Collective effects of radiation friction in laser-driven "hole boring" of dense plasma targets

NIC Symposium

T. V. Liseykina[1], S.V. Popruzhenko[2], A. Macchi[3] & D. Bauer[1]

[1] University of Rostock, Germany
[2] Prokhorov General Physics Institute RAS & MEPhI, Moscow, Russia
[3] National Institute of Optics & E. Fermi Department of Physics University of Pisa, Italy

28th February 2020 – FZ Jülich

Outline

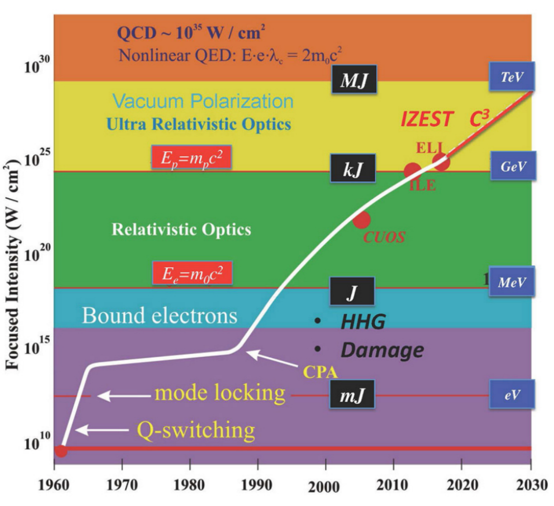
- Motivations
  - radiation friction: from classical to quantum modeling
  - looking for experimental tests of radiation friction models
- First experiments with ultraintense lasers at GEMINI: findings and limitations
- Our research
  - Gigagauss magnetic field generation by radiation friction
  - Simulation results
  - Modeling vs simulations
  - Impact of quantum effects
- Conclusion & Outlook

Forthcoming lasers such as ELI, APOLLON, XCELS... will produce electromagnetic fields strong enough to make the electron dynamics dominated by the emission of incoherent high-energy radiation (mostly γ-rays):

$$\omega_{\text{rad}} \simeq a_0^3 \omega_{\text{laser}}$$

$$a_0 \equiv \frac{eE_{\text{laser}}}{m_e c \omega_{\text{laser}}} \gtrsim 10^2.$$

A reliable modeling of radiation *friction* is needed.

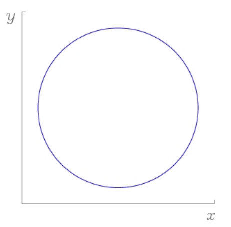


Picture evolved through the years from Mourou, Barty & Perry, *Phys. Today* **51** (1988)

Introducing Radiation Friction I

- Electron in a magnetic field $\mathbf{B}_0$

$$m_e \frac{d\mathbf{v}_\perp}{dt} = -e(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}) = \mathbf{F}_L = -e(\frac{\mathbf{v}}{c} \times \mathbf{B}_0)$$

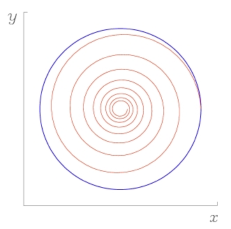


- Solution: uniform circular motion

$$|\mathbf{v}_\perp| = v = \text{const}, \omega_c = \frac{eB_0}{m_e c}, r = \frac{v}{\omega_c}, K = \frac{1}{2} m_e v^2 = \text{const}$$

- BUT the electron radiates:

$$P_{\text{rad}} = \frac{2e^2}{3c^3} \left(\frac{d\mathbf{v}_\perp}{dt} \right)^2 = \frac{2e^2}{3c^3} \omega_c^2 v^2$$



- Energy loss due to radiation:

$$\frac{dK_\perp}{dt} = -P_{\text{rad}} \longrightarrow v(t) = v(0) e^{-t/\tau}, \; \tau = \frac{3 m_e c^3}{2 e^2 \omega_c^2}$$

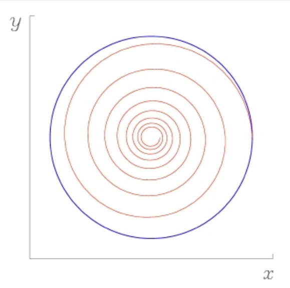
Introducing Radiation Friction II

The Lorentz force does not describe the electron motion consistently $\Longrightarrow$ extra force

$$m_e \frac{d\mathbf{v}}{dt} = \mathbf{F}_L + \mathbf{f}_{\text{rad}}$$

Work done by extra force = energy loss

$$\int_0^t \mathbf{f}_{\text{rad}} \cdot \mathbf{v} dt = -\int_0^t P_{\text{rad}} dt$$



- radiation affects the motion of the electron itself (*self-force*).
- naively: $\mathbf{f}_{\text{rad}} = 2e^2/3c^3\ddot{\mathbf{v}}$

BUT

in the absence of an external field there exist a solution: $\dot{\mathbf{v}}(t) \propto \exp^{t/\tau}$

need of "extra" initial condition $\dot{\mathbf{v}}(0)$

Classical Radiation Friction Force: LL approach

A longstanding and controversial issue of classical electrodynamics (with several recent proposals of "better" theories..)

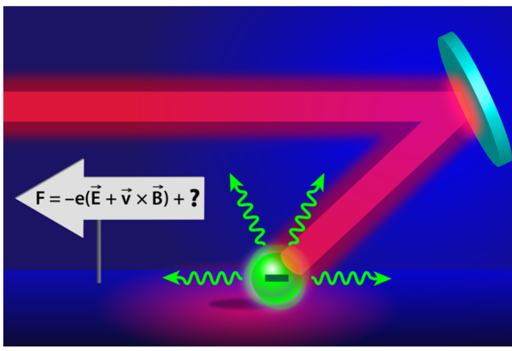
Eventual consensus (+ robust theoretical background) for Landau-Lifshitz's textbook expression

$$\frac{d\mathbf{p}}{dt} = -e\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) + f_{\text{rad}} = \mathbf{F}_{\text{L}} + f_{\text{rad}}$$

LL iterative approach is valid if $|\mathbf{f}_{\text{rad}}| \ll |e\mathbf{E}|$ in the instantaneous frame:

$$\lambda \gg r_c = \frac{e^2}{m_e c^2} = 2.8 \times 10^{-13}\text{cm}$$

$$B \ll \frac{m_e c^2}{e r_c} = 6 \times 10^{15}\ \text{G},\ E \ll 2 \times 10^{18}\text{V/cm}$$



Picture from Macchi, *Physics* **11** (2018) (credit: APS/Alan Stonebracker)

$$f_{\text{rad}} = -\frac{2}{3} r_c^2 \left\{ \gamma^2 \left(\frac{\mathbf{F}_{\text{L}}^2}{e^2} - \left(\frac{\mathbf{v}}{c} \cdot \mathbf{E}\right)^2 \right) \frac{\mathbf{v}}{c} + \frac{\mathbf{F}_{\text{L}}}{e} \times \mathbf{B} - \left(\frac{\mathbf{v}}{c} \cdot \mathbf{E}\right)\mathbf{E} + \gamma \frac{m_e c}{e} \left(\frac{d\mathbf{E}}{dt} + \frac{\mathbf{v}}{c} \times \frac{d\mathbf{B}}{dt} \right) \right\}$$

Why worry about Radiation Friction?

The relevant fields seem out of reach, BUT

- Depending on the interaction geometry the field amplitudes and frequencies are much higher in the rest frame of the electron

  Example: collision of an electron with $\gamma \gg 1$ and a plane electromagnetic wave

$$F = \frac{2}{3}\left(\frac{e^2}{m_e c^2}\right)^2 |\mathbf{E} \times \mathbf{B}| = \frac{8\pi}{3} r_c^2 I \Longrightarrow F' = \frac{8\pi}{3} r_c^2 \left(4\gamma^2 I\right) \gg F$$

Onset of Quantum Effects

Photon recoil is important when $\hbar\omega_{\rm rad} \sim m_e c^2 a_0$

and in general QED effects dominate when $\chi \equiv \frac{e\hbar}{m^3 c^4}\sqrt{-(F^{\mu\nu}p_\nu)^2} \sim 1$

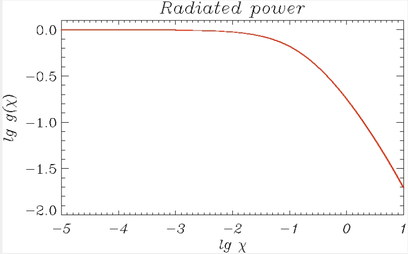
$$\chi \equiv \frac{E'}{E_{\rm cr}}, \qquad E_{\rm cr} \equiv \frac{m_e c^2}{e\lambda_c} = \frac{m_c^2 c^3}{e\hbar}$$

E' electric field in electron rest frame

$E_{\rm cr}$ Schwinger field

"Semiclassical" approach: the classical radiation friction force is modified to cut off photons with unphysically high frequency (reduction factor from quantum calculation of synchrotron emission)

$$\mathbf{f}_{\rm rad} \longrightarrow \mathbf{f}_{\rm rad}\, g(\chi)$$



$$g(\chi) = (1{+}12\chi{+}21\chi^2{+}3.7\chi^3)^{-4/9}$$

Ritus, *J. Sov. Las. Res.* **6** (1985)
Kirk et al, *Plasma Phys. Contr. Fusion* **8** (2009)

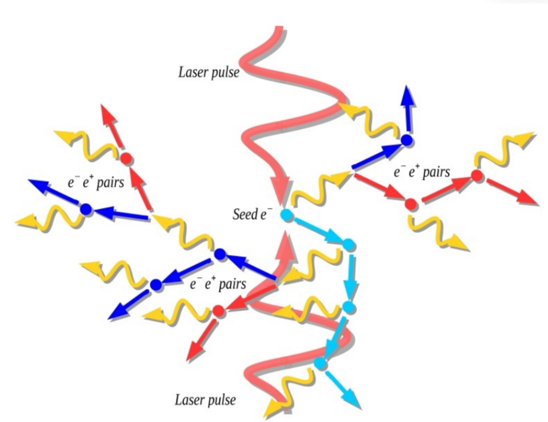
Radiation Friction in QED

In principle: there is *no* radiation friction issue in QED (laser photons are absorbed, $\gamma-$photons are emitted...)

In practice: an exact QED calculation of the scattering matrix is unfeasible (and the laser field is semiclassical anyway...)

Qualitative difference: discrete photon emission makes electron dynamic *stochastic* instead of deterministic as in the (semi) classical model

Neitz & Di Piazza, *Phys. Rev. Lett.* **111** (2013)
Blackburn et al, *Phys. Rev. Lett.* **112** (2014)



Picture: courtesy A. Di Piazza and C.H. Keitel

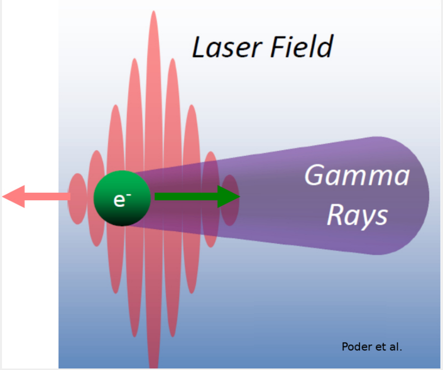
THE GEMINI EXPERIMENTS

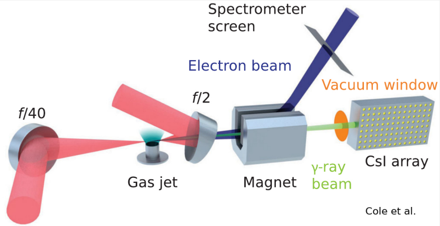
Search for quantum radiation friction in *head-on* collision of 2 GeV electron bunches with the GEMINI laser pulse
(40 fs, 4×10^{20} Wcm^{-2}, $a_0 = 10$)

Thomson back-scattering geometry maximizes $\chi \approx 0.25$

Two "twin" experiments measured the "cooling" of the electron spectrum due to radiative losses and compared the results with different radiation friction models
Cole et al, *Phys. Rev. X* **8** (2018)
Poder at al, *Phys. Rev. X* **8** (2018)

The electron bunch is produced by laser wakefield acceleration





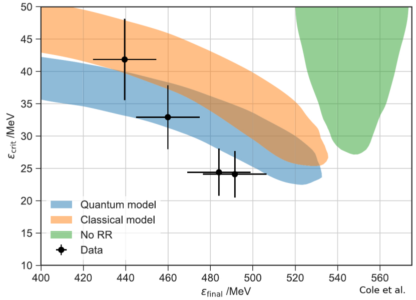
Issues in comparison with theory

Evidence of quantum radiation friction limited by statistics and laser/electron beam fluctuations

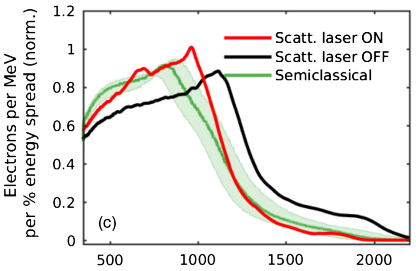
The "semiclassical" model reproduces the "cooled" elecron spectrum *better* than a "quantum" stochastic model:
breakdown of assumptions in the QED calculations?

Call to improve the quantum theory of radiation reaction.

A general issue: the radiation friction signatures are to be found in relatively small effects.



Cole et al.



Poder et al.

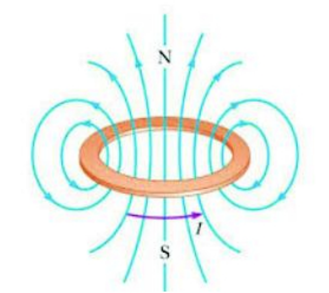
Inverse Faraday effect due to radiation friction

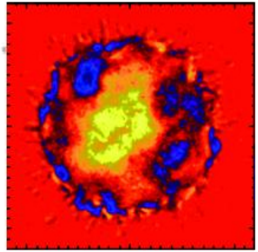
Classical viewpoint:
Inverse Faraday effect $\equiv$ *absorption of angular momentum* carried by a *circularly polarized laser wave* in a *dissipative medium* $\Rightarrow$ *generation of quasi static magnetic field*

Quantum viewpoint:
for each emitted γ-photon, many laser photons are annihilated

$$\hbar\omega_{\rm rad} \simeq N\hbar\omega_{\rm laser}, N \sim a_0^3 \gg 1$$

polarized photons $\leftarrow$ circular polarized laser light
an angular momentum amount $(N-1)\hbar \simeq N\hbar$ is transferred to the orbital motion of electrons
$\Rightarrow$ azimuthal current $\Rightarrow$ axial magnetic field

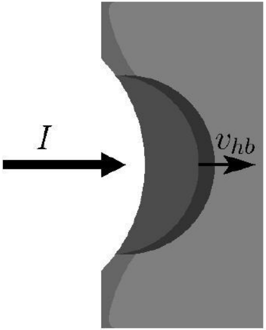




High conversion efficiency of laser energy into incoherent radiation is needed

Radiation losses in laser-dense plasma interaction

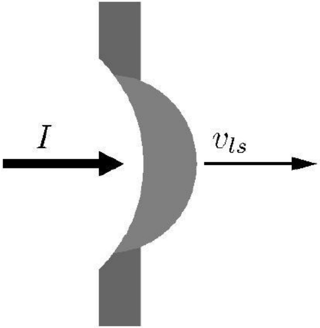
Hole Boring
"piston" push of the plasma surface



$$\frac{v_{\rm hb}}{c} = \frac{\sqrt{\Xi}}{1+\sqrt{\Xi}}\,, \qquad \Xi = \frac{I_L}{\rho c^3}$$

highly efficient radiation losses

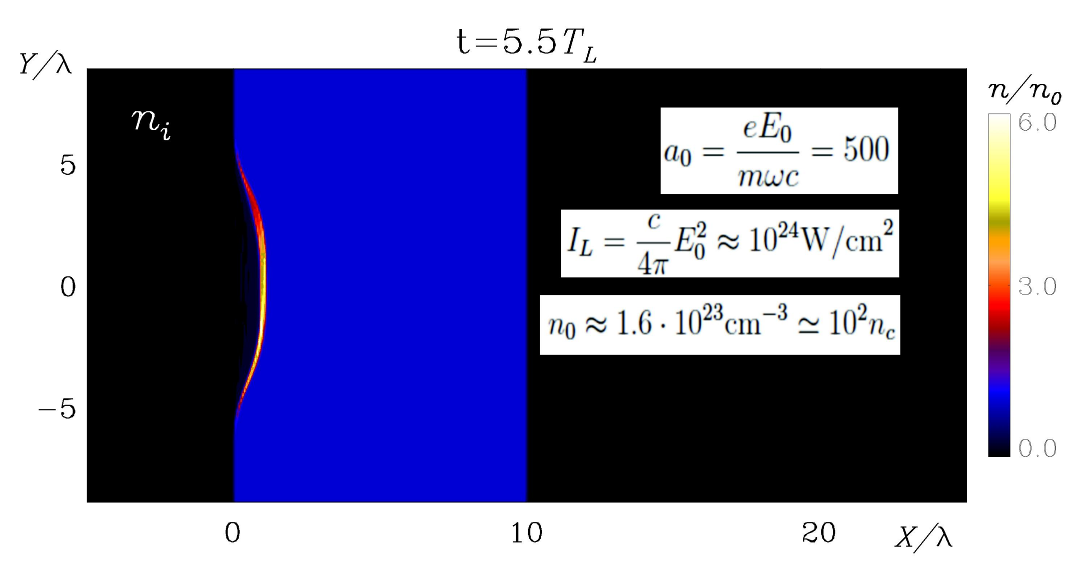
Light Sail
push of the whole thin foil target



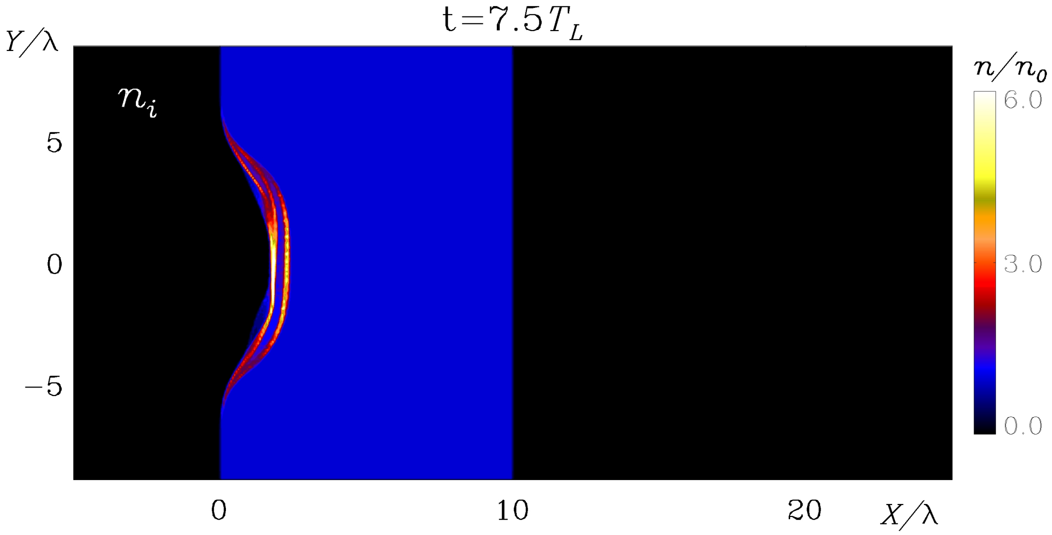
$$v_{\rm hb}\tau_L \gg D \rightarrow \frac{v_{\rm ls}}{c} \simeq 1$$

very weak radiation losses

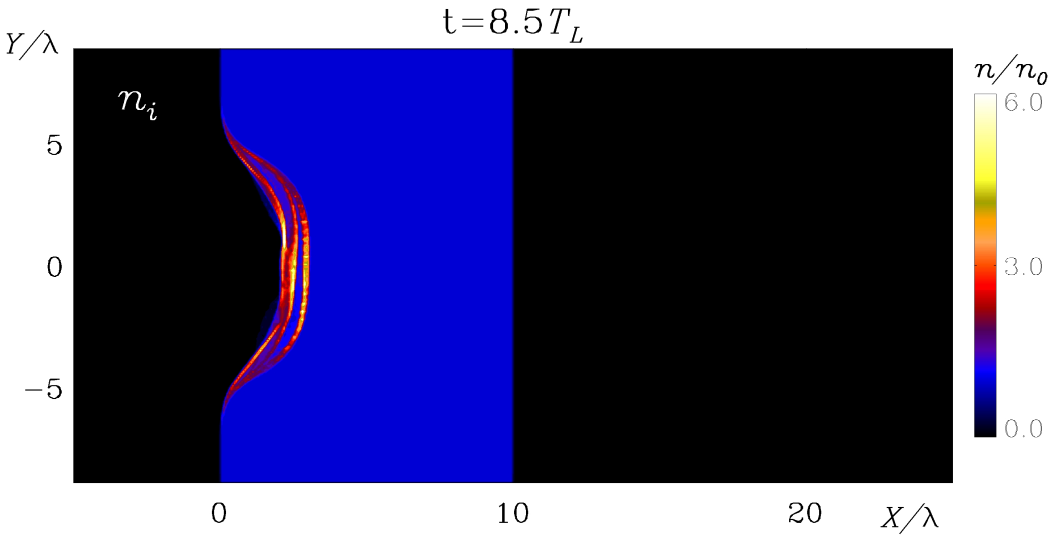
Hole-Boring regime



Hole-Boring regime



Hole-Boring regime



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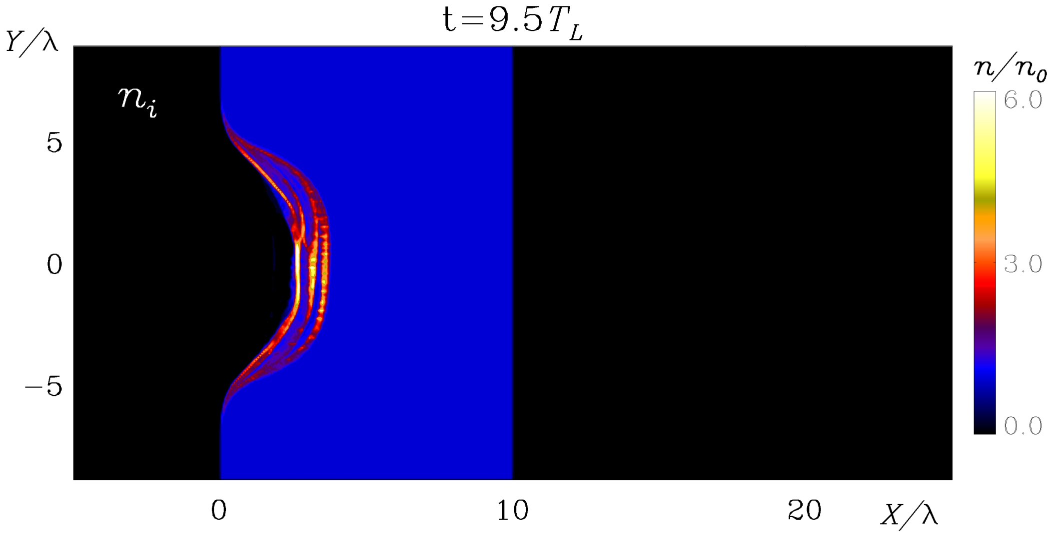

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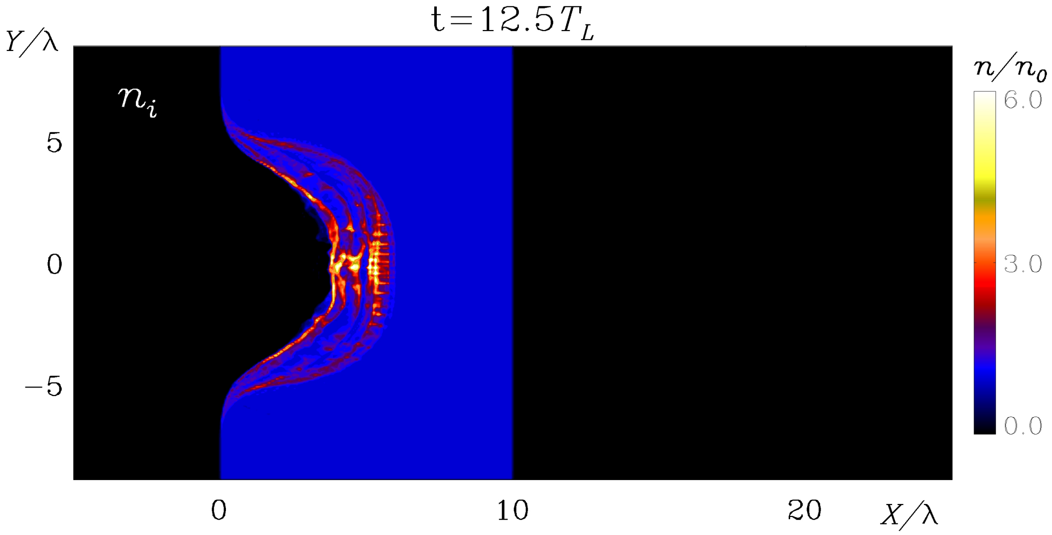

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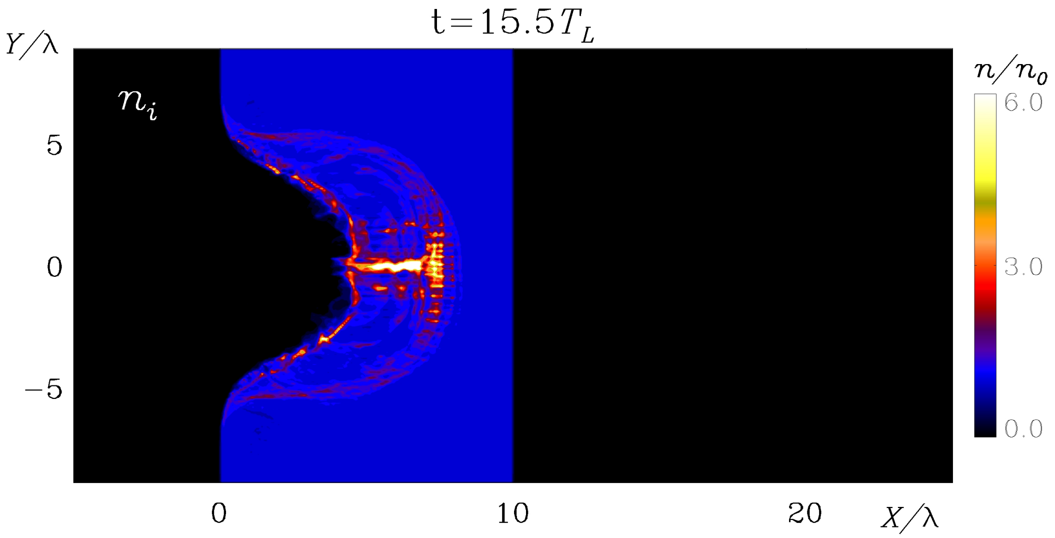

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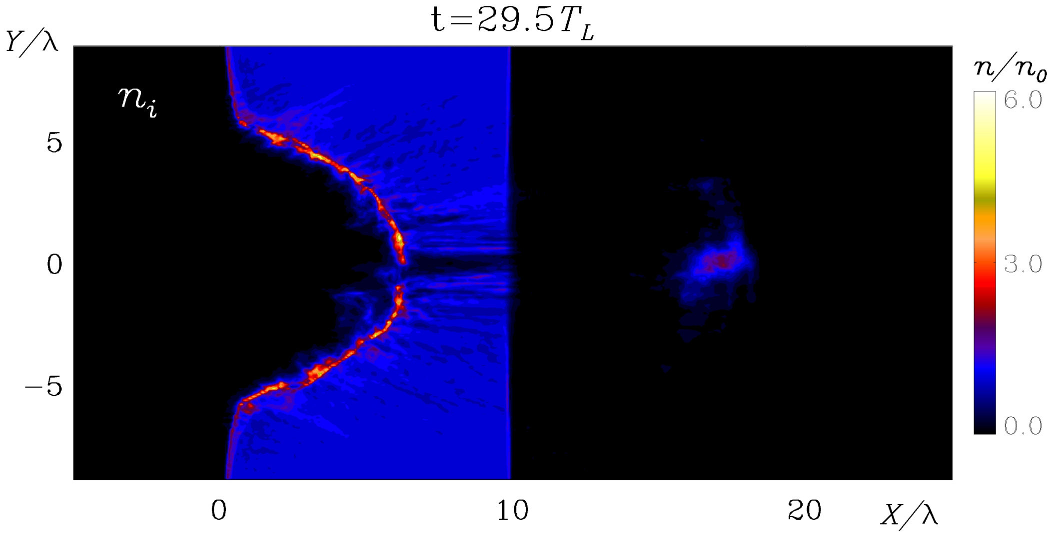

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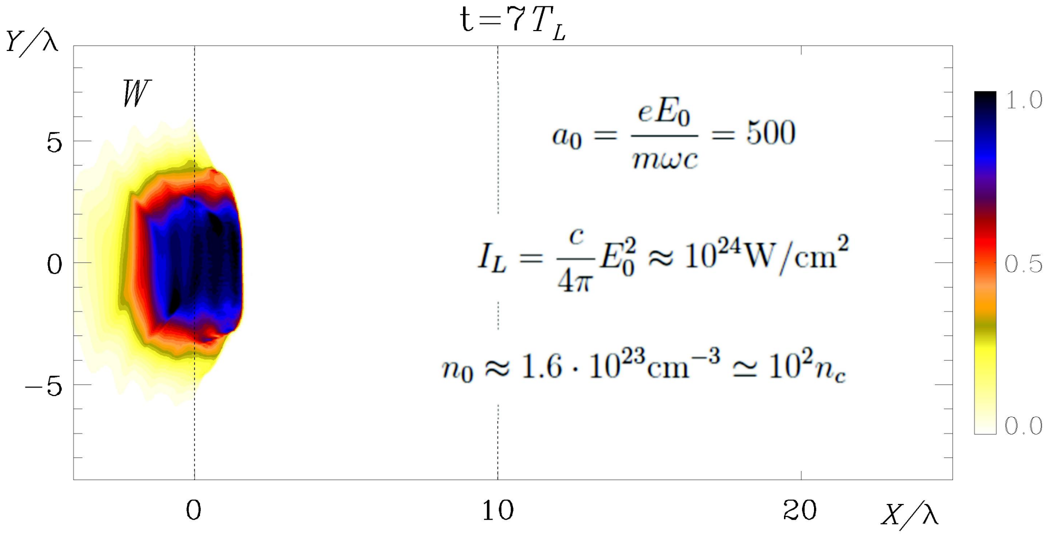

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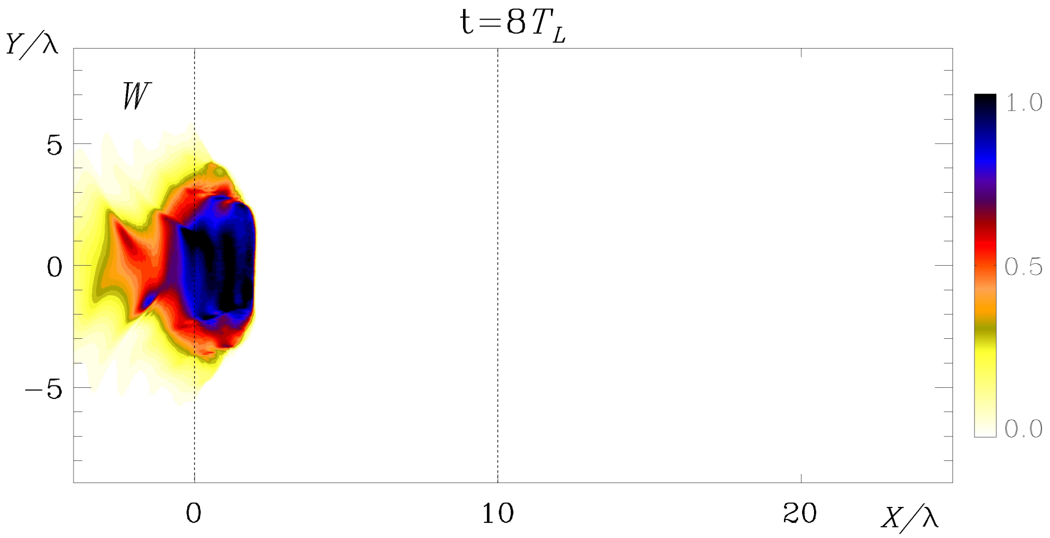

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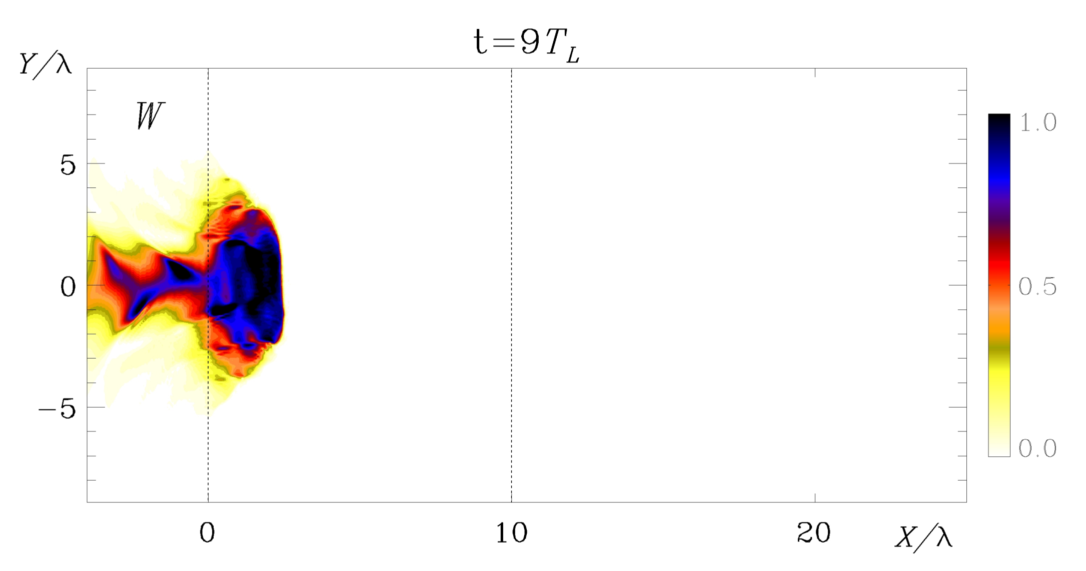

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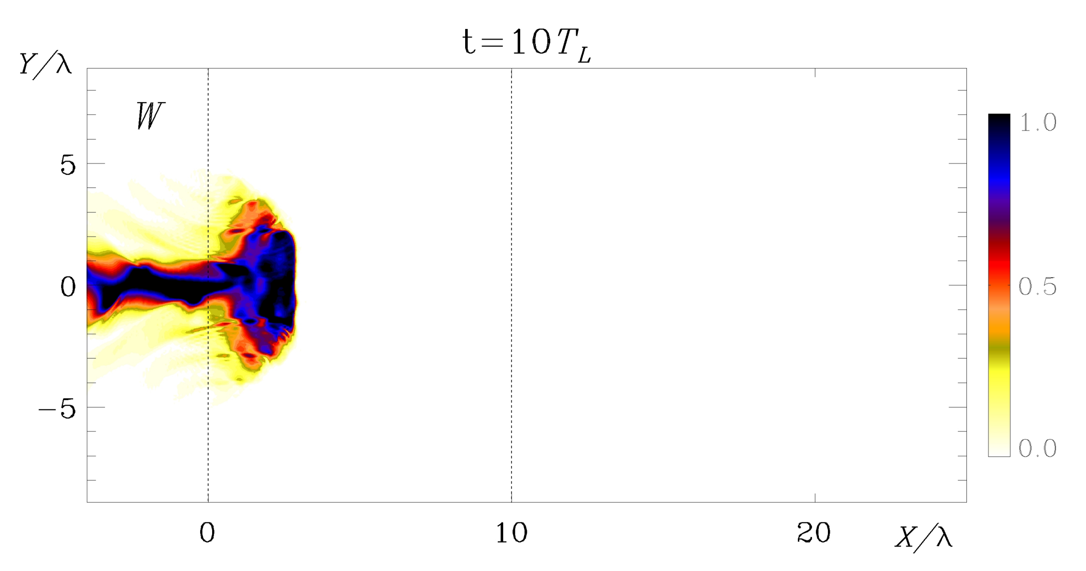

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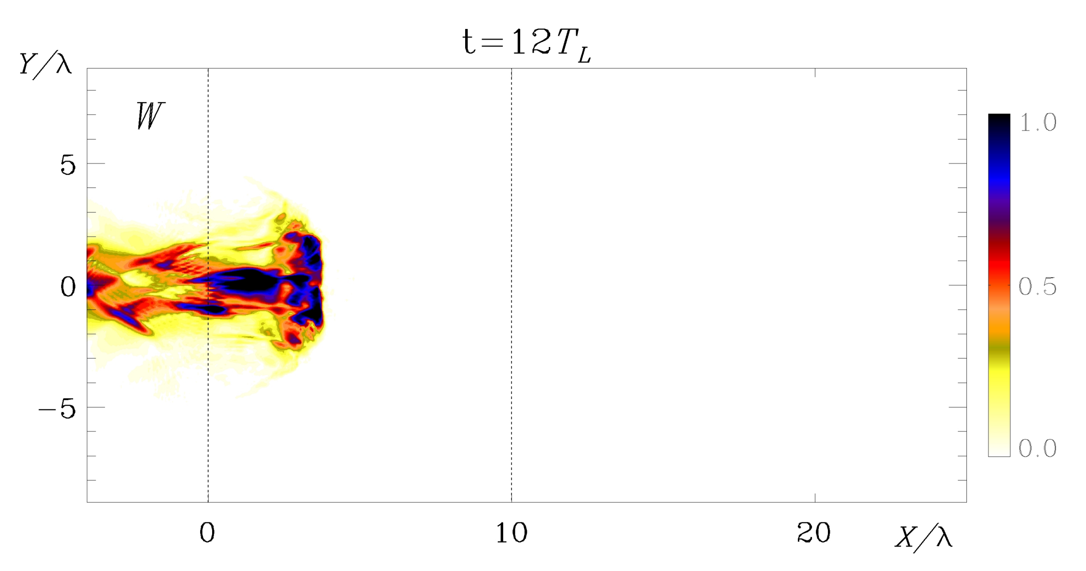

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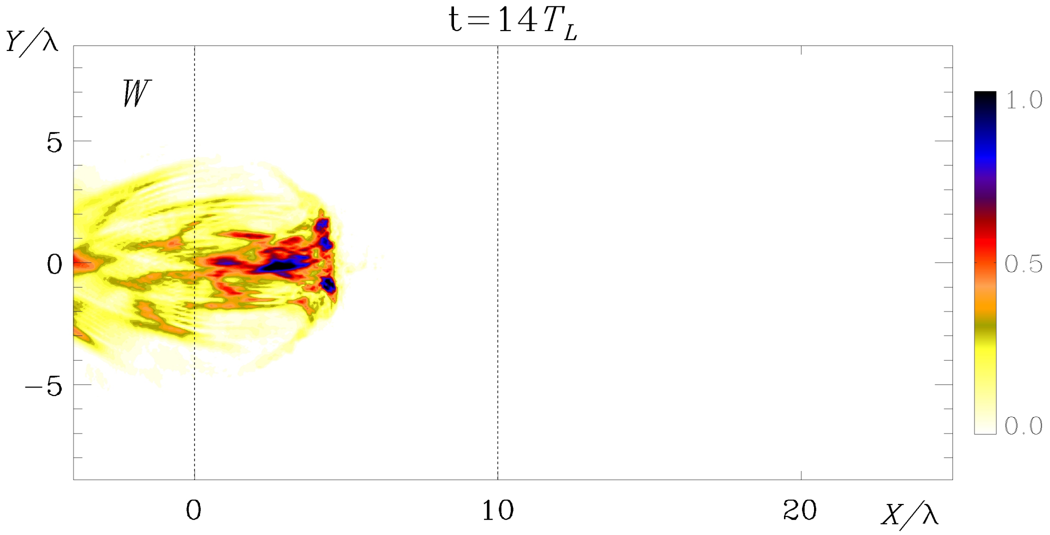

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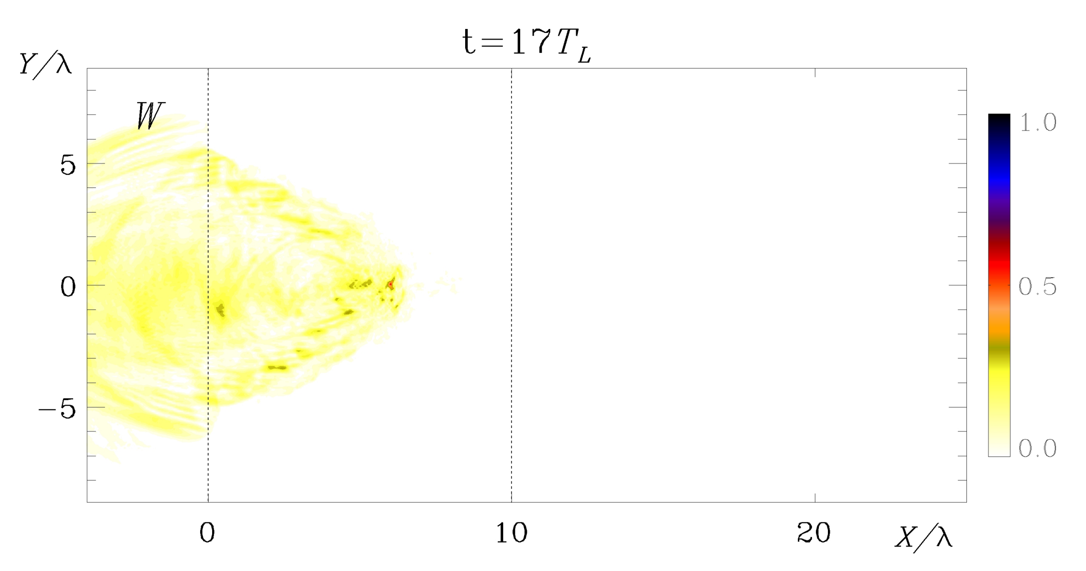
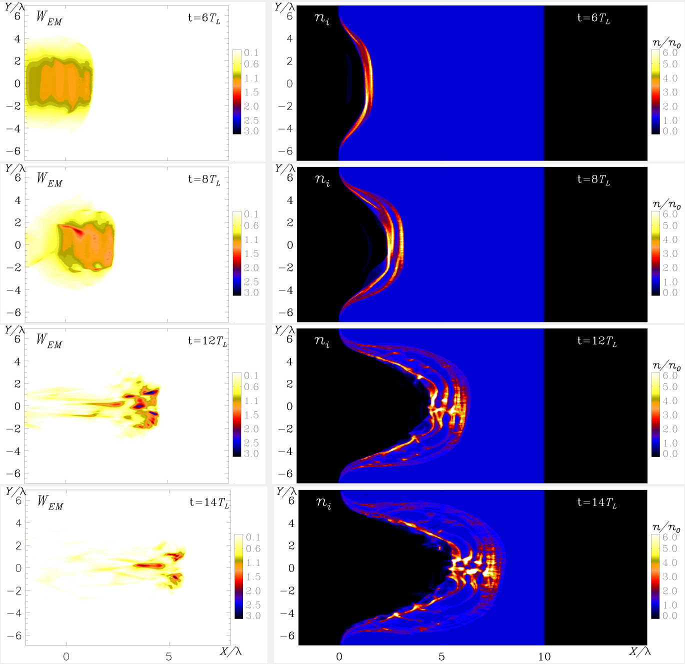




$$a_0 = \frac{eE_{\text{laser}}}{m_e \omega_{\text{laser}} c} = 500$$

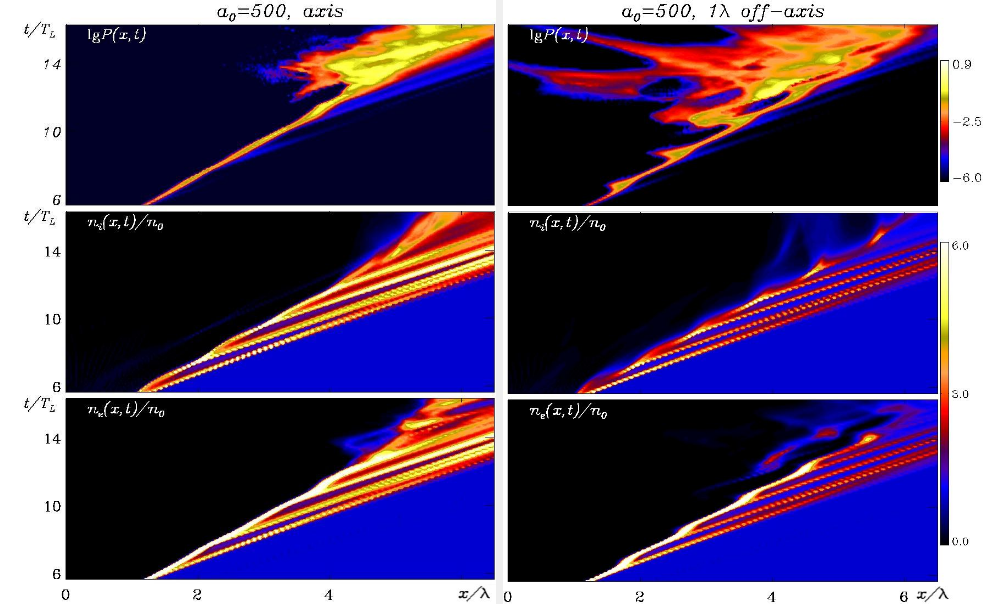
$$I_{\text{las}} = \frac{c}{4\pi} E^2_{\text{laser}} \simeq 10^{24} \text{Wcm}^{-2}$$

$$n_0 = 1.6 \times 10^{23} \text{cm}^{-3} \simeq 10^2 n_{\text{cr}}$$

$$I \simeq 10^{23} - 10^{25} \text{Wcm}^{-2}$$

$$\eta_{\text{rad}} \simeq 0.1 - 0.2$$

Radiation power: space–time plots

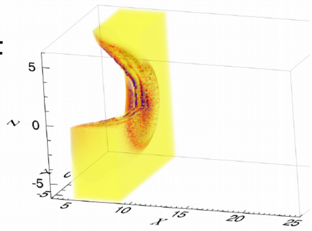


GIGAGAUSS MAGNETIC FIELDS

3D simulations with classical RF

B_x normalized to

$B_0 = m_e c\omega / e$
$= 1.34 \times 10^8$ G



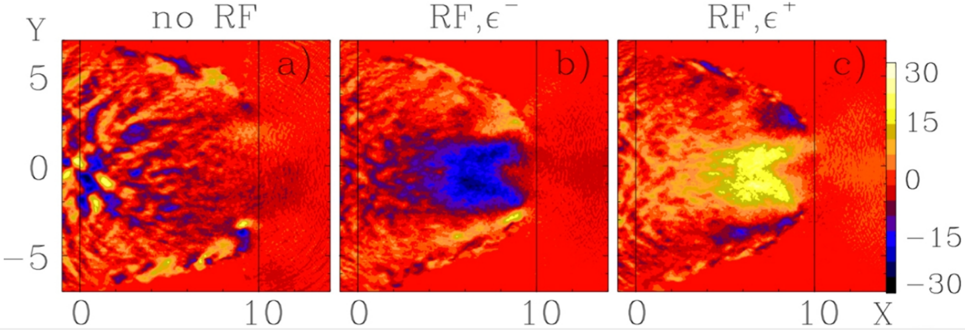
$\lambda = 0.8\ \mu$m

$n_e = 90 n_c = 1.6 \times 10^{23}$ cm^{-3}

$a_0 = (200 - 600)$

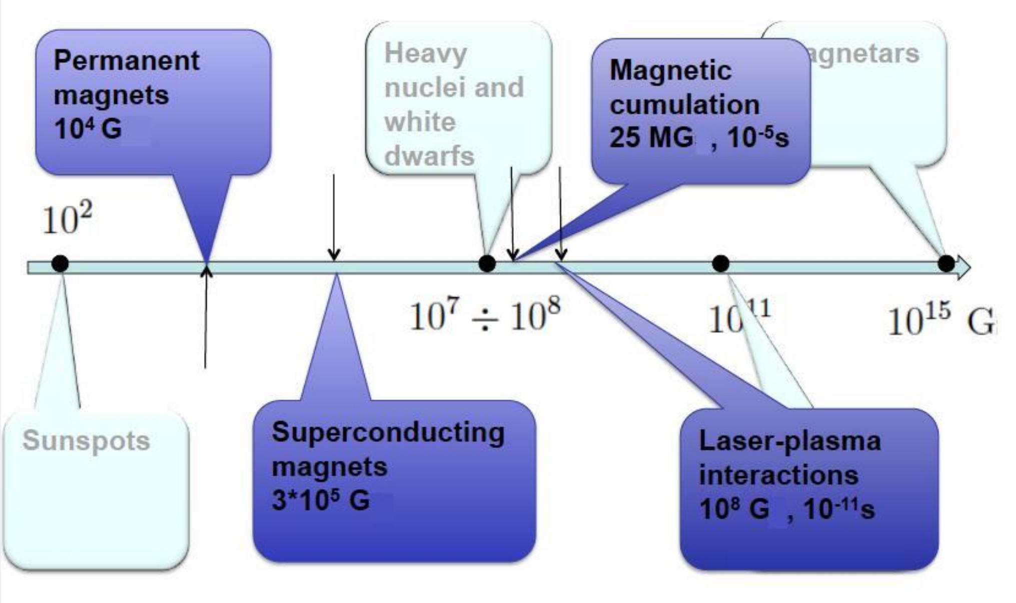
$I = (0.9 - 7.8) \times 10^{23}$ W cm^{-2}

$U = (0.4 - 4) \times 10^3$ J

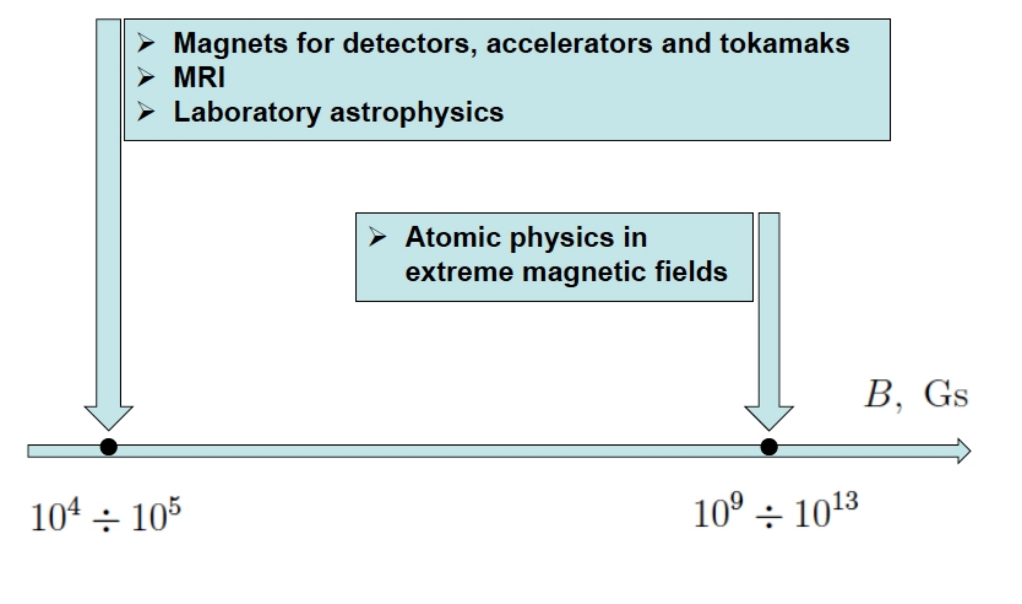


TL, Popruzhenko, Macchi, *New J. Phys* **18** (2016)

Strong magnetic fields in the laboratory



Strong magnetic fields for fundamental physics and applications



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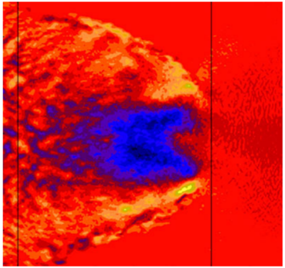
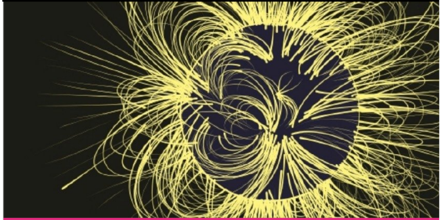
'Radiation friction' could make huge magnetic fields with lasers

Jul 19, 2016 2 comments



science alert



Physicists have calculated a whole new way to generate super-strong magnetic fields

Stronger than any magnetic field on Earth.

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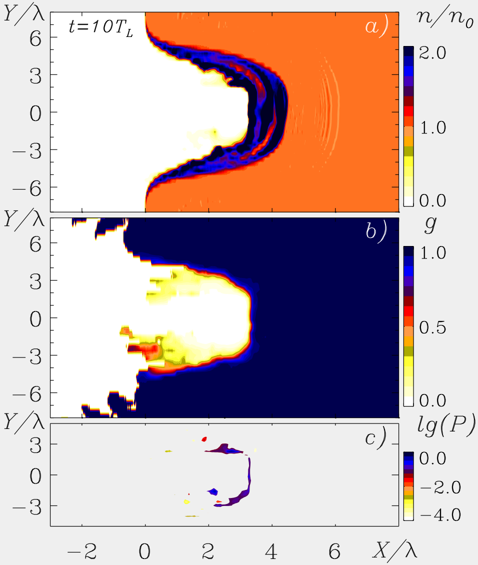
How to Create the World's Strongest Magnet

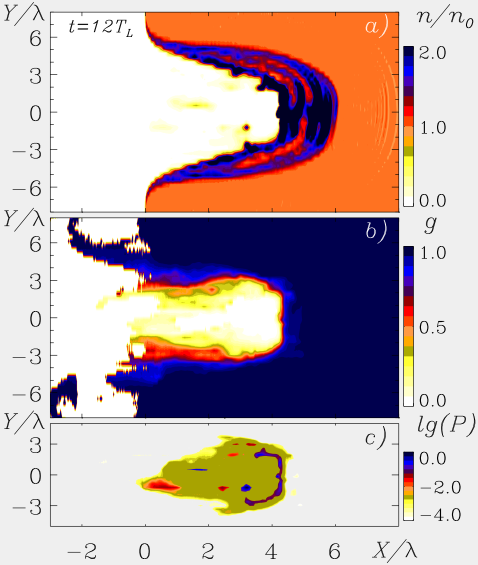
Quantum effect on magnetic field generation (preliminary)



$$\chi \equiv \frac{e\hbar}{m^3 c^4}\sqrt{-(F^{\mu\nu}p_\nu)^2}$$

$$g(\chi) = (1 + 12\chi + 21\chi^2 + 3.7\chi^3)^{-4/9}$$

Quantum effect on magnetic field generation (preliminary)



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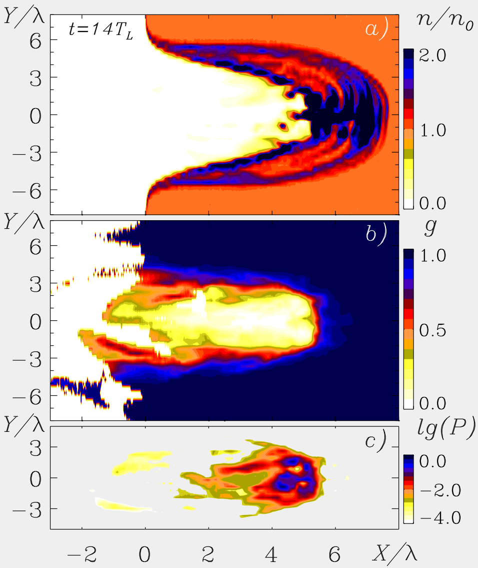

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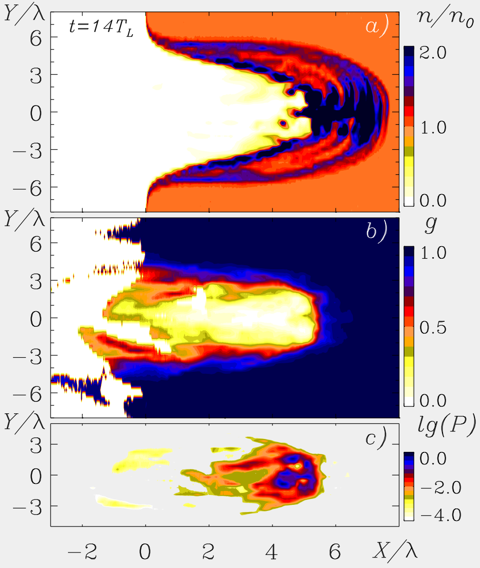

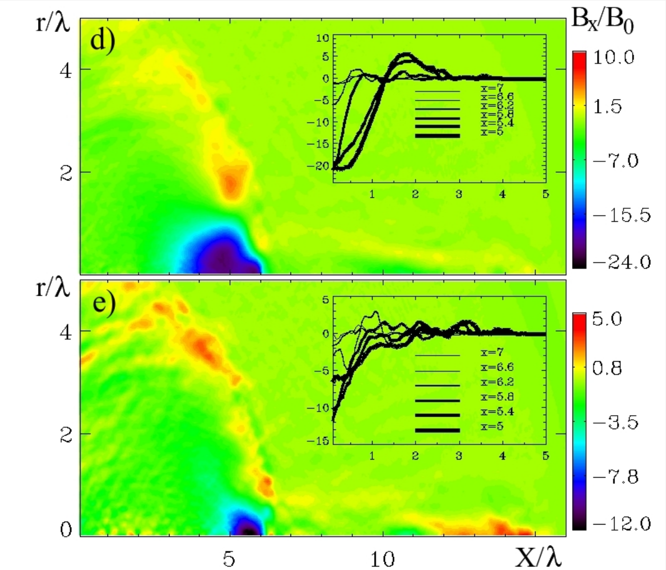

TL, Popruzhenko, Macchi, *in preparation*

Conclusion & Outlook

Radiation friction modeling in "extreme" laser-matter interactions is an open issue, crucial for next generation experiments at ELI, APOLLON etc.

The question is maybe more technical than fundamental, but improved classical models keep to be presented

First experiments face the challenge of superintense laser pulse stability to provide strong evidence for observed effects

Future experiments might allow the generation and study in the laboratory of radiation-dominated plasmas and related phenomena:

superintense magnetic fields
pair production and QED casades
efficient γ-ray generation

Thank you for your attention!

Questions?

Remarks?