CNR-INO

ISTITUTO NAZIONALE DI OTTICA

CONSIGLIO NAZIONALE DELLE RICERCHE

Investigating Quantum Radiation Friction

Relatore:

Andrea Macchi

Evento:

INO symposium 2019,
Sesto Fiorentino,
April 4

Outline and coworkers

Motivations

- radiation friction: from classical to quantum modeling
- looking for experimental tests of radiation friction models

Review of first experiments with ultraintense lasers

- experiments at GEMINI: findings and limitations
- a (personal) viewpoint

Our research

- Gigagauss magnetic field generation by radiation friction
- Simulation results
- Impact of quantum effects

Coworkers

Tatiana V. Liseykina
(Institute of Physics, University of Rostock, Germany)
Sergey V. Propruzhenko
(*MPI/PCS, Dresden, Germany, and Prokhorov Inst. RAS. Moscow, Russia*)

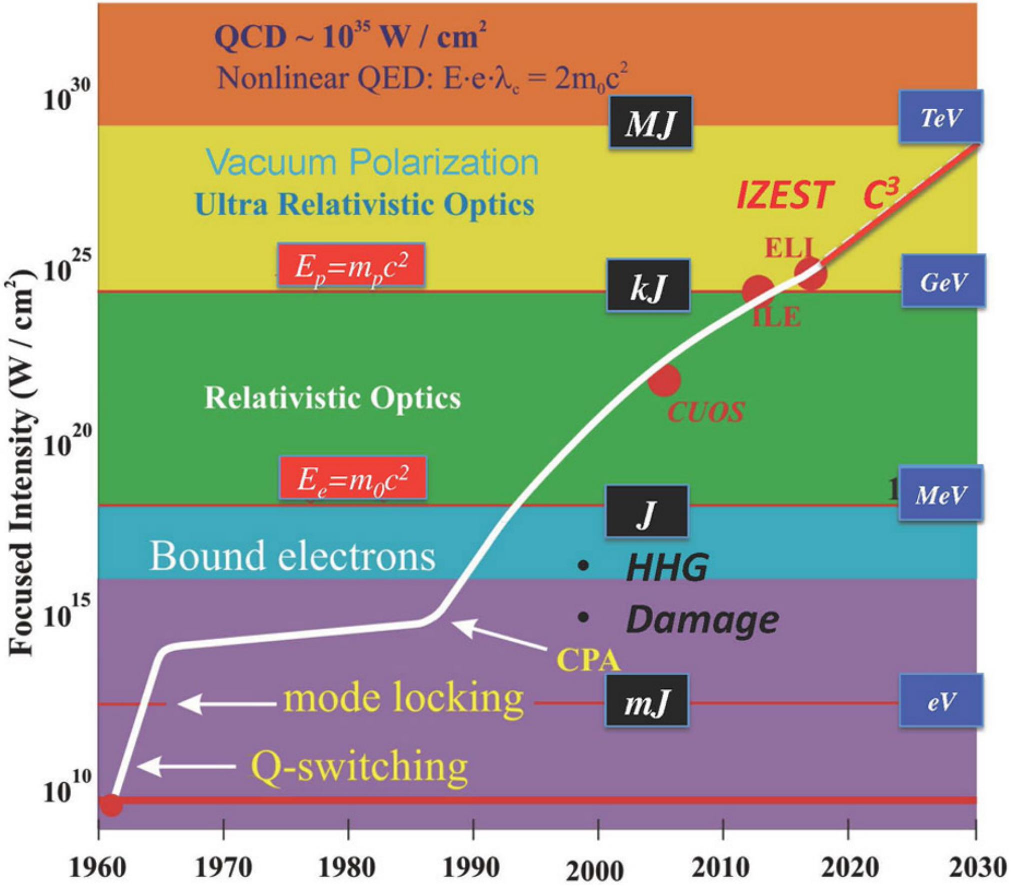
Motivations

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

$$\omega_{\rm rad} \simeq a_0^3\, \omega_{\rm laser}$$

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

A reliable modeling of *radiation friction* (aka *radiation reaction*) is needed

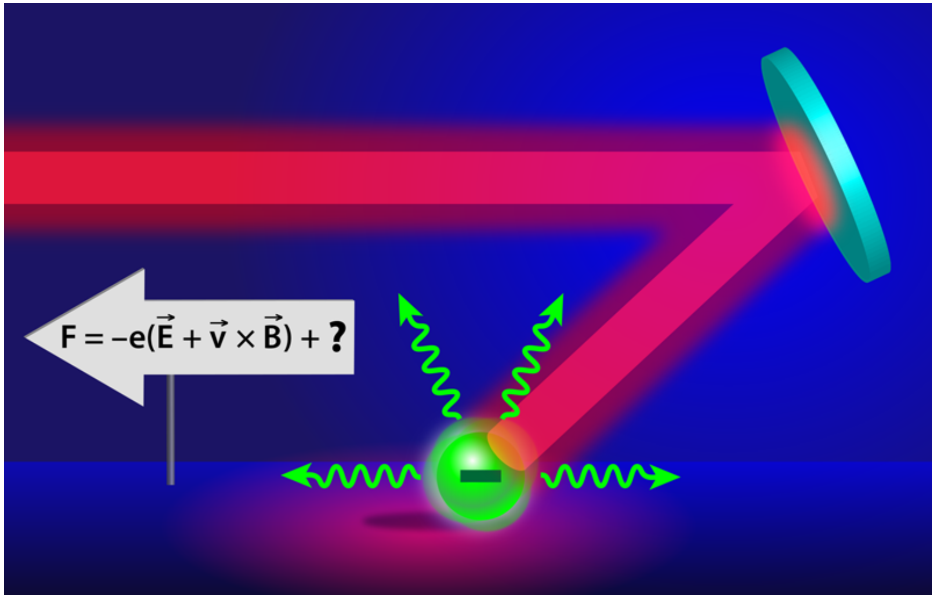


Picture evolved through the years from Mourou, Barty & Perry, *Phys. Today* **51** (1998)

Classical Radiation Friction Force

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

Eventual consensus (and robust theoretical ground) for Landau-Lifshitz's textbook expression:



Picture from: Macchi, *Physics* **11** (2018) 13
credit: APS / Alan Stonebraker

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

$$\begin{aligned}\mathbf{f}_{\rm rad} = -\frac{2r_c^2}{3}\Bigg\{&\gamma^2\left[\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)^2-\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)^2\right]\frac{\mathbf{v}}{c}\\ &-\left[\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)\times\mathbf{B}+\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)\mathbf{E}\right]+\gamma\frac{m_e c}{e}\left(\frac{d\mathbf{E}}{dt}+\frac{\mathbf{v}}{c}\times\frac{d\mathbf{B}}{dt}\right)\Bigg\}\end{aligned}$$

Onset of Quantum Effects

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

and in general QED effects dominate when $\chi \equiv \dfrac{e\hbar}{m_e^3 c^4}\,|F^{\mu\nu} p_\nu| \sim 1$

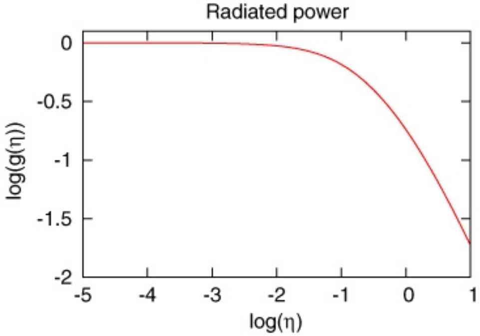
$$\chi \equiv \frac{E'}{E_{\mathrm{cr}}} \qquad E_{\mathrm{cr}} \equiv \frac{m_e c^2}{e\lambda_c} = \frac{m_e^2 c^3}{e\hbar}$$

E' : electric field in electron rest frame

E_{cr} : Schwinger field

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

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



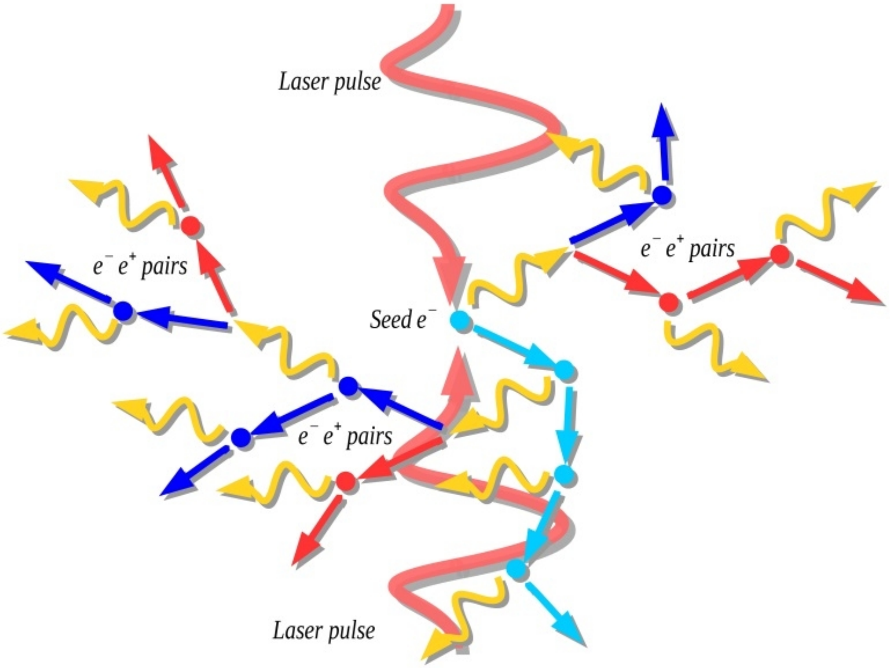
Ritus, *J. Sov. Las. Res.* **6** (1985) 497;
Kirk et al, *Plasma Phys. Contr. Fus.* **8** (2009) 85008

Radiation Friction in QED

In principle: there is *no* RF 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 dynamics *stochastic* instead of deterministic as in the (semi)classical model

Neitz & Di Piazza, *PRL* **111** (2013) 054802
Blackburn et al, *PRL* **112** (2014) 015001



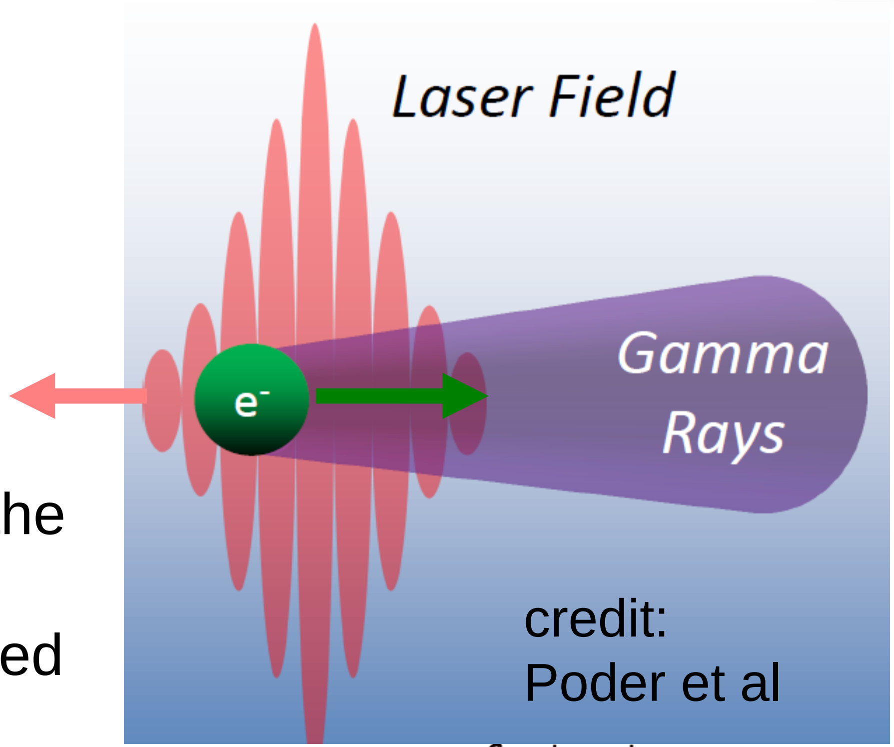
courtesy A. Di Piazza and C. H. Keitel

The GEMINI experiments

Search for quantum RF in head-on collision of 2 GeV electron bunches with the GEMINI laser

(40 fs, 4×10^{20} W/cm^2 , a_0=10)

Thomson backscattering geometry maximizes $\chi\approx 0.25$



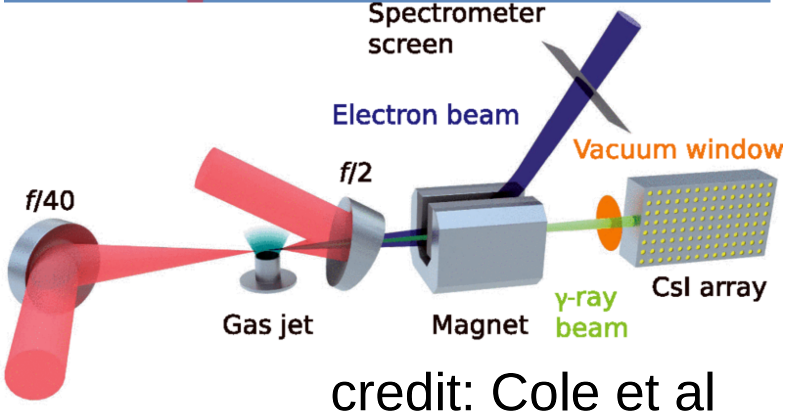
credit: Poder et al

Two “twin” experiments measured the “cooling” of the electron spectrum due to radiative losses and compared the results with different TF models

Cole et al, *Phys. Rev. X* **8** (2018) 011020

Poder et al, *ibid.* 031004

The electron bunch is produced by laser wakefield acceleration (large number of particles, less challenging synchronization)



credit: Cole et al

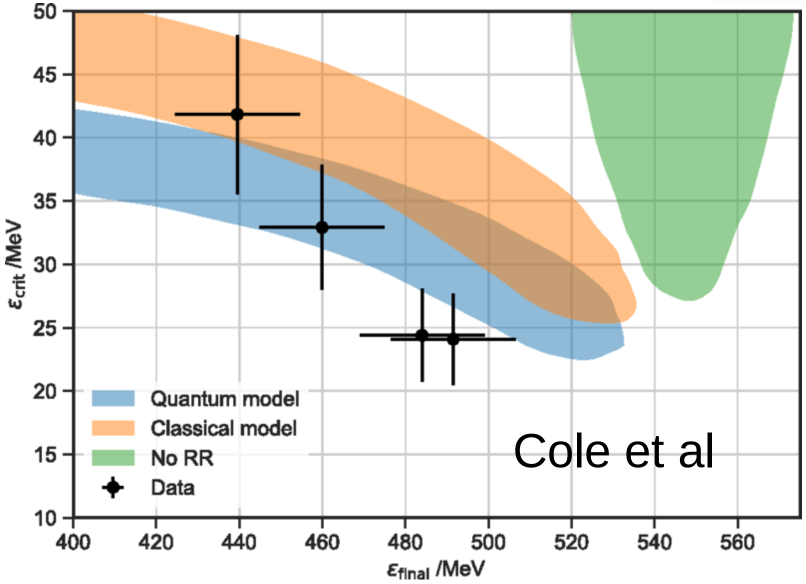
Issues in comparison with theory

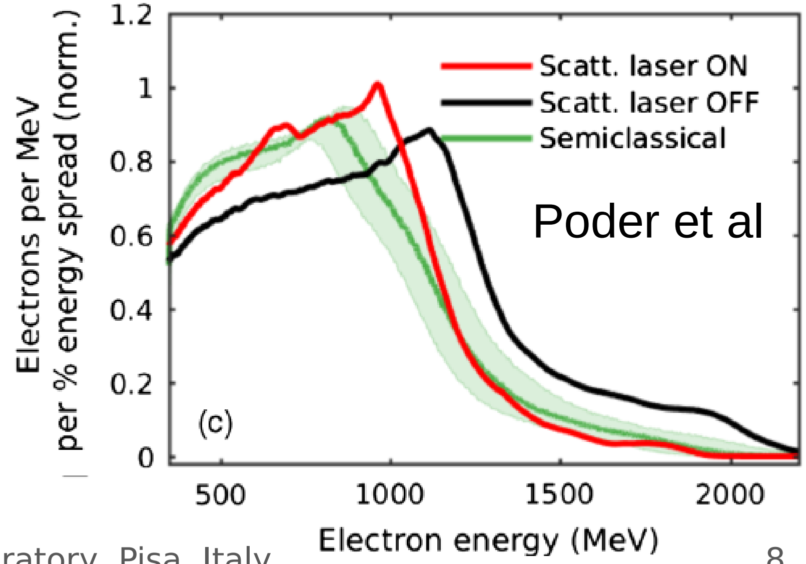
Evidence of quantum RF limited (~2σ) by statistics and laser/electron beam fluctuations

The “semiclassical” model reproduces the “cooled” electron spectrum *better* than a “quantum” stochastic model: *breakdown of assumptions in the QED calculation*?

A general issue: the RF signatures are to be found in relatively small effects

[Viewpoint: A. Macchi, *Physics* **11** (2018) 13]





“Inverse Faraday effect” by RF

IFE (almost a misnomer) consists in *absorption of EM angular momentum* in a *dissipative medium* leading to the *generation of quasistatic magnetic fields*

For each emitted gamma photon, many laser photons are destroyed

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

Using polarized photons (i.e. a circularly polarized laser), almost all the photon spin is transferred to electrons as orbital momentum
generation of azimuthal current and axial magnetic field

In dense targets the predicted radiative losses are high (>10%) thus favoring the generation of very strong fields which are an *unambigous signature of RF*

Analytical modeling of RF losses and IFE:
Lyseykina, Propruzhenko, Macchi, *New. J. Phys.* **18** (2016) 072001
Propruzhenko, Lyseykina, Macchi, *New. J. Phys.* **21** (2019) 033009

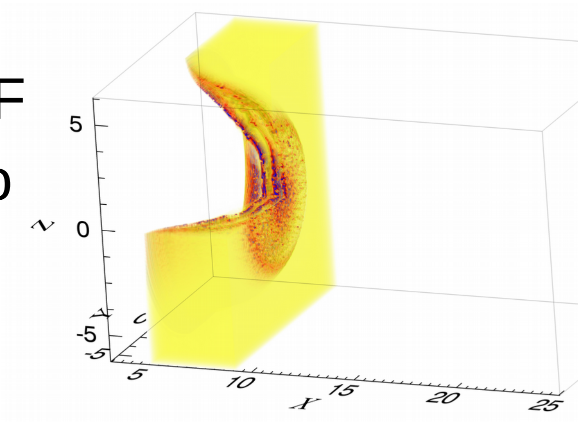
Gigagauss magnetic fields

3D simulations with classical RF

B_x normalized to

$B_0 = m_e c\omega/e$

$= 1.34 \times 10^8$ G



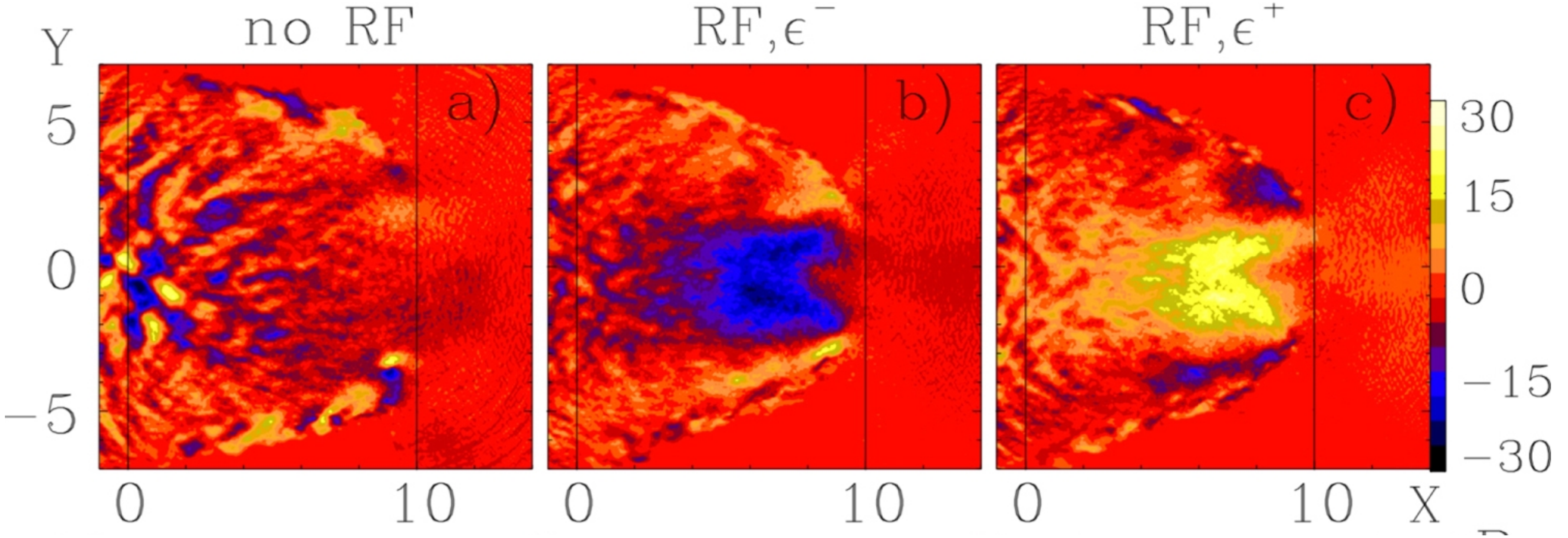
$\lambda = 0.8\ \mu$m

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

$a_0 = (200 - 600)$

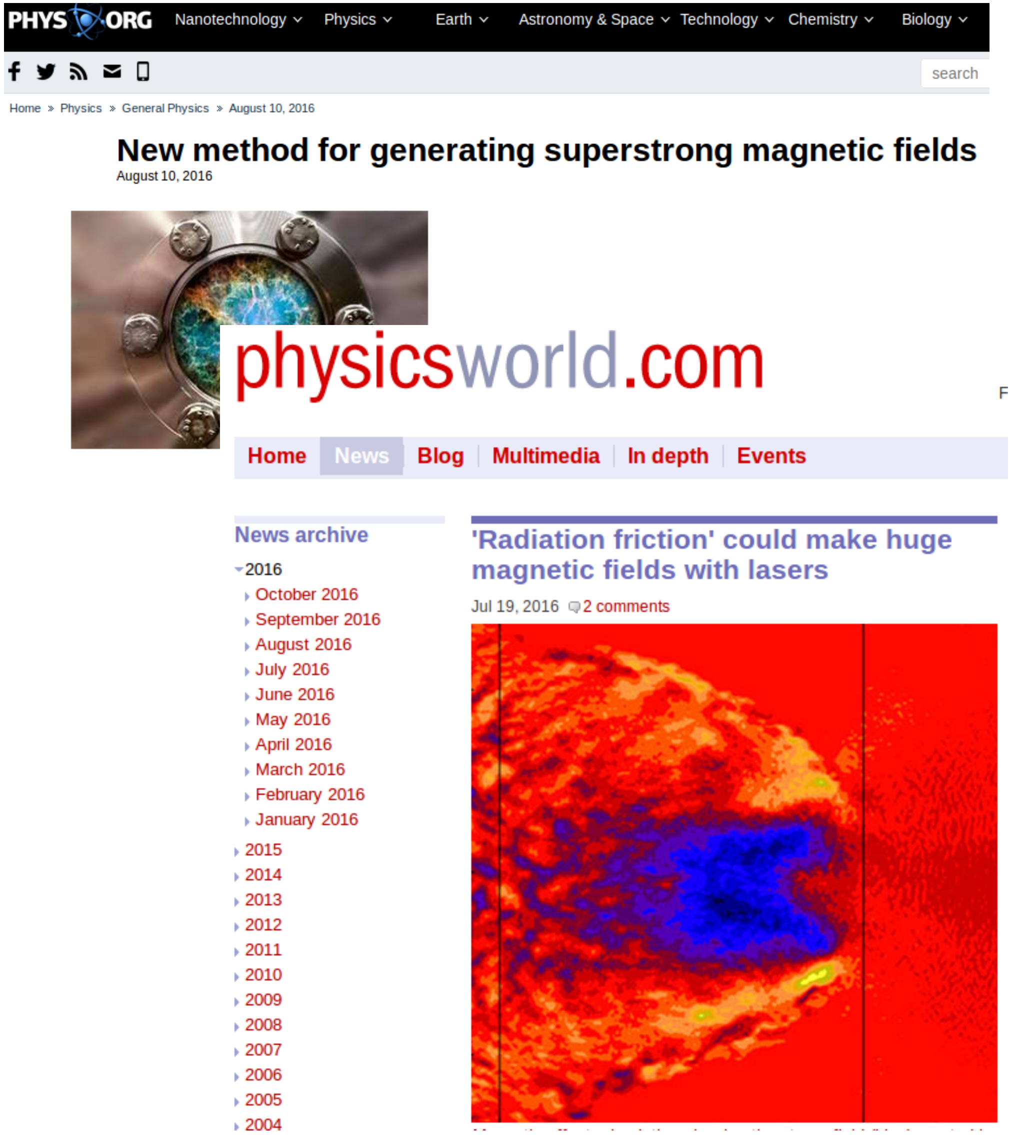
$I = (0.9 - 7.8) \times 10^{23}$ W cm^{-2}

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



Lyseykina, Propruzhenko, Macchi, *New. J. Phys.* **18** (2016) 072001

Popular reception …

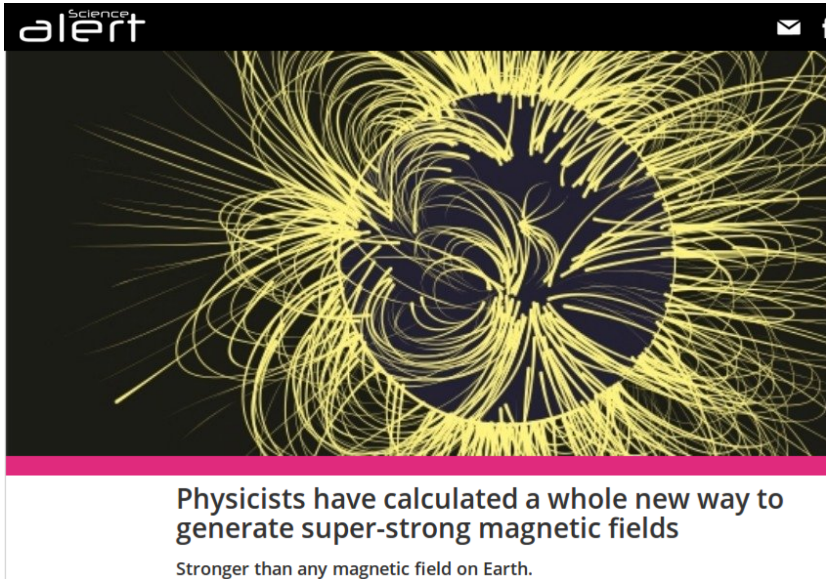


New method for generating superstrong magnetic fields

August 10, 2016

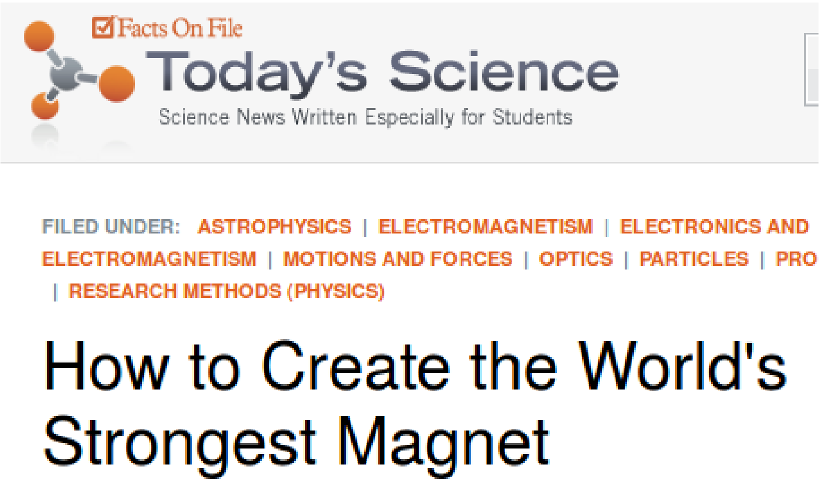
'Radiation friction' could make huge magnetic fields with lasers

Jul 19, 2016 2 comments



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

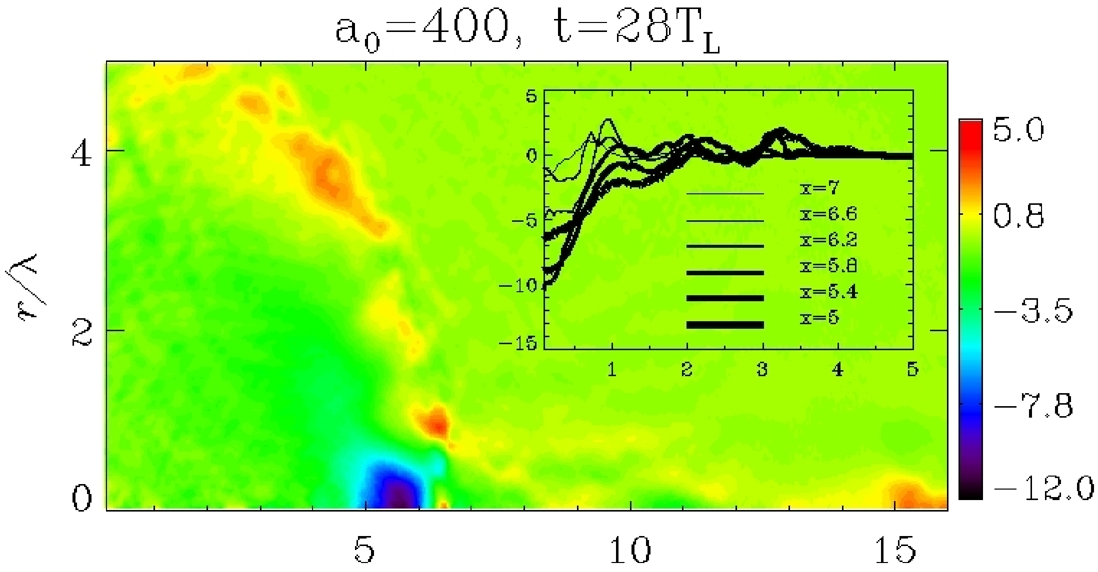
Stronger than any magnetic field on Earth.

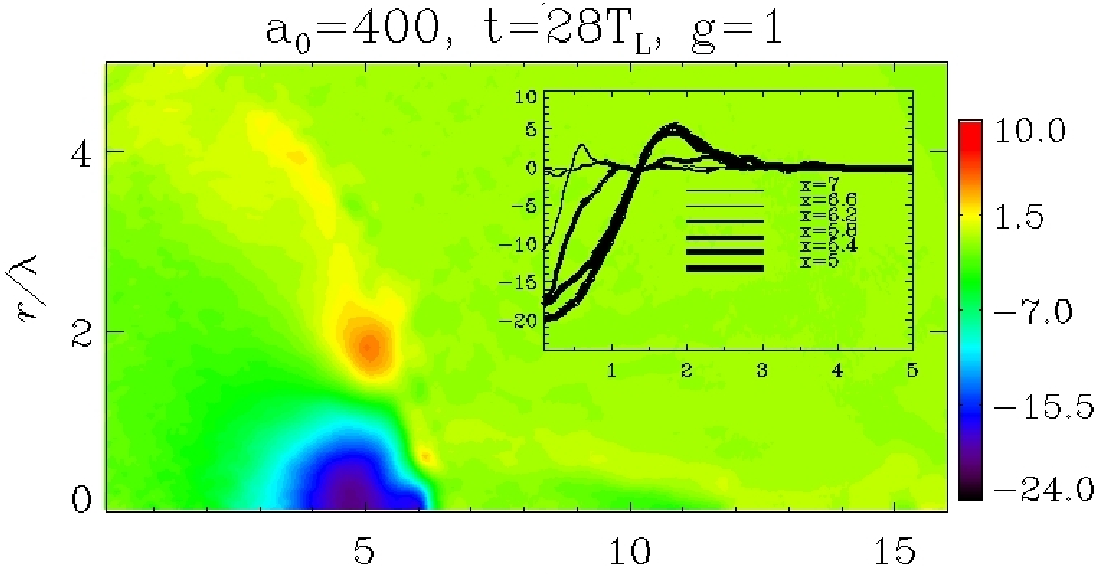


FILED UNDER: ASTROPHYSICS | ELECTROMAGNETISM | ELECTRONICS AND ELECTROMAGNETISM | MOTIONS AND FORCES | OPTICS | PARTICLES | PRO | RESEARCH METHODS (PHYSICS)

How to Create the World's Strongest Magnet

Quantum effects (preliminary)





Introduction of quantum corrections via the $g(\chi)$ factor yields some 50% reduction in the magnetic field

Measurements of B_x on the optical axis may discriminate against different RF models (in future experiments at ultra-high intensities ...)

Lyseykina, Propruzhenko, Macchi (2019) in preparation

Conclusions

Radiation Friction modeling in “extreme” laser-matter interactions is an open issue, crucial for next generation experiments at ELI 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 stability to provide strong evidence for effects observed)

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 cascades, efficient gamma-ray generation ...)

Inserire titolo slide a 32pt Trebuchet font