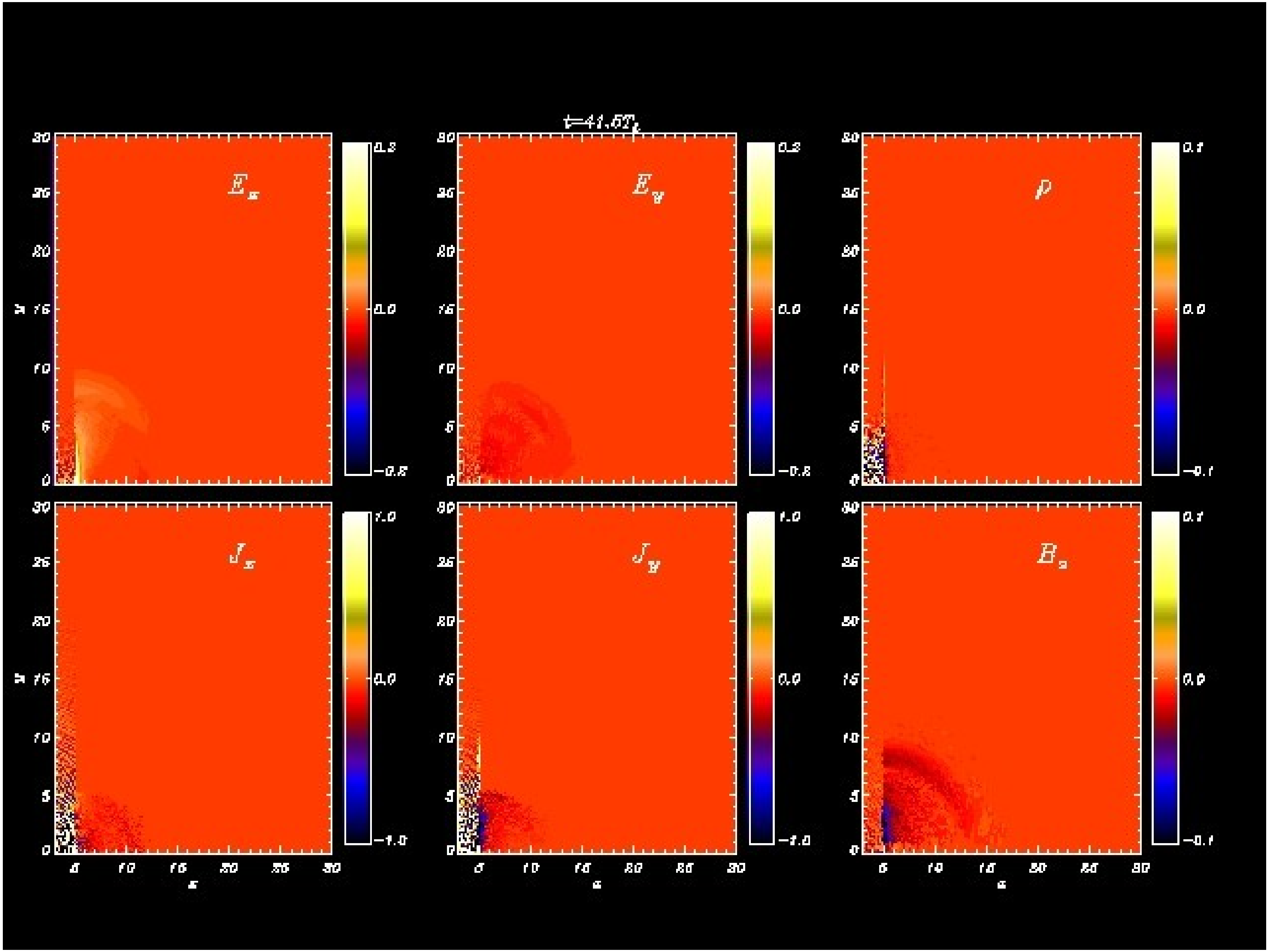

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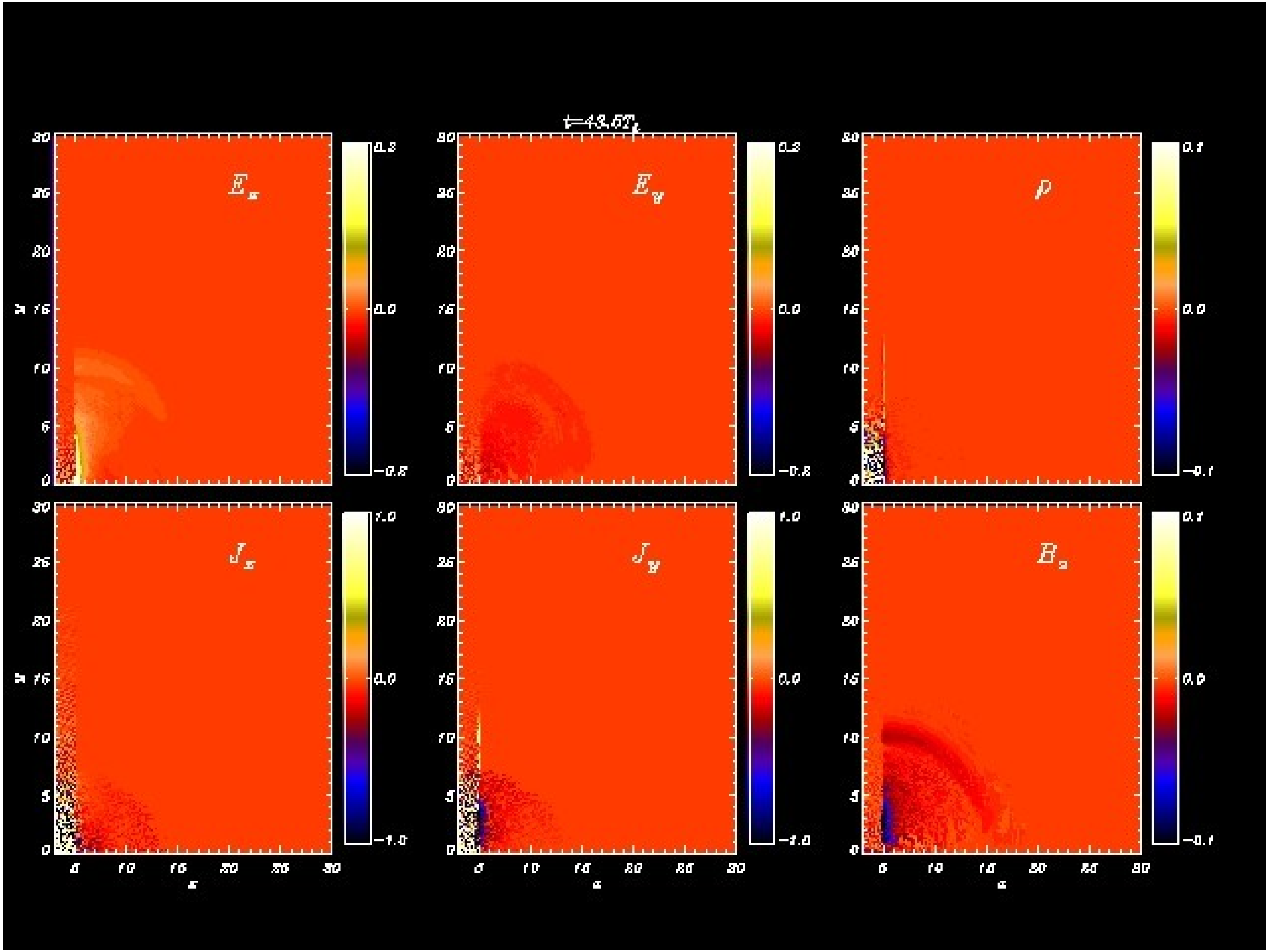

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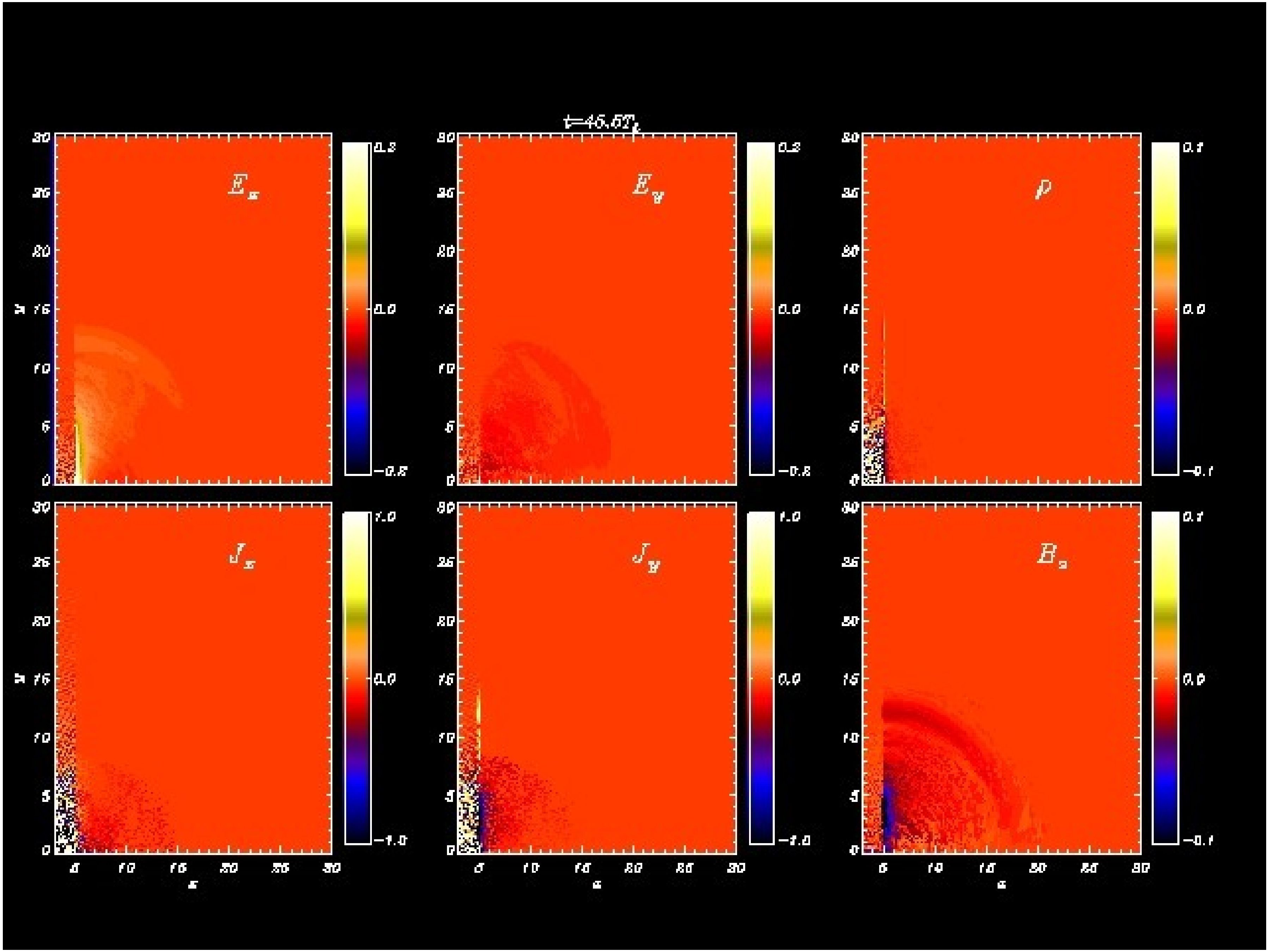

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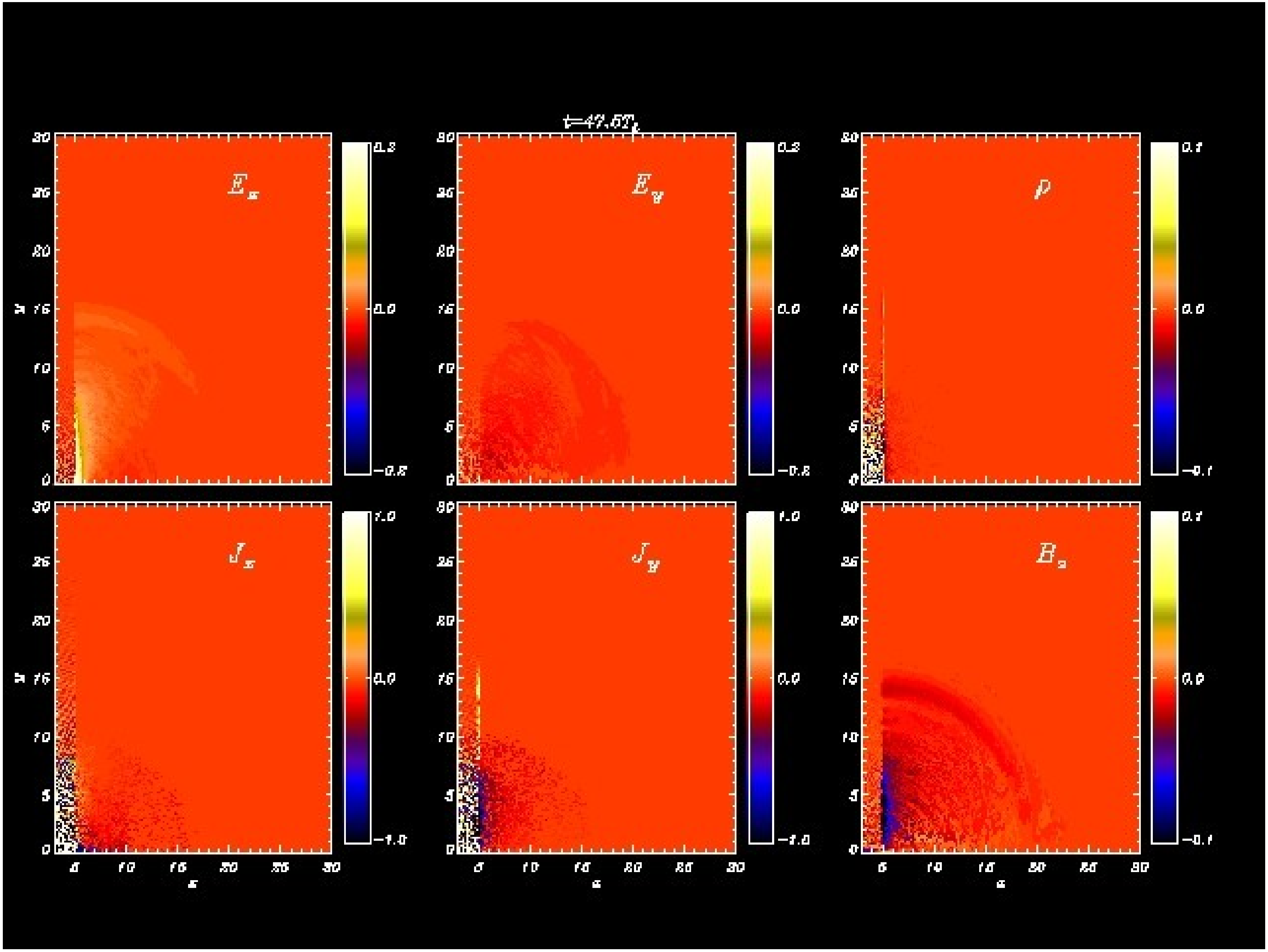

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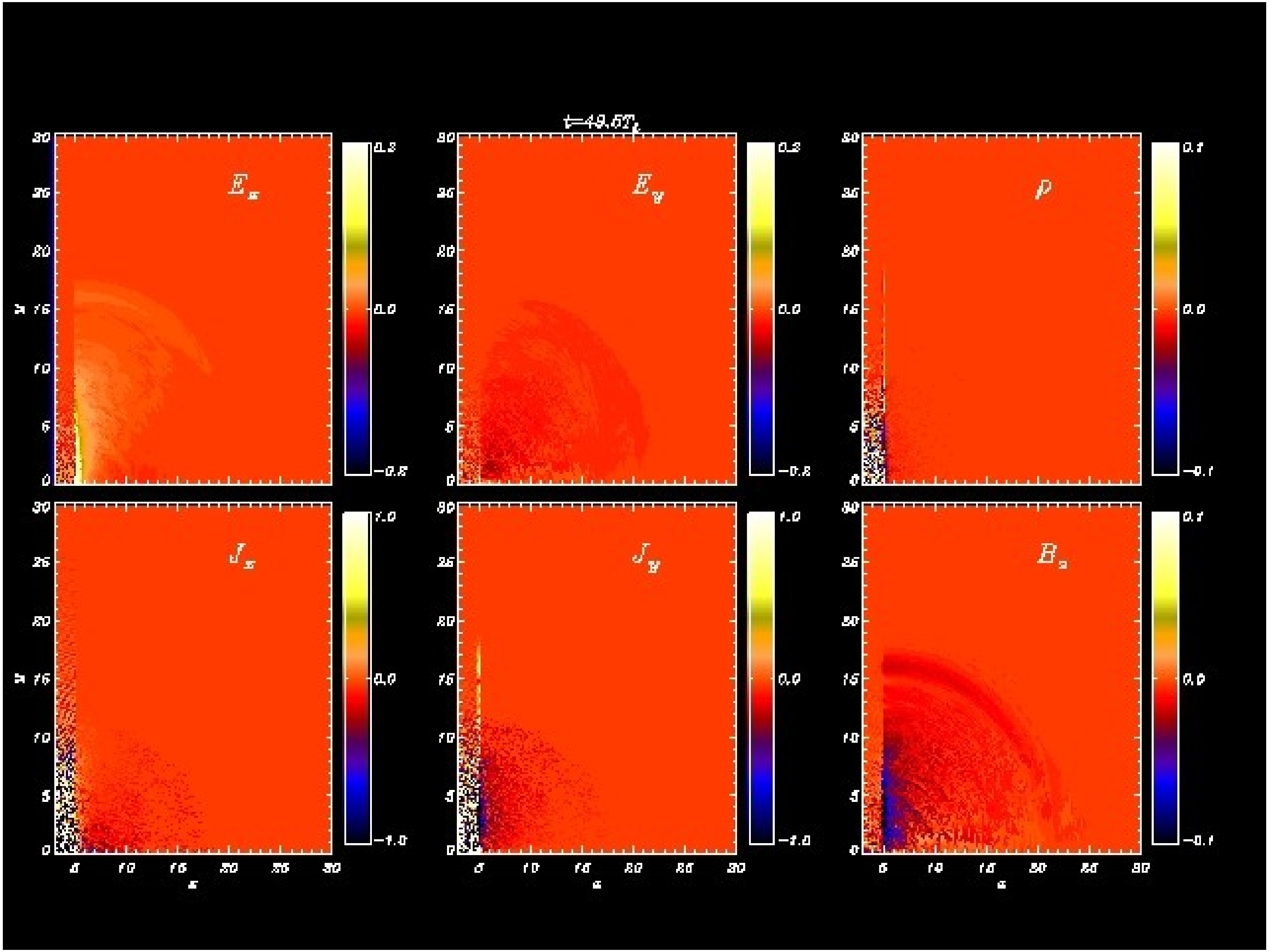

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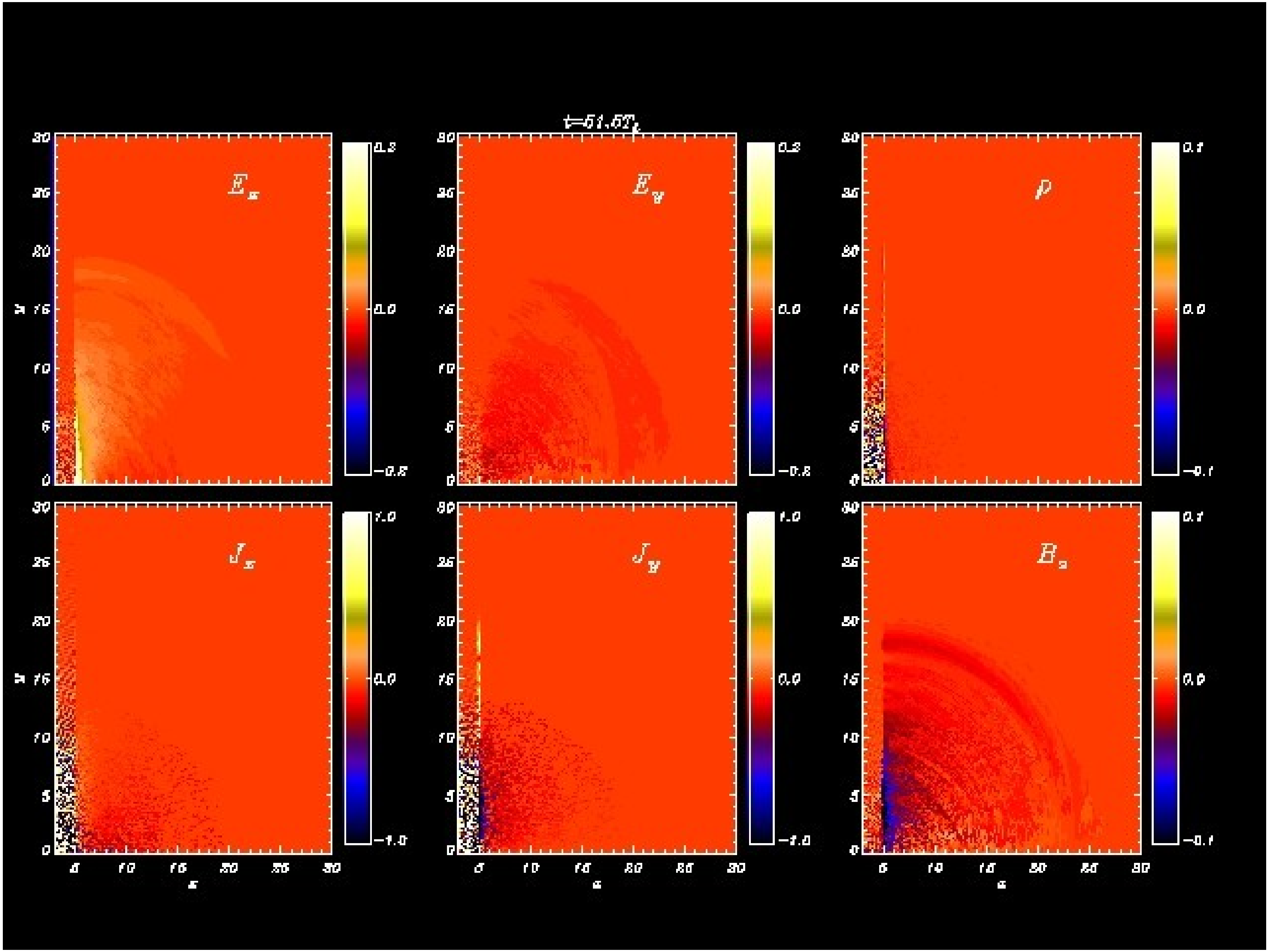

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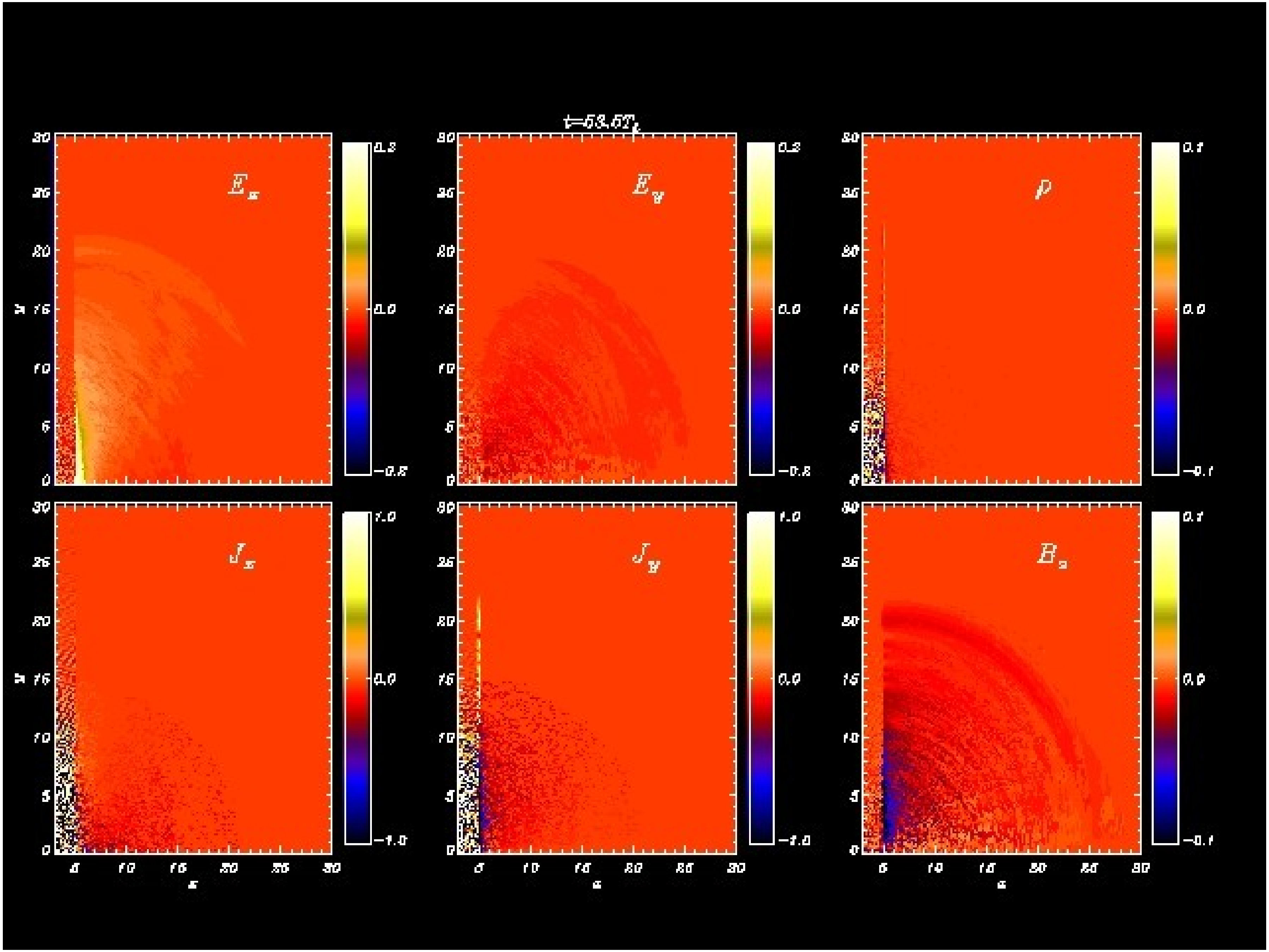

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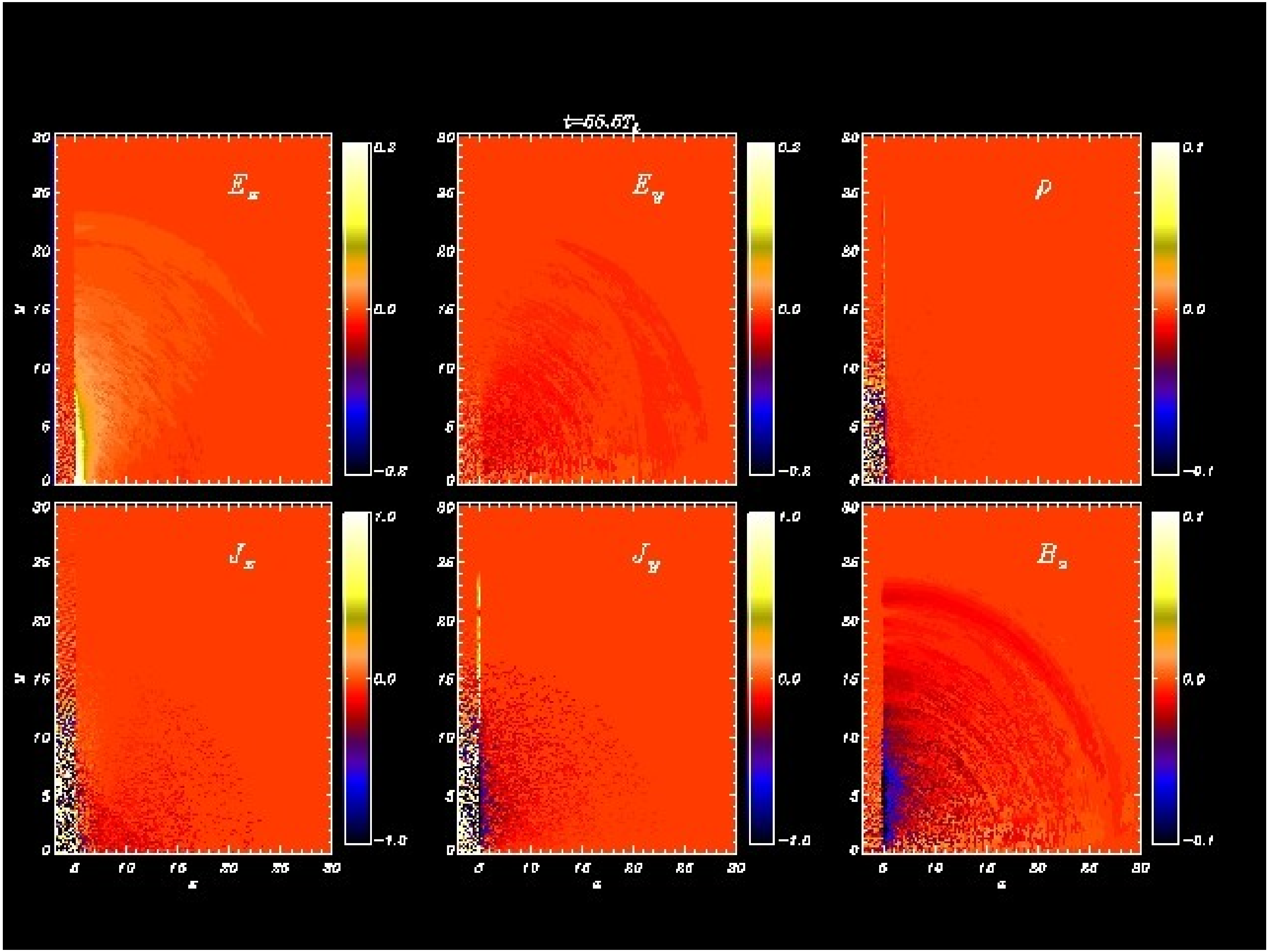

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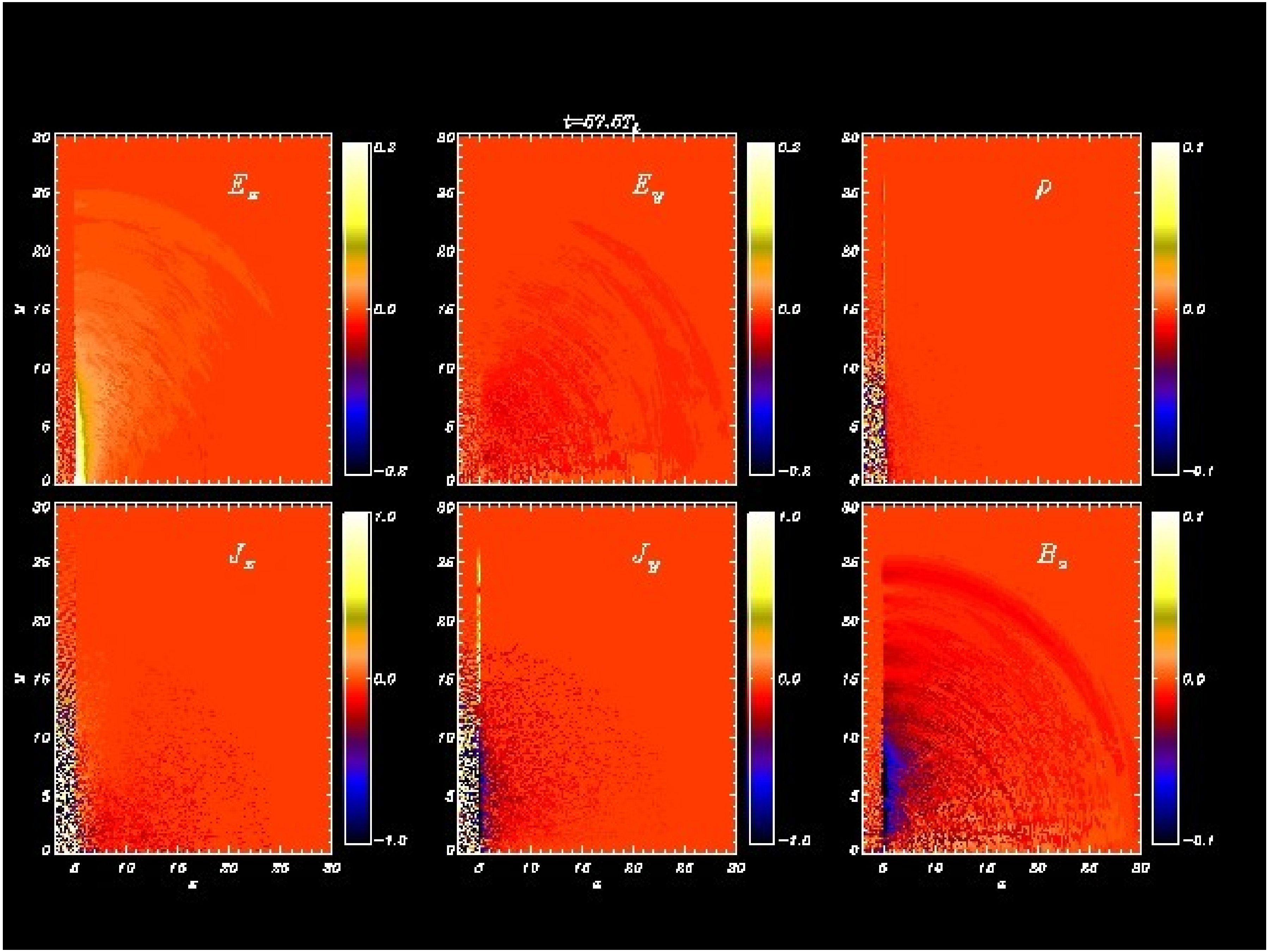

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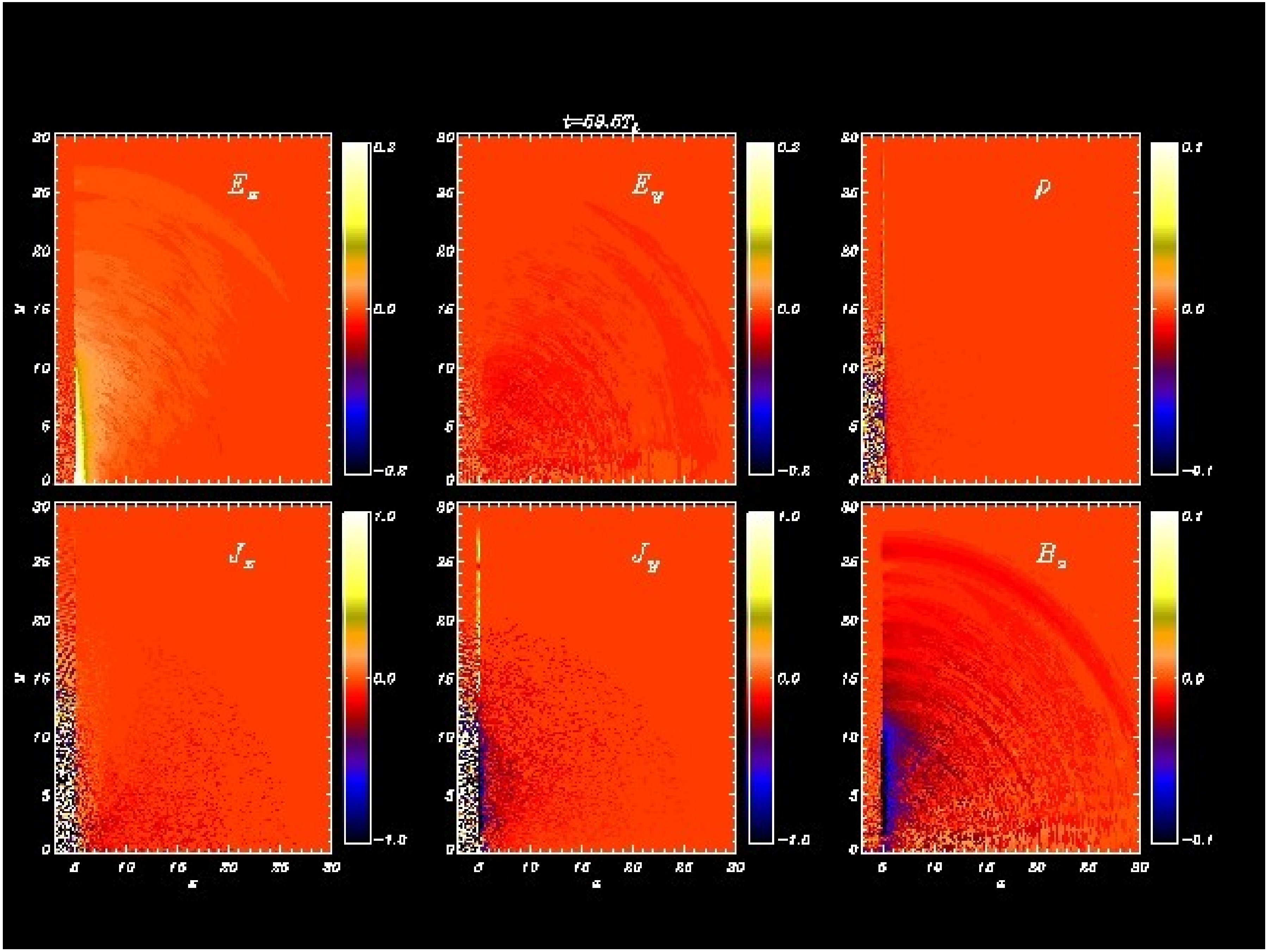

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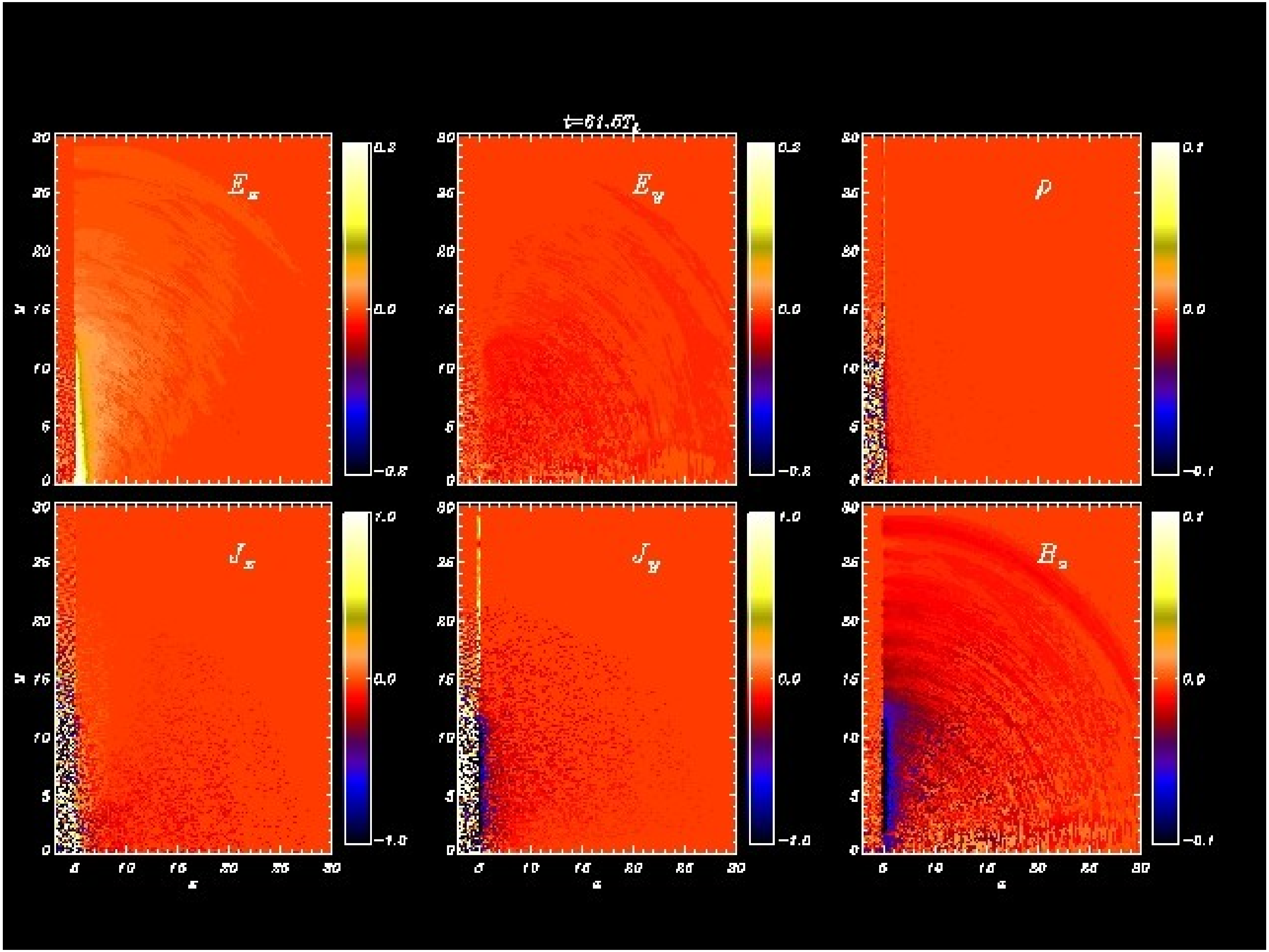

Conclusions

- The proton probing technique (PPT) with picosecond resolution allowed detailed studies of many relevant ultrafast phenomena in laser-plasma interactions for the first time, stimulating theoretical and computational work

- Noticeably, PPT improved our understanding of the physics of proton or ion acceleration itself

- The analysis of the “wire” experiment provides useful information for the development of “dynamic control” devices:

• velocity of space-charge wave along the surface

• detection of electromagnetic front due to “antenna” effect of escaping electrons

• estimate of number of electrons escaping in vacuum

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