Kinetic and finite ion mass effects on the transition to relativistic self-induced transparency in laser-driven ion acceleration

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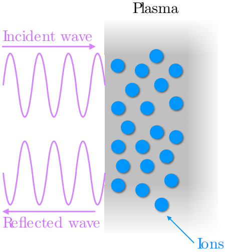
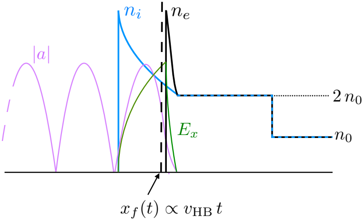
EAAC Workshop 2017

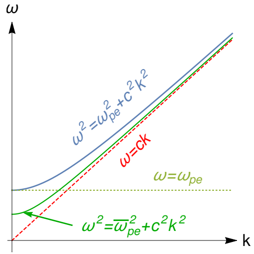
Motivation





- Hole boring scenario of radiation pressure acceleration
- Energy $\mathcal{E}_{\mathrm{HB}} \propto a_0^2/n_0$
- What is the lowest n_0 so that the pulse is reflected?

Relativistic transparency



- Relativistic correction to plasma frequency:

$$\overline{\omega}_{\mathrm{pe}} = \frac{\omega_{pe}}{\gamma} = \frac{\omega_{pe}}{\sqrt{1+a_0^2/2}}$$

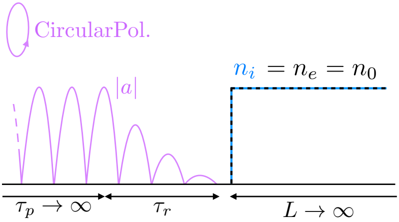
- Relativistic critical density:

$$n_c^{\mathrm{eff}} = \sqrt{1+a_0^2/2}\, n_c \,,$$

- Classical critical density:

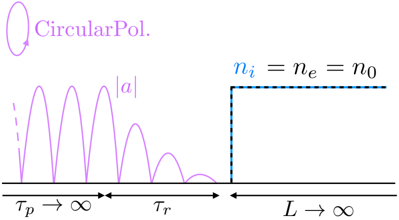
$$n_c = \epsilon_0 m_e \omega^2 / e^2$$

Effect of plasma boundary



- Plasma boundary effects complicate this picture
- Transition threshold depends on
  - Laser pulse envelope (fast electron generation)
  - Ion charge-to-mass ratio

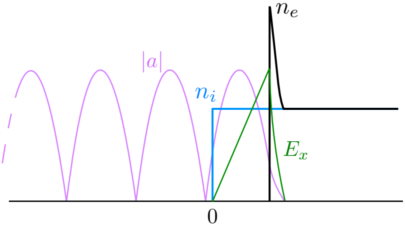
Effect of plasma boundary

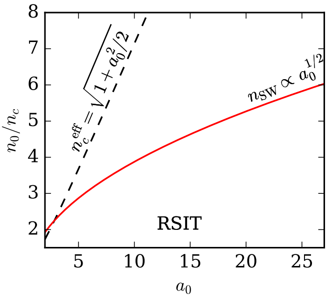


- 1D PIC simulations with EPOCH (U. Warwick)

Cattani *et al.* (PRE 2000)
Goloviznin & Schep (PoP 2000)
E.S. *et al.* (PRE 2012)
Weng *et al.* (NJP 2012)

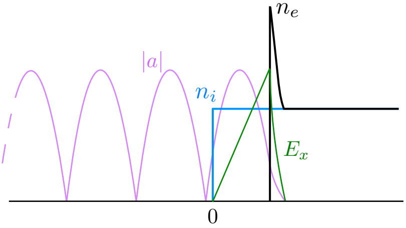
Transition for immobile ions

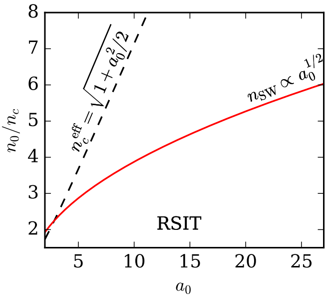




- Electron density spike
- Equilibrium between ponderomotive and electrostatic force

Transition for immobile ions



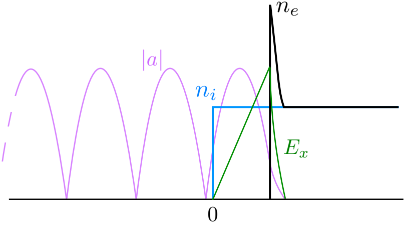


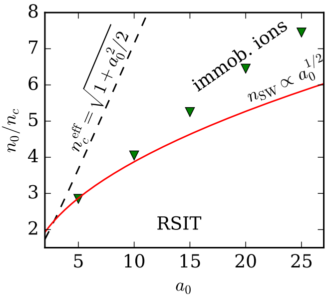
- Electron density spike
- Equilibrium between ponderomotive and electrostatic force
- Different scaling $n_c^{eff} \propto a_0^{1/2}$

Cattani *et al* (PRE 2000)

Goloviznin & Schep (PoP 2000)

Transition for immobile ions





- Different scaling $n_c^{eff} \propto a_0^{1/2}$

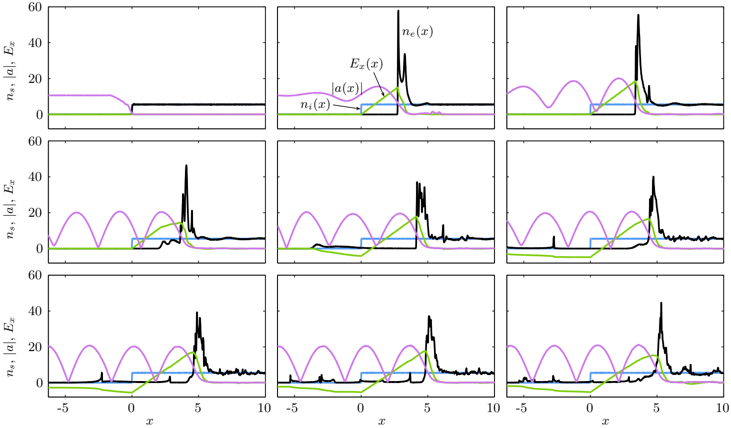
Cattani *et al* (PRE 2000)

Goloviznin & Schep (PoP 2000)

- PIC simulations show deviation for moderate a_0

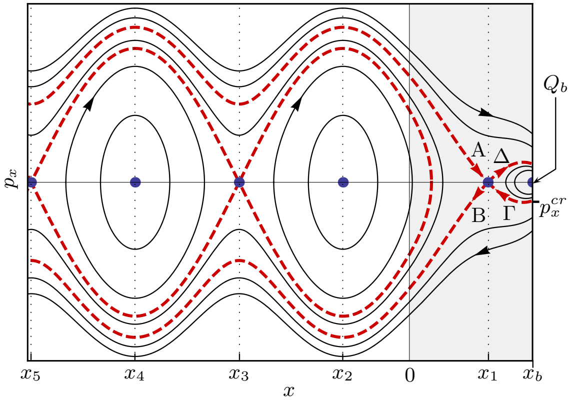
E.S. *et al* (PRE 2012)

PIC simulation



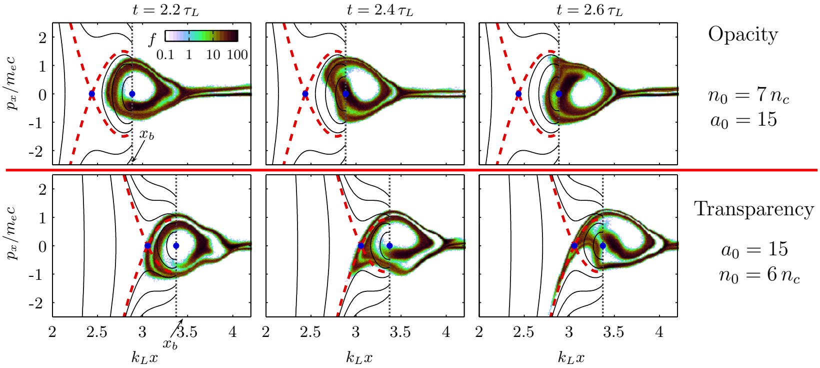
- $a_0 = 15$, $n_0 = 5.5n_c$
- Electron escape responsible for transition:
  - Electrostatic force is reduced
  - Ponderomotive force prevails

Single electron phase space



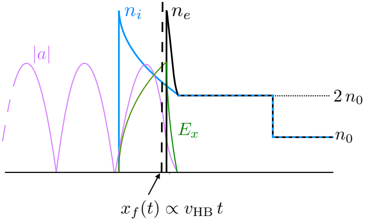
- Use steady-state fields
- Hamiltonian $H(x, p_x) = \gamma(x, p_x) - \phi(x) = \text{ const.}$
- $\gamma(x, p_x) = \sqrt{1 + a(x)^2 + p_x^2}$
- Critical momentum $|p_x^{cr}|$ decreases with n_0/n_c

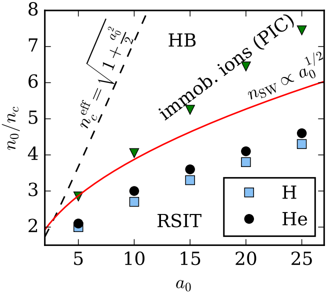
Theory vs PIC



- Electrons escape because separatrix width decreases for smaller n_0

Transition for mobile ions

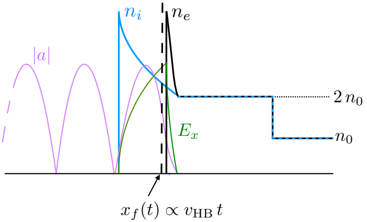


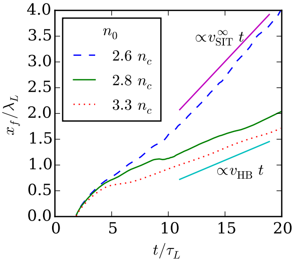


- Double layer or *laser-piston*
- Hole-boring velocity $v_{HB} \sim a_0/\sqrt{n_0}$
- Much lower transition thershold
- Transition threshold depends on charge to mass ratio

Weng *et al*, NJP (2012)

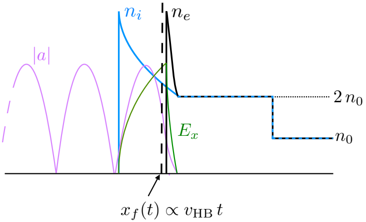
How we detect the transition threshold

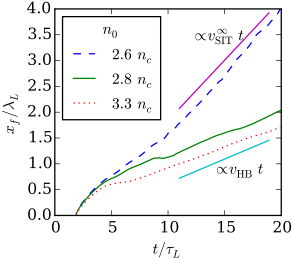




- For given a_0 vary n_0 and compare laser front velocity with
  - v_{SIT} from immobile ion simulations
  - v_{HB}

How we detect the transition threshold

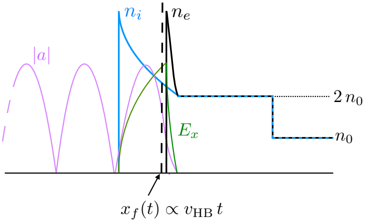


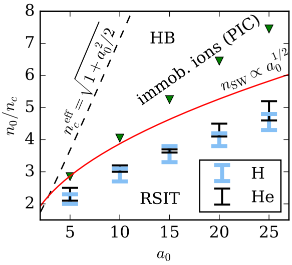


- For given a_0 vary n_0 and compare laser front velocity with
  - v_{SIT} from immobile ion simulations
  - v_{HB}
- Dynamic transition

E.S. *et al*, NJP (2017)

How we detect the transition threshold





- For given a_0 vary n_0 and compare laser front velocity with
    - v_{SIT} from immobile ion simulations
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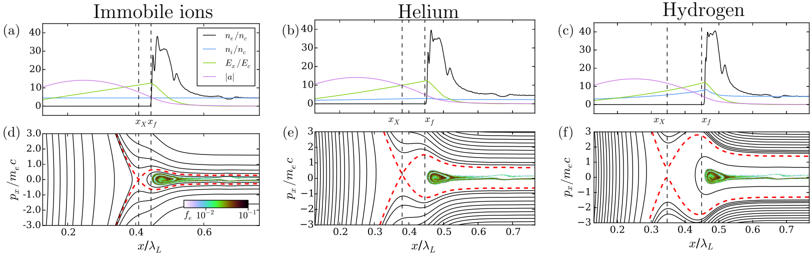
- Dynamic transition

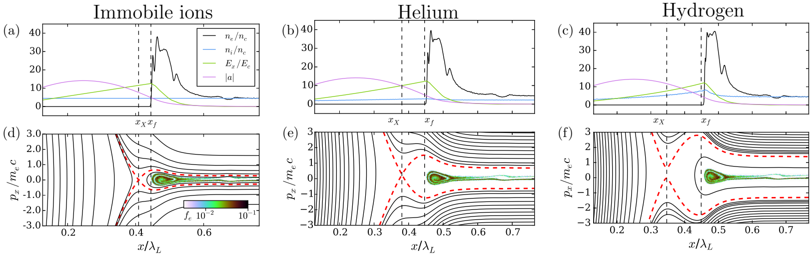
E.S. *et al*, NJP (2017)

Electron phase space



- Three cases in reflection regime ($n_0 = 4.5\, n_c$, $a_0 = 10$)
- $H(x, p_x, t) = \sqrt{1 + a(x,t)^2 + p_x^2} - \phi(x,t)$
- Quasistatic approximation
- Lorentz transform H to frame moving at v_f:
  $\bar{H} = \gamma_f \left[H - v_f\, p_x/(m_e c^2) \right] \simeq \text{ const.}$

Electron phase space



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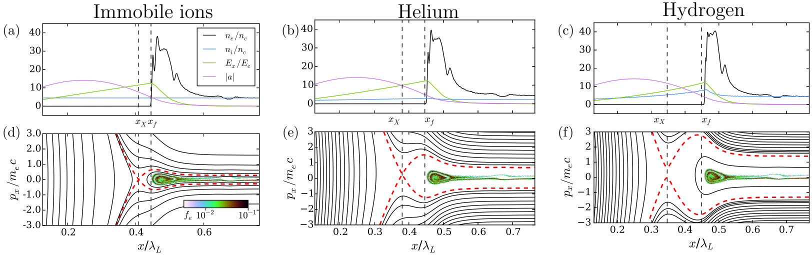
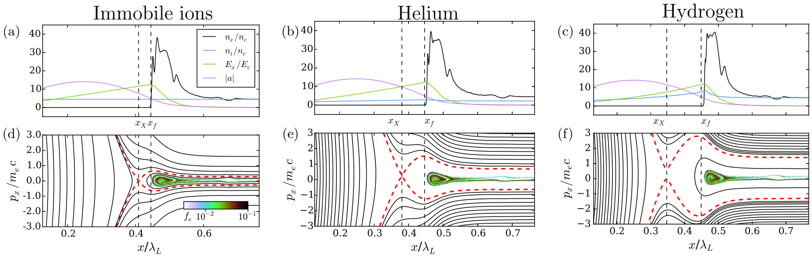
- Quasistatic approximation
- Lorentz transform H to frame moving at v_f:
  $\bar{H} = \gamma_f \left[H - v_f\, p_x/(m_e c^2)\right] \simeq \text{ const.}$
- Ion motion effects at time much sorter than $2\pi/\omega_{pi}$

Timescale for ion effects



- Strong electric field of order $E_x/E_c \simeq a_0$ where $E_c = m_e\, c\, \omega_L/e$.
- How soon does a change ΔE_x occur such that p_x changes by $m_e c$?

Timescale for ion effects



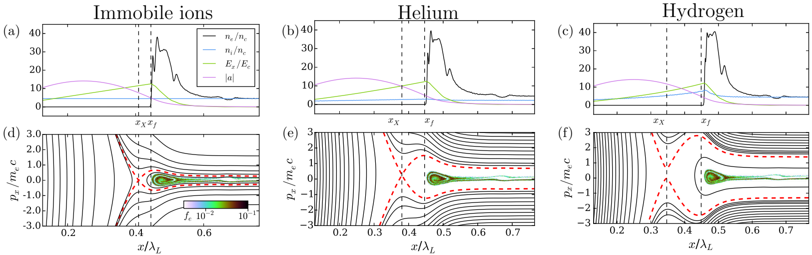
- Ion momentum:

$$m_i\, n_i \frac{\partial V_i}{\partial t} + m_i\, n_i\, V_i \frac{\partial V_i}{\partial x} = q_i n_i E_x(x,t)\,,$$

- Maxwell-Ampere:

$$q_i n_i V_i = -\epsilon_0 \frac{\partial E_x}{\partial t}\,.$$

Timescale for ion effects



- For $a_0 \gg 1$:

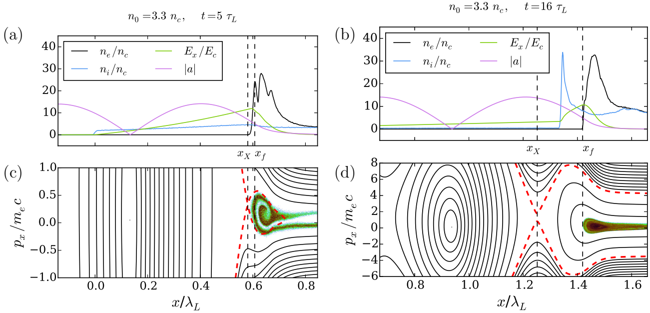
$$\tau_i = \frac{g(a_0)}{\omega_{pi}}$$

where

$$g(a_0) = \arccos\left(1 - \frac{1}{\sqrt{2}a_0}\right).$$

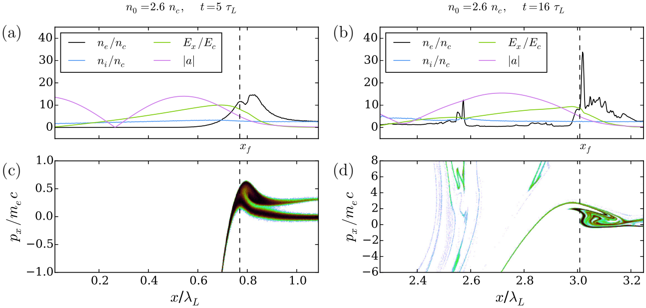
- $\tau_i = 1.2\tau_L \ll 2\pi/\omega_{pi} = 20\tau_L$
for hydrogen with $n_0 = 4.5n_c$, $a_0 = 10$.

Boundary of HB regime



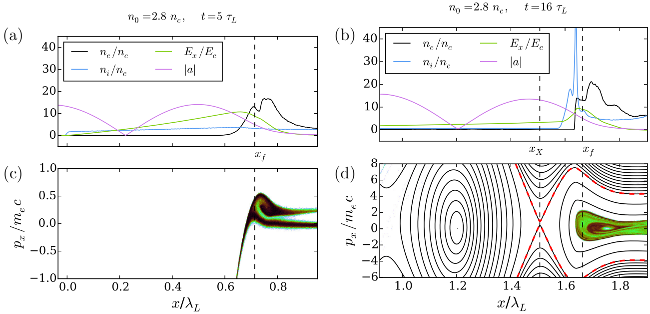
- In HB regime no electrons escape

A look at phase space: RSIT



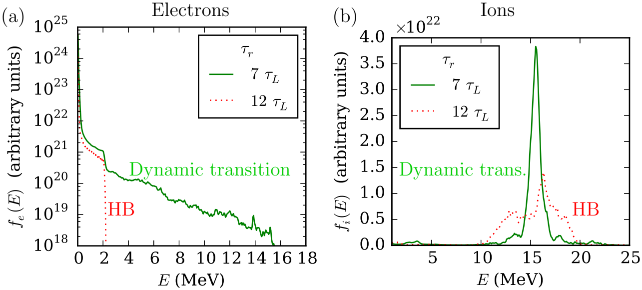
- In RSIT regime electrons escape continuously

A look at phase space: Dynamic transition



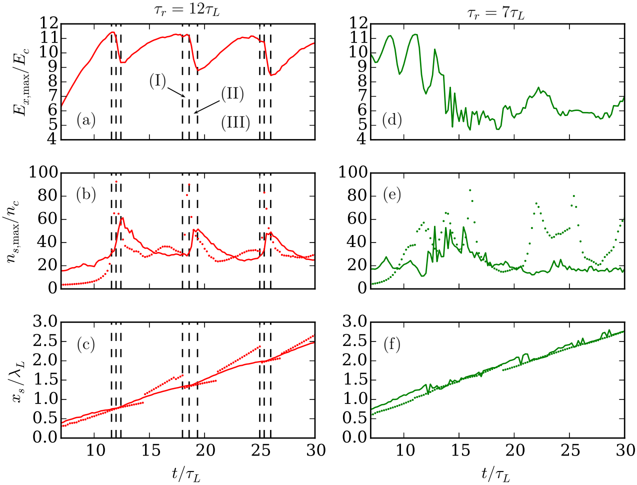
- In the dynamic transition regime electron escape stops due to widening of the separatrix
- At the final stage we get hole boring
- $\mathcal{E}_{\mathrm{H}B} \propto a_0^2/n_0$

Control heating

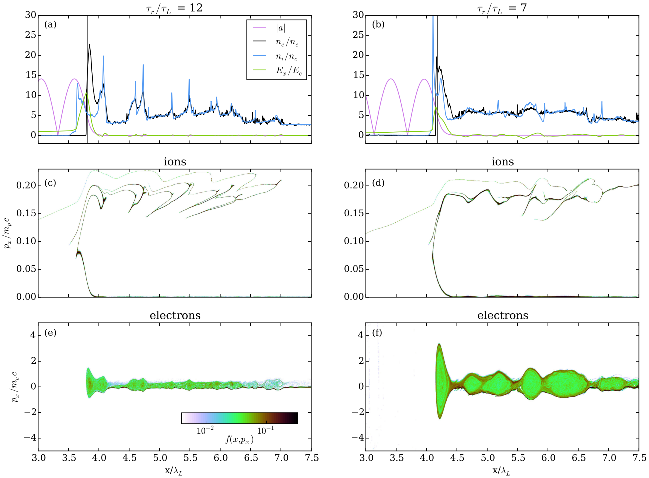


- Keep a_0, n_0 fixed
- Control heating by varying ramp-up time τ_r
- Decreased τ_r → increased ponderomotive force → increased heating
- Transient dynamics affects ion spectrum!

Piston oscillations



- Piston oscillations — Schlegel *et al*, PoP (2009)
- Estimate $\Delta E_x / E_{x,\max} \simeq 1/3$ — E.S. *et al*, NJP (2017)


$\tau_r/\tau_L = 12$
$\tau_r/\tau_L = 7$
(a)
(b)
$|a|$
n_e/n_c
n_i/n_c
E_x/E_c
ions
(c)
(d)
$p_x/m_p c$
electrons
(e)
(f)
$p_x/m_e c$
10^{-2}
10^{-1}
$f(x,p_x)$
x/λ_L
x/λ_L

Conclusions

- Complex transition physics
- Fast electron escape triggers propagation
- Ion motion mitigates electron escape
  by inducing widening of separatrix
- Dynamic transition:
  Short time transient → long time effect on ion spectra
- Transverse instabilities need to be controlled

- E. Siminos, M. Grech, B. Svedung Wettervik, T. Fülöp (2016), arXiv:1603.06436, to appear in NJP
- E. Siminos, M. Grech, S. Skupin, T. Schlegel, V. Tikhonchuk, Phys Rev E **86** 056404 (2012)