The world of electromagnetic matter

F. Pegoraro

Department of Physics "Enrico Fermi", University of Pisa
Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy
francesco.pegoraro@unipi.it

SIF 2016 Padova

UNIVERSITÀ DI PISA

EPJ.org
your physics journal

The world of *plasma* where the electromagnetic fields dominate the dynamics of matter

- It is a world without equilibrium that escapes the discipline of the thermodynamic rules. It is a world that can appear in a bewildering variety of forms[1].
- Its forms are shaped by the collective dynamics of fields and particles. This dynamics occurs on timescales that can be extremely shorter than those of the binary processes among individual particles.
- Its dynamics is dominated by nonlinearities and can produce unprecedented large energy densities, on mesoscopic scales in the laboratory and on huge spatial scales in the Universe.
- The imprint of this behaviour is ubiquitous in the Universe.

---

[1] Interestingly the word $\pi\lambda\alpha\sigma\mu\alpha$ stands, among other meanings, for something that has been *formed*

The world of *plasma* where the electromagnetic fields dominate the dynamics of matter

- It is a world without equilibrium that escapes the discipline of the thermodynamic rules. It is a world that can appear in a bewildering variety of forms[1].
- Its forms are shaped by the collective dynamics of fields and particles. This dynamics occurs on timescales that can be extremely shorter than those of the binary processes among individual particles.
- Its dynamics is dominated by nonlinearities and can produce unprecedented large energy densities, on mesoscopic scales in the laboratory and on huge spatial scales in the Universe.
- The imprint of this behaviour is ubiquitous in the Universe.

[1] Interestingly the word $\pi\lambda\alpha\sigma\mu\alpha$ stands, among other meanings, for something that has been *formed*

The world of *plasma* where the electromagnetic fields dominate the dynamics of matter

- It is a world without equilibrium that escapes the discipline of the thermodynamic rules. It is a world that can appear in a bewildering variety of forms[1].
- Its forms are shaped by the collective dynamics of fields and particles. This dynamics occurs on timescales that can be extremely shorter than those of the binary processes among individual particles.
- Its dynamics is dominated by nonlinearities and can produce unprecedented large energy densities, on mesoscopic scales in the laboratory and on huge spatial scales in the Universe.
- The imprint of this behaviour is ubiquitous in the Universe.

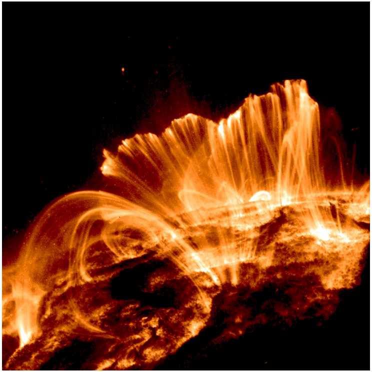
[1] Interestingly the word $\pi\lambda\alpha\sigma\mu\alpha$ stands, among other meanings, for something that has been *formed*

The world of *plasma* where the electromagnetic fields dominate the dynamics of matter

- It is a world without equilibrium that escapes the discipline of the thermodynamic rules. It is a world that can appear in a bewildering variety of forms[1].
- Its forms are shaped by the collective dynamics of fields and particles. This dynamics occurs on timescales that can be extremely shorter than those of the binary processes among individual particles.
- Its dynamics is dominated by nonlinearities and can produce unprecedented large energy densities, on mesoscopic scales in the laboratory and on huge spatial scales in the Universe.
- The imprint of this behaviour is ubiquitous in the Universe.

[1] Interestingly the word $\pi\lambda\alpha\sigma\mu\alpha$ stands, among other meanings, for something that has been *formed*

FORMS: Solar coronal magnetic loops - UV (Trace) Jet in the Centaurus A galaxy - X ray (Chandra)



Note that the solar corona ($> 10^6 K$) is much hotter than the Sun's surface ($\sim 5.8 \times 10^3\ K$)

Particle energy and density range of interest

- In a domain in the parameter space of particle energy $\mathscr{E}$ and density n, loosely within the bounds[2]

$$eV < \mathscr{E} < MeV, \qquad m^{-3} < n < 10^{26}\, m^{-3},$$

the *dynamical time* of a collection of charged particles is *many* orders of magnitude shorter than their *relaxation time*.

- The dynamical time is measured, in its most elementary form, by the inverse of the electron plasma (Langmuir) frequency

$$\omega_{pe} \equiv [4\pi n e^2/m_e]^{1/2},$$

the relaxation time by the so called binary collision frequency

$$\nu_{ei} \sim n\, \sigma_{Coulomb} [\mathscr{E}/m_e]^{1/2}, \qquad \sigma_{Coulomb} \propto 1/\mathscr{E}^2$$

defined so as to account for the difference between the full e.m. fields and their mean field approximation.

[2] These bounds are clearly not independent and may extend e.g., to even smaller energies for very dilute systems where atomic processes are infrequent. The upper energy bound is taken to be related to electron-positron pair creation threshold. Relativistic effects such as retardation effects are not explicitly included in these estimates.

Particle energy and density range of interest

- In a domain in the parameter space of particle energy $\mathscr{E}$ and density n, loosely within the bounds[2]

$$eV < \mathscr{E} < MeV, \qquad m^{-3} < n < 10^{26} m^{-3},$$

the *dynamical time* of a collection of charged particles is *many* orders of magnitude shorter than their *relaxation time*.

- The dynamical time is measured, in its most elementary form, by the inverse of the electron plasma (Langmuir) frequency

$$\omega_{pe} \equiv [4\pi n e^2 / m_e]^{1/2},$$

the relaxation time by the so called binary collision frequency

$$\nu_{ei} \sim n\, \sigma_{Coulomb} [\mathscr{E}/m_e]^{1/2}, \qquad \sigma_{Coulomb} \propto 1/\mathscr{E}^2$$

defined so as to account for the difference between the full e.m. fields and their mean field approximation.

---

[2] These bounds are clearly not independent and may extend e.g., to even smaller energies for very dilute systems where atomic processes are infrequent. The upper energy bound is taken to be related to electron-positron pair creation threshold. Relativistic effects such as retardation effects are not explicitly included in these estimates.

Frequencies and spatial scalelengths ordering

- This frequency ordering is a direct consequence of the long range nature of the interaction between charged particles[3].
- In turn, this ordering implies that the dynamical scalelength (taken here as the Debye length λ_D) is much shorted than the particle collisional mean free path ℓ_{mfp}.
  More important: conditions are not uncommon where the mean free path ℓ_{mfp} exceeds the size L of system.[4]
- These physical conditions are generally met by the visible matter in the Universe. They imply that in any open system that exchanges energy on the dynamical time scale, i.e. is not a frozen equilibrium such as the cosmic microwave background, *matter will not be found in a state of (local) thermodynamic equilibrium*, our Earth's environment being an obvious exception.

[3] Note in particular that for a scalar potential $\propto r^{-\alpha}$: for $k \to 0$ $\alpha > 3 \to \omega^2 = O(k^2)$, $1 < \alpha < 3 \to \omega^2 = O(k^{2-d+\alpha})$, A. Cintio, G Morchio, J. Math. Phys., **50**, 042102 (2009)

[4] This makes the plasma dynamics to be in general $\Rightarrow$ *nonlocal* $\Leftarrow$

Frequencies and spatial scalelengths ordering

- This frequency ordering is a direct consequence of the long range nature of the interaction between charged particles[3].
- In turn, this ordering implies that the dynamical scalelength (taken here as the Debye length λ_D) is much shorted than the particle collisional mean free path ℓ_{mfp}.
  More important: conditions are not uncommon where the mean free path ℓ_{mfp} exceeds the size L of system.[4]
- These physical conditions are generally met by the visible matter in the Universe. They imply that in any open system that exchanges energy on the dynamical time scale, i.e. is not a frozen equilibrium such as the cosmic microwave background, *matter will not be found in a state of (local) thermodynamic equilibrium*, our Earth's environment being an obvious exception.

---

[3] Note in particular that for a scalar potential $\propto r^{-\alpha}$: for $k \to 0$ $\alpha > 3 \to \omega^2 = O(k^2)$, $1 < \alpha < 3 \to \omega^2 = O(k^{2-d+\alpha})$, A. Cintio, G Morchio, J. Math. Phys., **50**, 042102 (2009)

[4] This makes the plasma dynamics to be in general $\Rightarrow$ *nonlocal* $\Leftarrow$

Frequencies and spatial scalelengths ordering

- This frequency ordering is a direct consequence of the long range nature of the interaction between charged particles[3].
- In turn, this ordering implies that the dynamical scalelength (taken here as the Debye length λ_D) is much shorted than the particle collisional mean free path ℓ_{mfp}.
  More important: conditions are not uncommon where the mean free path ℓ_{mfp} exceeds the size L of system.[4]
- These physical conditions are generally met by the visible matter in the Universe. They imply that in any open system that exchanges energy on the dynamical time scale, i.e. is not a frozen equilibrium such as the cosmic microwave background, *matter will not be found in a state of (local) thermodynamic equilibrium*, our Earth's environment being an obvious exception.

[3] Note in particular that for a scalar potential $\propto r^{-\alpha}$: for $k \to 0$ $\alpha > 3 \to \omega^2 = O(k^2)$, $1 < \alpha < 3 \to \omega^2 = O(k^{2-d+\alpha})$, A. Cintio, G Morchio, J. Math. Phys., **50**, 042102 (2009)

[4] This makes the plasma dynamics to be in general $\Rightarrow$ *nonlocal* $\Leftarrow$

Non equilibrium particle distribution functions in the expanding solar wind

Mean free path $\sim 1 A.U. \sim 1.5 \times 10^8\, Km$

Energy exchange mainly due to (low frequency and low phase velocity) magnetic wave turbulence in the solar wind plasma,

E. Marsch Space.Sci, rev. **172**, 23 (2012).

Helios mission

Dotted line: local direction of magnetic field

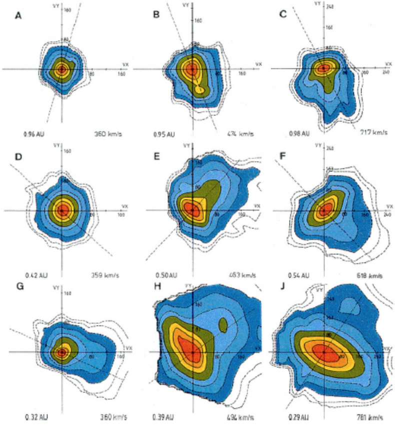


Fig. 1 Proton velocity distribution functions for three types of solar wind: Slow (*left column*), intermediate-speed (*middle*), and fast (*right*). The heliocentric distance decreases from top to bottom as indicated in the respective frames. Increasingly strong deviations from a Maxwellian occur at smaller distances from the Sun, with proton beams along the field (*dashed lines*) and large anisotropies perpendicular to the field in the core

Electromagnetic energy density versus particle density

An indicative scaling can be obtained from the following argument:

- If the charged particles in the system were at global thermodynamic equilibrium with the e.m. fields, the energy density in these fields would be independent of the particle density and would depend only on their temperature (Black-body radiation).
- If only local thermodynamic equilibrium had been achieved, the balance between the particle pressure and the Maxwell stress tensor would give a linear relationship between the e.m. energy density and the particle density (force balance).
- If instead coherent radiation of magnetic and electric waves due to collective nonequilibrium particle oscillations in the system is dominant, the e.m. energy density turns out to scale with the square of the particle density.

Electromagnetic energy density versus particle density

An indicative scaling can be obtained from the following argument:

- If the charged particles in the system were at global thermodynamic equilibrium with the e.m. fields, the energy density in these fields would be independent of the particle density and would depend only on their temperature (Black-body radiation).
- If only local thermodynamic equilibrium had been achieved, the balance between the particle pressure and the Maxwell stress tensor would give a linear relationship between the e.m. energy density and the particle density (force balance).
- If instead coherent radiation of magnetic and electric waves due to collective nonequilibrium particle oscillations in the system is dominant, the e.m. energy density turns out to scale with the square of the particle density.

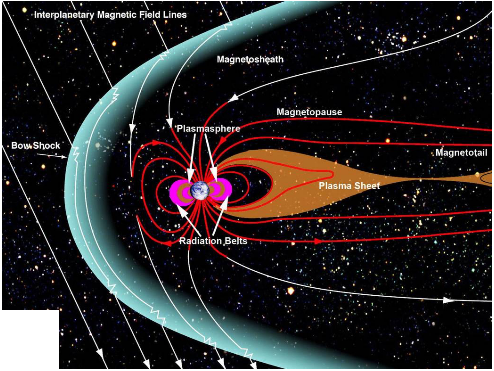
Electromagnetic energy density versus particle density

An indicative scaling can be obtained from the following argument:

- If the charged particles in the system were at global thermodynamic equilibrium with the e.m. fields, the energy density in these fields would be independent of the particle density and would depend only on their temperature (Black-body radiation).
- If only local thermodynamic equilibrium had been achieved, the balance between the particle pressure and the Maxwell stress tensor would give a linear relationship between the e.m. energy density and the particle density (force balance).
- If instead coherent radiation of magnetic and electric waves due to collective nonequilibrium particle oscillations in the system is dominant, the e.m. energy density turns out to scale with the square of the particle density.

Earth's magnetosphere The solar wind ram pressure balances the pressure of the Earth 's magnetic field

$$n(Mv^2/2) \approx B^2/(8\pi)$$



Journal of Geophysical Research

Volume 68, Issue 13
1 July 1963
Pages 4017–4063

Explorer 10 plasma measurements

A. Bonetti, H. S. Bridge, A. J. Lazarus, B. Rossi, F. Scherb

1 July 1963

DOI:
10.1029/JZ068i013p04017

Plasma measurements were made with a detector aboard the Explorer 10 satellite, launched on a highly elongated elliptical trajectory with the line of apsides about 33° to the antisolar direction. Magnetic field measurements were also carried out on Explorer 10 by the Goddard Space Flight Center of NASA. A plasma moving with a velocity of about 300 km sec^{-1} was first observed when the satellite reached a distance of about 22 earth radii. During the rest of the observations (which terminated about 40 hours later, at a distance

⇐ First satellite detection of the solar wind

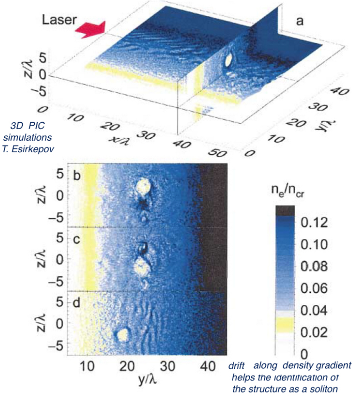
Note: *Bruno Rossi* a major figure in space research and quite important in the history of the Physics Institute of Padua University 1932 - 1938

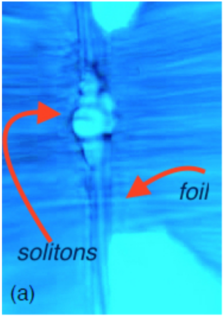
Laboratory plasma   Relativistic e.m. solitons

Radiation pressure acting on the electrons is balanced by the Maxwell stress tension of the charge separation electric field.

Relativistic Vlasov (PIC) simulation: soliton generated by ultraintense laser pulse drifts in inhomogeneous plasma density

Soliton detection: proton radiography at RAL





TRAPPING AND CONFINEMENT OF ELECTROMAGNETIC ENERGY

Pulsar : *coherent* cuvature radiation model
New laboratory e.m. radiation sources

THE ASTROPHYSICAL JOURNAL, 196: 51–72, 1975 February 15

THEORY OF PULSARS: POLAR GAPS, SPARKS, AND COHERENT MICROWAVE RADIATION

M. A. RUDERMAN*
AND
P. G. SUTHERLAND†
Department of Physics, Columbia University

However, the efficiency for single-particle, incoherent, curvature radiation in the magnetosphere is negligible. The fraction f of the total energy E radiated by a particle as it moves along a trajectory of curvature ρ is, from equations (43) and (44):

$$f = \frac{P\rho/c}{E} = \frac{2}{3}\frac{e^2}{\hbar c}\frac{\hbar\omega_c}{mc^2}\,, \tag{47}$$

where $\hbar\omega_c$ is the photon energy of the curvature radiation. Since $\omega_c \sim 10^{10}\ \mathrm{s}^{-1}$, $f \approx 10^{-13}$. That single-particle incoherent radiation is inadequate in explaining pulsar radiation is, of course, well known and not very surprising—the remarkably high brightness temperatures of order 10^{30} °K of some pulsar radio emission certainly means that the radiation must be produced coherently. However, the stream of secon-

X-ray Sources Driven by Ultrashort Laser Pulses

Plasma based X-ray lasers are now a well-established technology to produce coherent XUV radiation at high energy and intensity. Gas and solid laser pumped plasmas can be used to amplify high quality ultrashort X-ray pulses produced by high-harmonic-generation in the injection seeding method. The high energy available from ELI laser beams brings the possibility to generate coherent radiation in the water window.

ELI: Extreme Light Infrastrucure https://eli-laser.eu
is a EU Research Infrastructure presently under development
in central-eastern Europe

Plasmas: self-consistent collective interactions

These examples allow us to characterize a (high energy, dilute) plasma as a collection of charged particles, in general globally neutral, dominated by their collective interactions[5].
In particular, in the scalar potential model (electrostatic limit) a plasma is characterized by the inequalities [6]

$$\underbrace{L \gg \lambda_d}_{\text{self-consistent collective interaction}} \qquad \underbrace{l_{mfp} \gg \lambda_d}_{\text{collective interaction stronger than binary interactions}}$$

In addition these examples show that a plasma is a medium that is very effective both in producing and and manipulating high energy density e.m. fields and e.m. radiation.

---

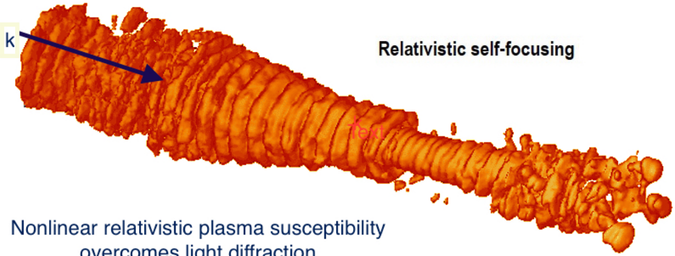
[5] An analogous definition holds for gravitational plasmas, in other words for galaxies (plasmas of stars)

[6] L characteristic spatial scale of the system, λ_d the Debye length, ℓ_{mfp} the collisional mean free path.
These orderings can be formalized by introducing the plasma parameter $g \equiv 1/(n\lambda_d^3) \ll 1$, $[g \sim 10^{-6} - 10^{-10}]$.

E.M. field manipulation:
relativistic self-focusing in a plasma

$$\omega^2 = k^2c^2 + \omega_{pe}^2(\gamma), \qquad \omega_{pe}^2(\gamma) = 4\pi n e^2/(m_e\gamma), \qquad \gamma \sim a^2$$

γ electron Lorentz factor, $a >> 1$ normalized laser pulse amplitude.



Nonlinear relativistic plasma susceptibility
overcomes light diffraction

PIC simulation. T. Esirkepov Circular polarization
Predicted by G.A. Askar'yan, Soviet Phys. JETP 15, 1088 (1962),
routinely observed in intense laser plasma interaction experiments.

Thermonuclear fusion research

- The fact that plasmas can store large energy densities lies at the very foundation of the magnetic fusion research that aims to produce *net* thermonuclear energy in a controlled way in the laboratory at relatively low particle densities.
- However the effectiveness of the collective interactions between the particles and the e.m. fields in plasmas can cause a fast energy transfer between particles and fields: in almost all conditions the transport properties of a plasma are determined by collective plasma excitations, not by binary processes.
- Far from thermodynamic equilibrium the amplitude of these particle-field fluctuations is orders of magnitude larger than that of the thermal fluctuations one encounters[7] in regimes of local equilibrium giving rise to *anomalous*, i.e. enhanced, transport.

[7] See fluctuation-dissipation theorem

Thermonuclear fusion research

- The fact that plasmas can store large energy densities lies at the very foundation of the magnetic fusion research that aims to produce *net* thermonuclear energy in a controlled way in the laboratory at relatively low particle densities.
- However the effectiveness of the collective interactions between the particles and the e.m. fields in plasmas can cause a fast energy transfer between particles and fields: in almost all conditions the transport properties of a plasma are determined by collective plasma excitations, not by binary processes.
- Far from thermodynamic equilibrium the amplitude of these particle-field fluctuations is orders of magnitude larger than that of the thermal fluctuations one encounters[7] in regimes of local equilibrium giving rise to *anomalous*, i.e. enhanced, transport.

[7] See fluctuation-dissipation theorem

Thermonuclear fusion research

- The fact that plasmas can store large energy densities lies at the very foundation of the magnetic fusion research that aims to produce *net* thermonuclear energy in a controlled way in the laboratory at relatively low particle densities.
- However the effectiveness of the collective interactions between the particles and the e.m. fields in plasmas can cause a fast energy transfer between particles and fields: in almost all conditions the transport properties of a plasma are determined by collective plasma excitations, not by binary processes.
- Far from thermodynamic equilibrium the amplitude of these particle-field fluctuations is orders of magnitude larger than that of the thermal fluctuations one encounters[7] in regimes of local equilibrium giving rise to *anomalous*, i.e. enhanced, transport.

[7] See fluctuation-dissipation theorem

Thermonuclear fusion research

- The fact that plasmas can store large energy densities lies at the very foundation of the magnetic fusion research that aims to produce *net* thermonuclear energy in a controlled way in the laboratory at relatively low particle densities.
- However the effectiveness of the collective interactions between the particles and the e.m. fields in plasmas can cause a fast energy transfer between particles and fields: in almost all conditions the transport properties of a plasma are determined by collective plasma excitations, not by binary processes.
- Far from thermodynamic equilibrium the amplitude of these particle-field fluctuations is orders of magnitude larger than that of the thermal fluctuations one encounters[7] in regimes of local equilibrium giving rise to *anomalous*, i.e. enhanced, transport.

[7] See fluctuation-dissipation theorem

A still very relevant piece of theory at ICPT

THE PHYSICS OF FLUIDS VOLUME 10, NUMBER 3 MARCH 1967

Instabilities due to Temperature Gradients in Complex Magnetic Field Configurations

B. Coppi, M. N. Rosenbluth, and R. Z. Sagdeev
International Centre for Theoretical Physics, International Atomic Energy Agency, Trieste, Italy
(Received 25 July 1966)

An integral equation governing an instability due to ion temperature gradients is derived. In the presence of magnetic shear, localized non-convective normal modes of instability are shown to exist if the relative temperature gradient is larger than that of density, unless the shear is exceedingly strong, i.e., the field shears through a large angle in the distance in which the temperature drops. Quasi-modes which are less localized in the direction of the gradient can be constructed from these normal modes and a large thermal diffusion may be expected. Conversely the mass diffusion is shown to be rather slow so that it is reasonable to assume that an effective "divertor" should keep the actual heat loss quite small.

The instability corresponds to the additional pumping due to the $\vec{E} \times \vec{B}$ drift along the ion temperature gradient in phase with the growing temperature of ion sound waves

Thermonuclear fusion research: a word of caution

- The physics of thermonuclear fusion in the laboratory is very different from that inside a star, or even from that of a thermonuclear weapon, because of its miniaturization.
- A star is dense and thus opaque to the e.m. radiation. It is at local thermodynamic equilibrium and loses energy mostly through Black Body radiation: losses are proportional to the star surface while gains (thermonuclear fusion power) are proportional to the star volume.
- To be hot and confined, a plasma in a laboratory magnetic fusion experiment must be dilute[8]: it is transparent to its own radiation (mainly bremsstrahlung) and suffers intrinsic losses that are proportional to the plasma volume as its fusion gains[9] are.

---

[8] The situation is partly different for inertial fusion plasmas which however are still transparent to the energetic neutrons produced by the fusion reactions.

[9] For these reasons fusion experiments must be hotter that the inner part of the Sun and need the much more energetic D-T cycle, T being produced by spallation reactions between the fusion neutrons and a Lithium blanket.

Thermonuclear fusion research: a word of caution

- The physics of thermonuclear fusion in the laboratory is very different from that inside a star, or even from that of a thermonuclear weapon, because of its miniaturization.
- A star is dense and thus opaque to the e.m. radiation. It is at local thermodynamic equilibrium and loses energy mostly through Black Body radiation: losses are proportional to the star surface while gains (thermonuclear fusion power) are proportional to the star volume.
- To be hot and confined, a plasma in a laboratory magnetic fusion experiment must be dilute[8]: it is transparent to its own radiation (mainly bremsstrahlung) and suffers intrinsic losses that are proportional to the plasma volume as its fusion gains[9] are.

[8] The situation is partly different for inertial fusion plasmas which however are still transparent to the energetic neutrons produced by the fusion reactions.

[9] For these reasons fusion experiments must be hotter that the inner part of the Sun and need the much more energetic D-T cycle, T being produced by spallation reactions between the fusion neutrons and a Lithium blanket.

Thermonuclear fusion research: a word of caution

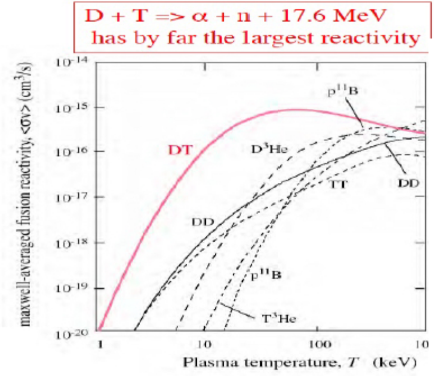
- The physics of thermonuclear fusion in the laboratory is very different from that inside a star, or even from that of a thermonuclear weapon, because of its miniaturization.
- A star is dense and thus opaque to the e.m. radiation. It is at local thermodynamic equilibrium and loses energy mostly through Black Body radiation: losses are proportional to the star surface while gains (thermonuclear fusion power) are proportional to the star volume.
- To be hot and confined, a plasma in a laboratory magnetic fusion experiment must be dilute[8]: it is transparent to its own radiation (mainly bremsstrahlung) and suffers intrinsic losses that are proportional to the plasma volume as its fusion gains[9] are.

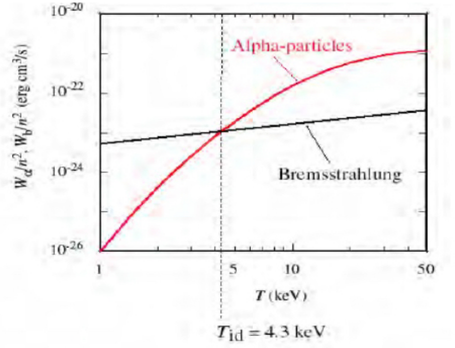
---

[8] The situation is partly different for inertial fusion plasmas which however are still transparent to the energetic neutrons produced by the fusion reactions.

[9] For these reasons fusion experiments must be hotter that the inner part of the Sun and need the much more energetic D-T cycle, T being produced by spallation reactions between the fusion neutrons and a Lithium blanket.

D-T Fusion Ideal Ignition (p-B : energy multiplication)





$$n + {}^6Li \rightarrow T + {}^4He, \quad n + {}^7Li \rightarrow T + {}^4He + n.$$

$${}^{10}p + {}^{11}B \rightarrow 3\,{}^4He + 8.7Mev$$

Accretion disks: anomalous transport of angular momentum

- The transport properties of astrophysical plasmas too can be controlled by collective plasma excitations, not by binary processes. Accretion disks are an example.
  Conservation of angular momentum would prevent accretion of matter rotating in a disk around, e.g., a compact stellar object.
- Collisional viscosity[10] is totally insufficient to explain the rate of accretion required in order to account for the emitted e.m. radiation: angular momentum must be transported *outwards* much more efficiently.
- Collective plasma excitations, e.g. the so called Magneto-Rotational (Velikhov) Instability[11], provide the mechanism that can account for the *anomalous* angular momentum transport.

---

[10] Often called molecular viscosity in the astrophysical literature

[11] It arises from the effect of the magnetic tension in a differentially rotating plasma

Accretion disks: anomalous transport of angular momentum

- The transport properties of astrophysical plasmas too can be controlled by collective plasma excitations, not by binary processes. Accretion disks are an example.
  Conservation of angular momentum would prevent accretion of matter rotating in a disk around, e.g., a compact stellar object.
- Collisional viscosity[10] is totally insufficient to explain the rate of accretion required in order to account for the emitted e.m. radiation: angular momentum must be transported *outwards* much more efficiently.
- Collective plasma excitations, e.g. the so called Magneto-Rotational (Velikhov) Instability[11], provide the mechanism that can account for the *anomalous* angular momentum transport.

[10] Often called molecular viscosity in the astrophysical literature

[11] It arises from the effect of the magnetic tension in a differentially rotating plasma

Accretion disks: anomalous transport of angular momentum

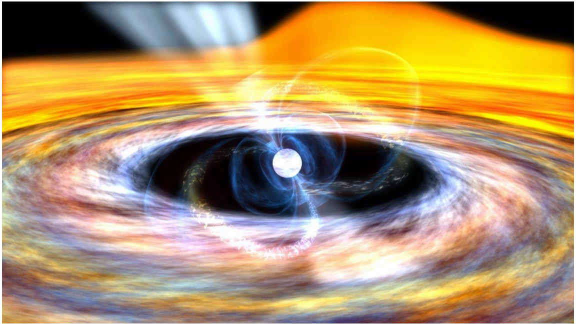
- The transport properties of astrophysical plasmas too can be controlled by collective plasma excitations, not by binary processes. Accretion disks are an example.
  Conservation of angular momentum would prevent accretion of matter rotating in a disk around, e.g., a compact stellar object.
- Collisional viscosity[10] is totally insufficient to explain the rate of accretion required in order to account for the emitted e.m. radiation: angular momentum must be transported *outwards* much more efficiently.
- Collective plasma excitations, e.g. the so called Magneto-Rotational (Velikhov) Instability[11], provide the mechanism that can account for the *anomalous* angular momentum transport.

---

[10] Often called molecular viscosity in the astrophysical literature

[11] It arises from the effect of the magnetic tension in a differentially rotating plasma

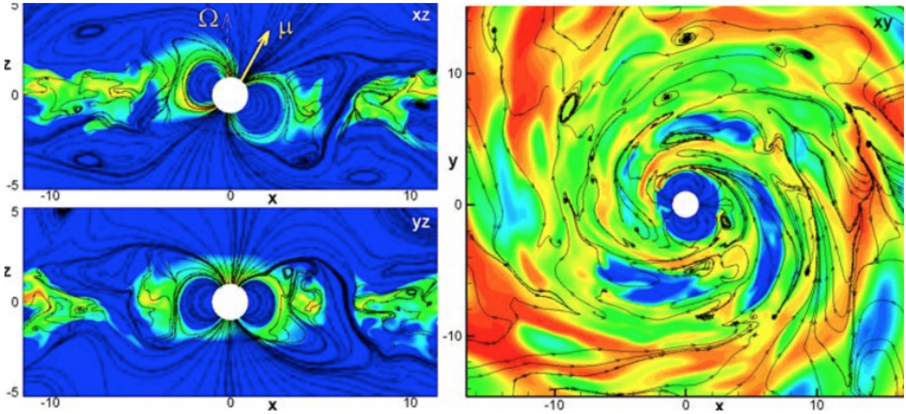
Accretion disks on a neutron star



Artist's impression of a neutron star accreting gas in a binary system. Material funnels from the companion star into an accretion disk surrounding the neutron star.

[NASA/Goddard Space Flight Center/Dana Berry]

3D simulation of MRI driven accretion onto magnetic stars



M. Romanova, G . Ustyugova, V. Kolboda, V. Lovelace, MNRAS, bf 421, 63 (2012)

Slices of the density distribution and sample field lines: a star with a dynamically important magnetic field and a large tilt

The way collective excitations work: Weibel instability and magnetic field generation

- As indicated in the case of the solar wind, anisotropy in momentum space[12] is a very common feature of particle distribution functions in plasmas. Binary processes (collisions) would eventually make the particle distribution function isotropic if it were not for faster mechanisms that reinforce anisotropy (e.g. synchrotron radiation in a magnetized plasma).
- *Then collective excitations take the role of the collisions.* In this case a transverse electromagnetic mode that, because of the magnetic part of the Lorentz force, propagates in an anisotropic plasma with a phase velocity smaller[13] than the speed of light c and can thus interact with the plasma particles.

[12] We could say with an anisotropic pressure tensor with different "temperatures" in different directions.

[13] In an isotropic plasma transverse modes $\omega^2 = k^2c^2 + \omega_{pe}^2$ have phase velocity larger than c

The way collective excitations work: Weibel instability and magnetic field generation

- As indicated in the case of the solar wind, anisotropy in momentum space[12] is a very common feature of particle distribution functions in plasmas. Binary processes (collisions) would eventually make the particle distribution function isotropic if it were not for faster mechanisms that reinforce anisotropy (e.g. synchrotron radiation in a magnetized plasma).
- *Then collective excitations take the role of the collisions.*
  In this case a transverse electromagnetic mode that, because of the magnetic part of the Lorentz force, propagates in an anisotropic plasma with a phase velocity smaller[13] than the speed of light c and can thus interact with the plasma particles.

[12] We could say with an anisotropic pressure tensor with different “temperatures” in different directions.

[13] In an isotropic plasma transverse modes $\omega^2 = k^2c^2 + \omega_{pe}^2$ have phase velocity larger than c

The way collective excitations work: Weibel instability and magnetic field generation

- This well known instability (*E.S. Weibel 1959*) feeds on the energy difference between the different degrees of freedom in momentum space, just as a thermal machine would do extracting heat from bodies at different temperatures.
- *Major difference in the "final" state.*
  Collisions would equalize the temperature of the two bodies. The Weibel instability instead transforms a part (corresponding approximately to energy equipartition) of the energy difference between the different degrees of freedom into (steady) magnetic field[14] energy (in a sense the work of the thermal machine).
  Moreover a real steady state is not reached and the plasma continues to evolve transferring e.g., energy to smaller scale excitations as in a turbulent cascade process.

[14] This is an important mechanism of magnetic field generation in space when collisional effects such as the so called Biermann battery are ineffective. It may provide the seed field that feeds the dynamo process that can produce magnetic fields on large spatial scales.

The way collective excitations work: Weibel instability and magnetic field generation

- This well known instability (*E.S. Weibel 1959*) feeds on the energy difference between the different degrees of freedom in momentum space, just as a thermal machine would do extracting heat from bodies at different temperatures.
- *Major difference in the "final„ state.*
  Collisions would equalize the temperature of the two bodies. The Weibel instability instead transforms a part (corresponding approximately to energy equipartition) of the energy difference between the different degrees of freedom into (steady) magnetic field[14] energy (in a sense the work of the thermal machine).
  Moreover a real steady state is not reached and the plasma continues to evolve transferring e.g., energy to smaller scale excitations as in a turbulent cascade process.

[14] This is an important mechanism of magnetic field generation in space when collisional effects such as the so called Biermann battery are ineffective. It may provide the seed field that feeds the dynamo process that can produce magnetic fields on large spatial scales.

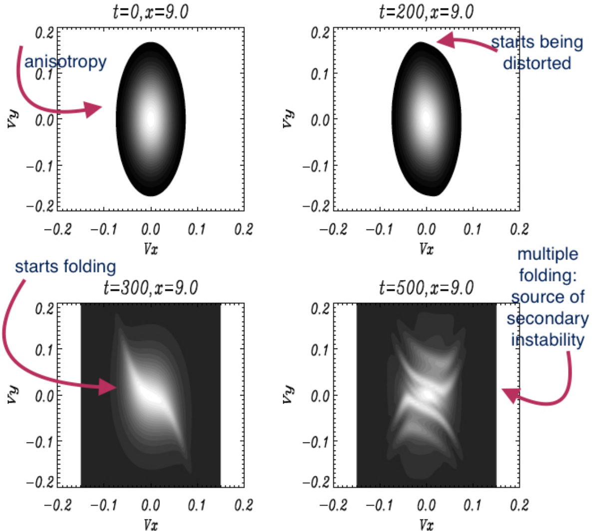
Weibel instability: time evolution of the particle distribution function in momentum space

Note the *filamentation* process in phase space:

phase mixing, not thermalization

source of secondary kinetic instabilities

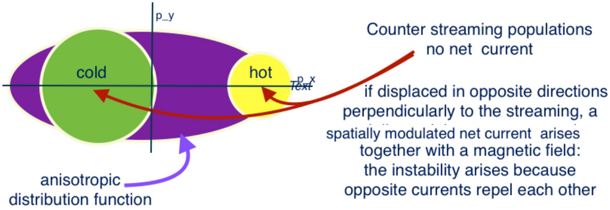
Pisa theory group



The “current filamentation” and the Weibel instabilities

A plasma with two counterstreaming particle populations, e.g„ with a minority population of high energy streaming electrons whose current is compensated by a return current of the bulk electrons, is subject to a closely related instability.

This instability provides an intuitive explanation of the Weibel mechanism. In fact two counterstreaming populations, seen as a whole, can be thought as forming an anisotropic distribution.



It is also unstable to the “two stream” longitudinal electric field instability which often dominates in nonrelativistic regimes. This latter instability determines e.g. the anomalously short penetration range of a particle beam in a plasma.

The “current filamentation” instability: towards the physics of laser produced relativistic plasmas

Counterstreaming electron populations occur naturally in the interaction of ultraintense laser pulses with the plasma that is formed almost instantaneously when such pulses interact with a gas jet or with solid material: electrons are accelerated to relativistic energies by the pulse penetrate in the material and the resulting charge imbalance induces a neutralizing return current.

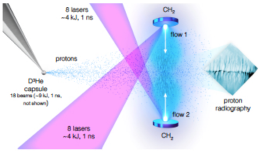
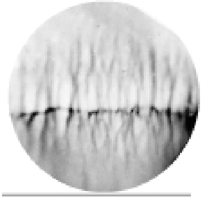


Figure 1: **Experimental configuration to generate opposing plasma flows probed by D^{3}He protons.** The experiment consists of a pair of (CH$_2$) plastic foils of diameter 2 mm and thickness 500 μm, oriented face-on and sep-



5.2 ns

Magnetic field structures
Proton imaging

C. M. Huntington *et al.*
Nat. Phys. **11**, 173 (2015)

Laser parameters: $\lambda \sim 1\mu$, focussed intensity $10^{22}\, Watt/cm^2$, pulse duration in the femtosecond range, dimensionless amplitude $a_0 \equiv (eE_0)/(m_e c\omega) \gg 1$, $\quad a_0 > 1 \rightarrow$ electrons in the e.m. wave become relativistic.

Collective relativistic dynamics in the laboratory

- *The recent developments in the generation of laser pulses with ultra-high power*[15] *(presently petawatt and progressing) have made it possible to obtain and to study mesoscopic amounts of relativistic (ionized) matter in the laboratory:*
  mesoscopic: size tens of microns, density $\sim 10^{21} - 10^{22} cm^{-3}$ close to solid density, electron energy in the GeV range, ion energy presently in the tens of MeV range.
- The theoretical study of the nonlinear collective dynamics of relativistic plasmas started some 50 years ago (mainly in USSR).
- Note that relativistic kinematics introduces an additional nonlinearity into the plasma dynamics. It arises from the nonlinear relationship between momentum and velocity and is responsible e.g., for the relativistic self-focusing of a laser pulse.

[15] Such high power ultra-short pulses are obtained by re-compression of a stretched and amplified pulse using dispersive optics.

Collective relativistic dynamics in the laboratory

- *The recent developments in the generation of laser pulses with ultra-high power*[15] *(presently petawatt and progressing) have made it possible to obtain and to study mesoscopic amounts of relativistic (ionized) matter in the laboratory:*
  mesoscopic: size tens of microns, density $\sim 10^{21} - 10^{22} cm^{-3}$ close to solid density, electron energy in the GeV range, ion energy presently in the tens of MeV range.
- The theoretical study of the nonlinear collective dynamics of relativistic plasmas started some 50 years ago (mainly in USSR).
- Note that relativistic kinematics introduces an additional nonlinearity into the plasma dynamics. It arises from the nonlinear relationship between momentum and velocity and is responsible e.g., for the relativistic self-focusing of a laser pulse.

[15] Such high power ultra-short pulses are obtained by re-compression of a stretched and amplified pulse using dispersive optics.

Collective relativistic dynamics in the laboratory

- *The recent developments in the generation of laser pulses with ultra-high power*[15] *(presently petawatt and progressing) have made it possible to obtain and to study mesoscopic amounts of relativistic (ionized) matter in the laboratory:*
  mesoscopic: size tens of microns, density $\sim 10^{21} - 10^{22} cm^{-3}$ close to solid density, electron energy in the GeV range, ion energy presently in the tens of MeV range.
- The theoretical study of the nonlinear collective dynamics of relativistic plasmas started some 50 years ago (mainly in USSR).
- Note that relativistic kinematics introduces an additional nonlinearity into the plasma dynamics. It arises from the nonlinear relationship between momentum and velocity and is responsible e.g., for the relativistic self-focusing of a laser pulse.

[15] Such high power ultra-short pulses are obtained by re-compression of a stretched and amplified pulse using dispersive optics.

Collective relativistic dynamics in the laboratory

The availability in the laboratory of relativistic plasmas that can be studied in relatively compact size experiments[16] opens the way to new developments in fields that range from

- *nonlinear system dynamics and nonlinear relativistic optics*, to
- *novel powerful radiation sources at high energy,*

X-ray lasers, attosecond pulses,

- *high field gradient ($\approx GeV/cm$), particle acceleration techniques,*

laser wake field acceleration, radiation pressure ion acceleration,

- *high energy astrophysics,*

extreme particle acceleration e.g., for cosmic ray physics, relativistic shocks and magnetic reconnection,

- *plasmas dominated by high frequency incoherent radiation*

i.e., radiation friction, and, in the near future,

- *by Quantum ElectroDynamics effects*

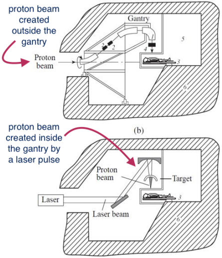
such as the creation of an *electron positron pair plasma*.

---

[16] Miniaturization to “table top” size is a major advantage of high energy density plasmas

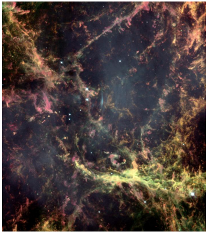
Collective relativistic dynamics in the laboratory

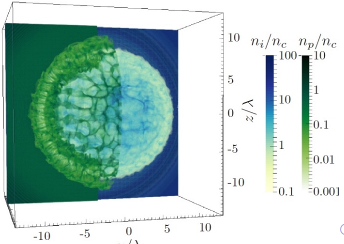
Each of the topics mentioned above leads either to important technological developments or to the creation of interdisciplinary knowledge or both. Two examples:



Ion acceleration $\rightarrow$
"room-size" proton (Carbon)
accelerators for hadrontherapy.

Rayleigh-Taylor instability:
"light" pushing "heavy"
Crab nebula (Hubble)
Thin foil (Pisa group).
Note patterns $\Rightarrow$





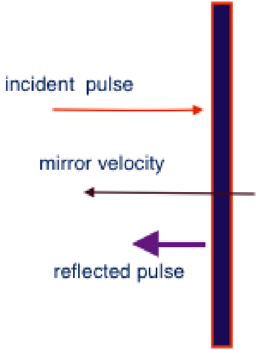
Relativistic plasma mirrors: coherent laser pulse interaction with an electron foil

The coherent interaction between a high intensity e.m. pulse and a foil of relativistic electrons counterpropagating at a velocity βc close to the speed of light provides a new method of reaching unprecedented e.m. energy density.

Einstein formula (at normal incidence)

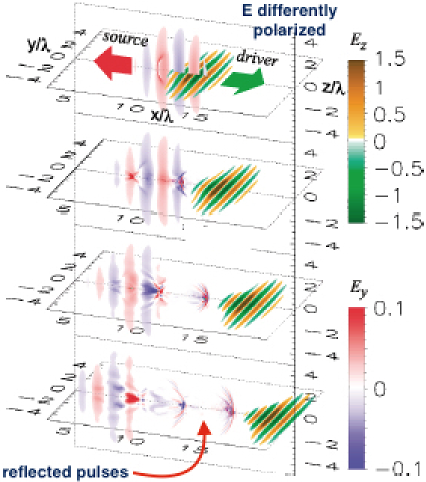
$$\omega_{refl} = \omega_{inc}(1+\beta)/(1-\beta)$$

$$\omega_{refl} = 4\gamma^2\,\omega_{inc} \text{ for } \beta \to 1$$

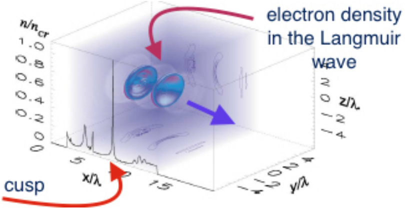


The foil of the relativistic electrons can be produced using the electrons accelerated at wave breaking in a nonlinear Langmuir wave generated in the plasma by a second laser pulse.

Relativistic plasma mirror: electron foil at wave break



If in a longitudinal nonlinear wave (such as a large amplitude Langmuir wave with phase velocity close to c induced in a plasma by the driver pulse) electrons in their oscillatory motion are accelerated to velocities larger than the wave phase velocity, the wave breaks.



At the wave break position a cusp develops in the electron density and their oscillatory motion is transformed into a net relativistic motion in the direction of the breaking wave.

S.V. Bulanov *et al.* PRL, **91**, 085001 (2003)

Relativistic plasma mirror: coherent interaction

- There are important issues to be addressed, such as the reflectivity of the mirror[17] formed by the foil of the electrons accelerated at wake break, its parabolic shape that can focus the reflected pulse etc., but

  • *the main physics point is that the reflected pulse is not the result of the incoherent superposition of (inverse) Thomson (Compton) scattered waves but of the coherent response of the plasma electrons* that, as in a FEL[18], satisfy the condition $n\lambda^3 >> 1$:

  here physical processes are not described by single particle scattering cross sections.

- The aim the PRL from which I have taken the previous figures was to indicate a novel possibility provided by plasmas in order to increase the e.m. pulse intensity: try to *use the plasma ability to concentrate the e.m. energy* of available laser systems instead of simply looking for bigger and bigger systems.

[17] To be evaluated for the pulse frequency in the mirror frame

[18] or for the Pulsar curvature radiation,

Relativistic plasma mirror: coherent interaction

- There are important issues to be addressed, such as the reflectivity of the mirror[17] formed by the foil of the electrons accelerated at wake break, its parabolic shape that can focus the reflected pulse etc., but

  • *the main physics point is that the reflected pulse is not the result of the incoherent superposition of (inverse) Thomson (Compton) scattered waves but of the coherent response of the plasma electrons* that, as in a FEL[18], satisfy the condition $n\lambda^3 >> 1$:

  here physical processes are not described by single particle scattering cross sections.

- The aim the PRL from which I have taken the previous figures was to indicate a novel possibility provided by plasmas in order to increase the e.m. pulse intensity: try to *use the plasma ability to concentrate the e.m. energy* of available laser systems instead of simply looking for bigger and bigger systems.

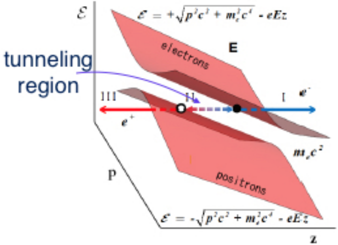
---

17 To be evaluated for the pulse frequency in the mirror frame

18 or for the Pulsar curvature radiation,

Schwinger field, nonlinear QED and laser pulses

- The 2003 S.V. Bulanov et al. PRL title was "*Light Intensification towards the Schwinger Limit*" and stated that " we can achieve extremely high electric fields (in the laboratory reference frame) approaching the QED critical field with the present-day laser technology". [probability pair generation $w \propto \exp(-\pi E_s/E)$]



$$E_s = m_e^2 c^3/(e\hbar) = 11.3 \times 10^{18}\, V/m,$$

it would correspond to a pulse with intensity $\sim 4 \times 10^{29}\, Watt/cm^2$.

E_s corresponds to a an electron mass energy on a Compton length

- *For transverse waves in a plasma* $E > B$ and $B = 0$ in the frame boosted at v_g.

The nonlinear dynamics of electromagnetic field in vacuum is described by the Euler-Heisenberg correction to the e.m. Lagrangian that depends on the Lorentz invariants $E^2 - B^2$ and $E \cdot B$ that vanish for a plane wave in vacuum. This does not apply to focused or intersecting pulses.

Electron-positron γ plasmas in the laboratory

Dense Electron-Positron Plasmas and Ultraintense γ rays from Laser-Irradiated Solids

C. P. Ridgers,[1,2] C. S. Brady,[3] R. Duclous,[4] J. G. Kirk,[5] K. Bennett,[3] T. D. Arber,[3] A. P. L. Robinson,[2] and A. R. Bell[1,2]
[1]*Clarendon Laboratory, University of Oxford, Parks Road, Oxford, OX1 3PU, United Kingdom*
[2]*Central Laser Facility, STFC Rutherford-Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, United Kingdom*
[3]*Centre for Fusion, Space and Astrophysics, University of Warwick, Coventry, CV4 7AL, United Kingdom*
[4]*Commissariat à l'Energie Atomique, DAM DIF, F-91297 Arpajon, France*
[5]*Max-Planck-Institut für Kernphysik, Postfach 10 39 80, 69029 Heidelberg, Germany*
(Received 30 September 2011; published 19 April 2012)

In simulations of a 10 PW laser striking a solid, we demonstrate the possibility of producing a pure electron-positron plasma by the same processes as those thought to operate in high-energy astrophysical environments. A maximum positron density of 10^{26} m^{-3} can be achieved, 7 orders of magnitude greater than achieved in previous experiments. Additionally, 35% of the laser energy is converted to a burst of γ rays of intensity 10^{22} W cm^{-2}, potentially the most intense γ-ray source available in the laboratory. This absorption results in a strong feedback between both pair and γ-ray production and classical plasma physics in the new "QED-plasma" regime.

$\Leftarrow$ 10^{20} positrons per cm^3 (simulation)

$\Downarrow$ 10^{16} positrons per cm^3 (experimental)

Presently the only experiment in Nonlinear QED is the 1996-97 *E-144* experiment at SLAC (light by light scattering - Breit Wheeler process)

$$s\omega + e^- \to e^- + \gamma, \qquad s\omega + \gamma \to e^- + e^+$$

Bethe-Heitler process $\Rightarrow$

$$e^- \to e^- + (\gamma) \to e^- + (e^- e^+)$$

in the fields of the nuclei.

Generation of neutral and high-density electron-positron pair plasmas in the laboratory

G. Sarri[1], K. Poder[2], J.M. Cole[2], W. Schumaker[3,†], A. Di Piazza[4], B. Reville[1], T. Dzelzainis[1], D. Doria[1], L.A. Gizzi[5,6], G. Grittani[5,6], S. Kar[1], C.H. Keitel[4], K. Krushelnick[3], S. Kuschel[7], S.P.D. Mangles[2], Z. Najmudin[2], N. Shukla[8], L.O. Silva[8], D. Symes[9], A.G.R. Thomas[3], M. Vargas[3], J. Vieira[8] & M. Zepf[1,7]

ASTRA GEMINI at RAL

Nature Communications 2015

Electron-positron pair plasmas represent a unique state of matter, whereby there exists an intrinsic and complete symmetry between negatively charged (matter) and positively charged (antimatter) particles. These plasmas play a fundamental role in the dynamics of ultra-massive astrophysical objects and are believed to be associated with the emission of ultra-bright gamma-ray bursts. Despite extensive theoretical modelling, our knowledge of this state of matter is still speculative, owing to the extreme difficulty in recreating neutral matter-antimatter plasmas in the laboratory. Here we show that, by using a compact laser-driven setup, ion-free electron-positron plasmas with unique characteristics can be produced. Their charge neutrality (same amount of matter and antimatter), high-density and small divergence finally open up the possibility of studying electron-positron plasmas in controlled laboratory experiments.

The laser wakefield-accelerated electrons impact onto a solid target, initiating a quantum electrodynamic cascade involving electrons, positrons and photons

High field QED: a new relativistic plasma nonlinearity

REVIEWS OF MODERN PHYSICS, VOLUME 84, JULY–SEPTEMBER 2012

Extremely high-intensity laser interactions with fundamental quantum systems

A. Di Piazza,* C. Müller,† K. Z. Hatsagortsyan,‡ and C. H. Keitel§

Different schemes have been proposed to observe e^+-e^- pair production at intensities below the Schwinger limit which seems now to be feasible in the near future, at least from a theoretical point of view. Corresponding studies would complement the results of the pioneering E-144 experiment and deepen our understanding of the QED vacuum in the presence of extreme electromagnetic fields. This is also connected with the recent investigations on the development of QED cascades in laser-laser collisions. In addition to being intrinsically interesting, the development of QED cascades is expected to set a limit on the maximal attainable laser intensity. However, the study of quantum cascades in intense laser fields has started relatively recently and is still under vivid development. More advanced analytical and numerical methods are required in order to describe realistically and quantitatively such a complex system as an electron-positron-photon plasma in the presence of a strong driving laser field.

Conjecture of perturbative QED breakdown at $\alpha\chi^{2/3} \gtrsim 1$

Based on the work of N.B. Narozhny

Alexander Fedotov

National Research Nuclear University "MEPhI" (Moscow Engineering Physics Institute), Kashirskoe sh. 31, 115409 Moscow, Russian Federation

E-mail: am_fedotov@mail.ru

Abstract. Invited talk given at Symposium "Extreme Light Technologies, Science, and Applications" (LPHYS'16, Yerevan, 11-15 July 2016). The old Ritus-Narozhny conjecture of possible breakdown of Intense Field QED perturbation theory for ultrarelativistic particles passing transversely through a strong electromagnetic field is reviewed with a special emphasis on its possible significance for near-future experiments.

However, his probably the most deep and significant contribution (or at least claimed as such in his Dr.Sc. dissertation back in 1982), the α^3-order IFQED calculations [8–10] proving the original Ritus conjecture [11] of possible breakdown of perturbative QED at $\alpha\chi^{2/3} \gtrsim 1$, still remains rather unknown. In this talk I am going to give the review of that old idea. My

$\chi \equiv e\hbar|p^\mu F_{\mu\nu}|/(m_e^3 c^4)$, Quantum nonlinearity parameter

$\chi \rightarrow 10^3$ for $20^{25} Watt/cm^2$ and $\mathscr{E} \sim 100 GeV$

A new mathematical framework for the plasma dynamics will be needed

Where are we going?

- Inside plasmas — We will be able to study the collective dynamics of $e^+ - e^-$ globally neutral *plasmas*, which display an interesting charge symmetry, and more generally the collective dynamics of “electromagnetic matter” dominated by QED effects.
- Using plasmas as tools — We will be able to enhance e.m. fields approaching the Schwinger field and use them to investigate nonlinear optics in vacuum experimentally: vacuum birefringence, photon splitting, pair seeded $e^+ - e^-$ cascades...
- These investigations are clearly significant in themselves, but perhaps it is even more significant that the study of collective plasmas in such regimes will allow us to explore conditions of interest for high energy astrophysics and beyond in the same way as magnetically confined plasmas in fusion experiments have allowed us to investigate phenomena of interest for space and solar physics and for X-ray astrophysical sources.

Where are we going?

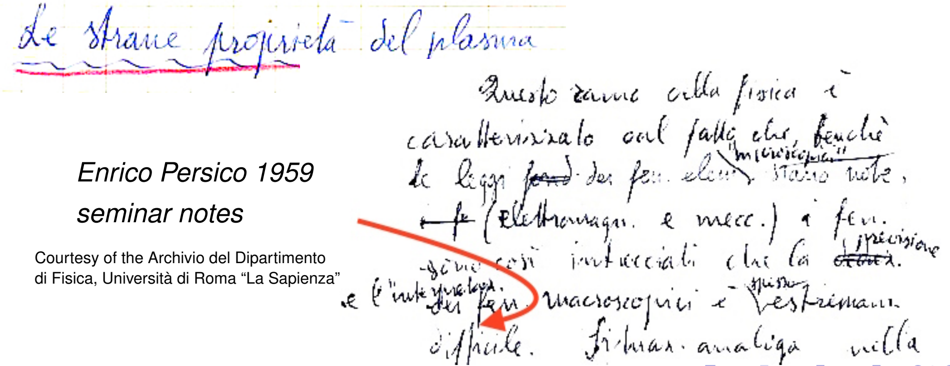
- Inside plasmas — We will be able to study the collective dynamics of $e^+ - e^-$ globally neutral *plasmas*, which display an interesting charge symmetry, and more generally the collective dynamics of "electromagnetic matter" dominated by QED effects.
- Using plasmas as tools — We will be able to enhance e.m. fields approaching the Schwinger field and use them to investigate nonlinear optics in vacuum experimentally: vacuum birefringence, photon splitting, pair seeded $e^+ - e^-$ cascades...
- These investigations are clearly significant in themselves, but perhaps it is even more significant that the study of collective plasmas in such regimes will allow us to explore conditions of interest for high energy astrophysics and beyond in the same way as magnetically confined plasmas in fusion experiments have allowed us to investigate phenomena of interest for space and solar physics and for X-ray astrophysical sources.

Where are we going?

- Inside plasmas — We will be able to study the collective dynamics of $e^+ - e^-$ globally neutral *plasmas*, which display an interesting charge symmetry, and more generally the collective dynamics of “electromagnetic matter” dominated by QED effects.
- Using plasmas as tools — We will be able to enhance e.m. fields approaching the Schwinger field and use them to investigate nonlinear optics in vacuum experimentally: vacuum birefringence, photon splitting, pair seeded $e^+ - e^-$ cascades...
- These investigations are clearly significant in themselves, but perhaps it is even more significant that the study of collective plasmas in such regimes will allow us to explore conditions of interest for high energy astrophysics and beyond in the same way as magnetically confined plasmas in fusion experiments have allowed us to investigate phenomena of interest for space and solar physics and for X-ray astrophysical sources.

THANKS FOR YOUR ATTENTION

Understanding the collective behaviour that governs the world of electromagnetic matter is of fundamental importance: since most of the visible universe is made of plasma, it is unlikely that we can understand the structure of the physical word within an approach based exclusivelv on individual elementary processes.



Enrico Persico 1959

seminar notes

Courtesy of the Archivio del Dipartimento di Fisica, Università di Roma "La Sapienza"