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Contribution for the JETP special issue in honor of L.P. Pitaevskii's 85th birthday

Concepts for a Deuterium–Deuterium Fusion Reactor[1]

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Abstract—We revisit the assumption that reactors based on deuterium–deuterium (D–D) fusion process have to be necessarily developed after the successful completion of experiments and demonstrations for deuterium–tritium (D–T) fusion reactors. Two possible mechanisms for enhancing the reactivity are discussed. Hard tails in the energy distribution of the nuclei, through the so-called κ-distribution, allow to boost the number of energetic nuclei available for fusion reactions. At higher temperatures than usually considered in D–T plasmas, vacuum polarization effects from real e^+e^- and $\mu^+\mu^-$ pairs may provide further speed-up due to their contribution to screening of the Coulomb barrier. Furthermore, the energy collection system can benefit from the absence of the lithium blanket, both in simplicity and compactness. The usual thermal cycle can be bypassed with comparable efficiency levels using hadron calorimetry and third-generation photovoltaic cells, possibly allowing to extend the use of fusion reactors to broader contexts, most notably maritime transport.

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1. INTRODUCTION

It is usually assumed that the first commercial fusion reactors will be based on D–T mixtures, and within this frame a well-defined path has been paved with the ongoing development of ITER, following the successful operation of JET and other tokamaks which have produced significant amount of fusion power. This path has two recognized drawbacks: the shortage of natural tritium sources [1, 2] and the irradiation damage caused by 14.06 MeV neutrons, including the associated contamination of the reactor. A lithium blanket to create tritium in situ is a nontrivial issue, as it must satisfy several competing requirements, such as the need to breed tritium with easy extraction processes and generate heat, while sustaining a large neutron flux. All these issues are avoided by using D–D reactors. Deuterium is easily available in water, the 2.45 MeV neutrons induce a irradiation damage two orders of magnitude smaller than the one released in D–T fusion processes, and radioactive contamination is mitigated and mainly contained to the tritium produced in one of the two channels of the fusion reaction. However, the D–D cross-section in the interesting energy range is about two orders of magnitude smaller than the corresponding D–T cross-section, and therefore the requirements for igniting and self-sustaining the reaction are more demanding [3].

In this contribution, we outline two proposals for enhancing the reactivity of D–D fusion processes, and discuss the possibility of bypassing the thermal cycle for electricity production. More specifically, we discuss non-Boltzmann steady state configurations represented by power-law energy distributions, with an estimate of the expected enhancement in the reactivity with respect to Boltzmann-state reactivities. At higher temperatures than the ones currently achieved for a D–D plasma, the possibility to create real electron–positron pairs from vacuum may lead to a lowering of the Coulomb barrier, with a consequent enhancement of the reactivity. Finally, we discuss the possibility for combining recent progress in high yield scintillating materials and hadron calorimetry with third-generation photovoltaic cells. This could lead to energy conversion at an initially nearly comparable efficiency with respect to a thermal cycle, with unknown margins for improvement, and within a compact design. Neutron damage induced in the calorimeter and the consequent possible decrease in the light yield indicate that applications of this energy conversion are limited to about 1 MW of fusion power, more than enough for maritime transport and for low power plants in low-density populated areas for instance. This paper

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[1] The article is published in the original.

should be considered as an overview of work in progress, and as such limited by the contingency of contributing to the Festschrift, with three distinct research directions to be pursued more quantitatively in the close future.

2. ENHANCING THE REACTIVITY VIA NON-BOLTZMANN ENERGY DISTRIBUTIONS

The usual comparison between D–D and D–T fusion rates relies on the hypothesis of Boltzmann energy distributions. Considering the complex dynamics occurring for a confined plasma, it is worth to scrutinize about the adequacy of this assumption. If the plasma is heated by neutral beam injection, a steady state situation can occur in which the heating power is significantly higher than the relaxation rate to equilibrium of the plasma itself. Analogous situations already occur in low-density, low-temperature plasmas characteristic, for instance, of solar wind [4]. Under this circumstance the high-energy tail of the distribution may be enhanced—basically because of the large pile-up of energy which is hardly transferred to lower energy particles—generating large deviations from the Boltzmann distribution. These energy distributions, named κ-distributions, have been discussed since several decades, see for instance [5] for a comprehensive overview with applications in astrophysical environments, and [6] for an application to solve systematic discrepancies in determining electron temperatures in HII regions and planetary nebulae. The characterization of these κ-distributions requires the introduction of two parameters, the kinetic temperature, an effective temperature such that the energy U per unit of particle can still be written as $U = 3k_BT_U/2$ as in the Boltzmann case, and the κ-parameter (with values in the $3/2 < \kappa < +\infty$ range). The energy probability density is expressed as [6]

$$P(E) = \frac{C(\kappa)}{(k_BT_U)^{3/2}} \frac{E^{1/2}}{\left[1 + \frac{E}{(\kappa - 3/2)k_BT_U}\right]^{\kappa+1}}, \tag{1}$$

where

$$C(\kappa) = \frac{2\Gamma(\kappa+1)}{\pi^{1/2}(\kappa - 3/2)^{3/2}\Gamma(\kappa - 1/2)}.$$

The Boltzmann distribution is recovered in the case of $\kappa \to +\infty$ case, with the kinetic temperature of the κ distribution tending to the temperature T_{core} of the Boltzmann distribution interpolating its "core" distribution, i.e. the region of energies with the most probable population, $T_{\mathrm{core}} = (1 - 3/2\kappa)T_U$. The specific value of κ is usually determined from a best fit of the observed energy distribution and, as far as we are aware of, there is not yet a kinetic model to predict its value. For now, we will assume values of k as typically inferred by space plasma physics, to have a commonsense, perhaps questionable, benchmark.

Since most of the fusion reactions occur in the high-energy tail of the energy distribution, and the κ-distributions are characterized by a hard, power-law tail, a first exercise may consist in evaluating the gain in reactivity for various fusion reaction by using κ-distributions instead of Boltzmann ones. To be fair in the comparison, we will compare κ-distributions with effective temperature T_U to the Boltzmann distributions with the corresponding core temperature T_{core} as defined above. We have used parameterized cross-sections for D–T and the two channels of the D–D fusion process from [7]. As customary for fusion processes, the cross-section is described in terms of the S-factor capturing the nuclear physics of the fusion process and softly dependent on the energy (modulo possible resonance phenomena) and a factor which incorporates the tunneling process through the Coulomb barrier, typically determined through a Wentzel–Kramers–Brillouin (WKB) approximation

$$\sigma(E) = \frac{S(E)}{E}\exp\left(-\frac{B_G}{\sqrt{E}}\right), \tag{2}$$

where B_G is the Gamow constant. Here, the S-factor is fitted with a Padé polynomial, following the notation introduced in [7], that is

$$S(E) = \frac{A_1 + E\{A_2 + E[A_3 + E(A_4 + EA_5)]\}}{1 + E\{B_1 + E[B_2 + E(B_3 + EB_4)]\}}. \tag{3}$$

The numerical values of A_i and B_j are determined with a best fit and tabulated in Table 4 in [7]. The corresponding values of the cross-sections are reliable within few % in the 3–400 keV energy range, enough for our discussion. Fusion reactivities are then evaluated by averaging the product of the fusion cross-section and the relative velocities v between the two nuclei over the corresponding energy distribution. For Boltzmann-distributed energies, this implies

$$\langle\sigma v\rangle = \left(\frac{8}{\pi m_r}\right)^{1/2} \frac{1}{(k_BT_{\mathrm{core}})^{3/2}} \int_0^\infty dE E e^{-\beta E}\sigma(E), \tag{4}$$

where m_r is the reduced mass of the system made of two colliding nuclei and β is the inverse temperature $\beta = (k_BT)^{-1}$. The reactivity depends on temperature, which allows for a comparison to the parametrized fusion reactivities tabulated in Table 7 in [7]. In the case of the κ-distribution, we have

$$\langle\sigma v\rangle = \left(\frac{8}{\pi m_r}\right)^{1/2} \frac{C(\kappa)}{(k_BT_U)^{3/2}} \times \int_0^\infty dE \frac{E\sigma(E)}{\left[1 + \frac{E}{(\kappa - 3/2)k_BT_U}\right]^{\kappa+1}}. \tag{5}$$

In Fig. 1 we show the temperature dependence of the reactivities evaluated with averages over Boltzmann and κ-distributions for both D–D and D–T fusion reactions. There is a significant advantage in using κ-distributions, which should be also beneficial for the D–T reactors at relatively low temperatures, with reactivity gains of almost two orders of magnitude for temperatures in the few keV range. Figure 1 also shows that the κ-distribution is not consistently preferable to the Boltzmann distribution over the entire temperature range. The κ-distributions are peaked at an energy lower than the corresponding Boltzmann distribution, with a larger peak probability (see for instance Fig. 3 in [6]). It is therefore understandable that, for a given dependence of the fusion cross-section on energy and with respect to the corresponding Boltzmann distribution, they can prevail at lower temperatures, then have an intermediate region of marginal or no gain, and prevail again at higher temperatures. It is also worth to note that the D–D fusion reaction has a Coulomb barrier of about 450 keV. This means that the high temperature behavior of the reactivity presented in Fig. 1a, purely based on tunneling phenomena, is a sort of lower bound on its actual value. Ongoing work here mainly consists in developing kinetic models capable, for instance given the power level of neutral beam injection heating, of finding if the plasma energy may be expressed in terms of a κ-distribution, including predictions for the value of κ and its dependence upon the experimental parameters. Characterization of non-Boltzmann energy distributions is of current experimental interest, as witnessed by recent work at the ASDEX upgrade tokamak [8].

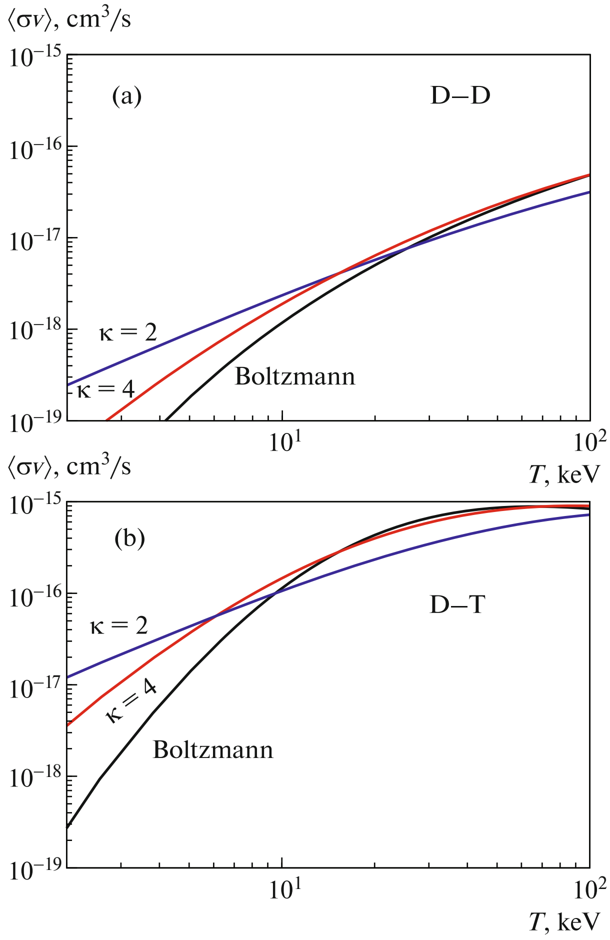

Fig. 1. (Color online) Reactivities for D–D (a) and D–T (b) fusion processes averaged over Boltzmann energy distributions (black) and over two κ-distributed energies, $\kappa = 2$ (blue) and $\kappa = 4$ (red), in the 2–100 keV temperature range. Reactivities and temperatures in the two plots are expressed with the same scales allowing for an easier comparison. The D–D reactivity is obtained summing over both reaction channels, D(d, p)T and D(d, n)^{3}He.

3. ENHANCING THE REACTIVITY VIA VACUUM POLARIZATION EFFECTS

Another possible mechanism which can be used to enhance reactivities consists in exploiting vacuum polarization effects. The Boltzmann-averaged reactivity of the D–T fusion process is maximum at about 70 keV with a relatively broad peak, therefore there is no gain in increasing the temperature of a D–T plasma above this value. As a matter of fact, plasma temperatures of operating D–T tokamaks are in the 10–30 keV range at most. Instead, for D–D plasmas, it is advantageous to operate at higher temperatures, as the reactivity increases monotonically until it reaches an even broader peak at temperatures of about 1 MeV. For instance, the same reactivity of D–T fusion at the temperature of 10 keV is achieved for D–D fusion only at the temperature of about 300 keV. Pursuing this high-temperature scenario obviously opens up challenging technological issues due to the heat irradiated on the first wall, and to the large energy losses due to electron bremsstrahlung. At the same time, it is interesting to notice that the range of temperatures required for sustained D–D fusion reactions is not dissimilar from the one in which real electron–positron pairs can be generated. These electron–positron pairs make the medium between the two nuclei endowed with an effective dielectric constant, and therefore in principle may reduce the Coulomb barrier.

The production of particle–antiparticle pairs is a process studied in finite temperature and density quantum field theory, with applications to a variety of research contexts ranging from astrophysics and cosmology to the observation of quark–gluon plasma at proton colliders (see for instance [9–11]). The process is non-perturbative in character, and the particle–antiparticle production rate scales with the mass of the particle and the environmental temperature as $\exp(-2mc^2/k_BT)$. Therefore, aiming for electrical polarizability effects, and considering the temperature achievable in thermonuclear fusion, we initially limit the attention to electron–positron (e^+e^-) pairs alone.

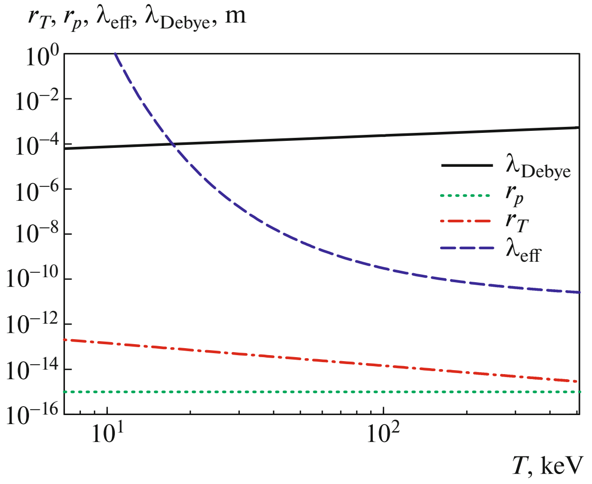

Fig. 2. (Color online) Length scales relevant for screening the Coulomb repulsion between nuclei. The effective Compton wavelength for a finite temperature e^+e^- plasma is evaluated according to Eq. (6). The Debye length $\lambda_{\rm Debye} = (\epsilon_0 k_{\rm B}T/ne^2)^{1/2}$ is evaluated for a typical ion density of $n = 10^{20}$ ions/m^3, with the consequent crossover between the screening length scales $\lambda_{\rm Debye}$ and $\lambda_{\rm eff}$ occurring in the 15–20 keV temperature range.

Even in this case, if one considers plasma temperatures of the order of 100 and 200 keV for instance, the corresponding exponential suppression factors are respectively 3.6×10^{-5} and 6.4×10^{-3}. A detailed discussion of the effective potential between two charges separated by a sea of electrons and positrons at finite temperature and density is available in [12]. For temperatures low enough with respect to the production threshold of $2m_ec^2 \approx 1$ MeV and negligible chemical potential, an effective Yukawa potential has been evaluated [12]

$$V_{\rm eff}(r) = -\frac{e^2}{4\pi\epsilon_0 r}\exp\left(-\frac{r}{\lambda_{\rm eff}}\right), \tag{6}$$

where ϵ_0 is the vacuum permittivity, and the Yukawa range $\lambda_{\rm eff}$ is

$$\lambda_{\rm eff} = \frac{\hbar}{2m_ec^2}\left(\frac{\pi m_ec^2}{2\alpha_{\rm em}^2 k_{\rm B}T}\right)^{1/4}\exp\left(\frac{m_ec^2}{2k_{\rm B}T}\right), \tag{7}$$

where $\alpha_{\rm em}$ is the fine structure constant.

The above can be interpreted as a temperature-dependent Compton wavelength for the electron–positron pairs, or alternatively as an effective, temperature-dependent, photon mass. This leads to a space-dependent weakening of the electrostatic repulsion between two nuclei. In Fig. 2 we plot the dependence on temperature in a range of interest for D–D fusion processes of various relevant length scales, namely the effective Yukawa range from Eq. (7), the Debye length of a plasma with densities usually achieved in tokamaks, the distance of minimum approach between two nuclei with a kinetic energy equal to $k_{\rm B}T$, $r_T = e^2/4\pi\epsilon_0 k_{\rm B}T$, and, for comparison, the (constant) distance at which strong interactions give rise to fusion processes, of the order of the proton radius r_p. It is worth to notice that around $T \simeq 17$ keV the screening due to the electron–positron plasma takes over the usual Debye screening, and becomes dominant at higher temperatures.

Unfortunately, in spite of the favorable scaling of the effective Yukawa range with temperature with respect to the Debye length, the polarization effect is rather small. This is already visible in Fig. 2 as the effective Compton wavelength, although decreasing by increasing temperature at variance with the Debye length, is still about four orders of magnitude larger than the average distance of minimum approach between the nuclei. This is confirmed by a more quantitative analysis by introducing an average polarizability coefficient ϵ_r,

$$\epsilon_r^{-1} = \frac{3}{r_T^3 - r_p^3}\int_{r_p}^{r_T} dr r^2 \exp\left(-\frac{r}{\lambda_{\rm eff}}\right), \tag{8}$$

such that the effective potential in Eq. (6) is obtained via the substitution $\epsilon_0 \to \epsilon_r\epsilon_0$. The weakening of the electrostatic repulsion due to quantum vacuum screening expressed by Eq. (8) is considered in the classically forbidden volume used for the WKB evaluation of the tunneling rate, i.e. between the nuclei distance r_p (of the order of a proton radius) and the distance of minimum approach r_T. After integration and series expansion of the exponential term, one gets an effective relative permittivity by which the Coulomb electrostatic repulsion is weakened as $\epsilon_r \approx 1 + r_T/4\lambda_{\rm eff}$ which is negligible for $r_T/\lambda_{\rm eff} \ll 1$.

The gain in reactivity evaluated in this way should be considered no more than an estimate, providing an upper bound to the reactivity enhancement, which can be evaluated for instance using screening corrections as discussed in [13–15]. However, the more energetic nuclei which are mainly responsible for fusion have a classical distance of approach much smaller than their average value r_T, thus shielding is not effective in that part of the trajectory. For the same reason, the screening effect expected for a κ-distribution is even smaller. On the other hand, the electron–positron plasma has a smaller inertia than the ions, so it can adapt itself to the new situation creating a time-dependent barrier with an intermediate effectiveness. A dynamic response model is required to accurately describe this effect.

It seems that the spontaneous creation of electron–positron pairs at finite temperature is not enough to improve screening of the Coulomb potential, and alternative and more complex schemes should be considered. For instance, the possibility to enhance reactivity via controlled microexplosions as a compression stage has been discussed in [16]. One could think to increase the screening by injecting a large amount of electrons to upset the densities of electrons and ions. The latter situation has also the advantage of improving sympathetic heating of the ions in case electron cyclotron resonance heating is implemented, due to the favorable heat capacity matching. Unfortunately, it is easy to show that the densities required to have at least an electron–positron pair at the distance of minimum approach of two nuclei are prohibitive. A less impossible idea is to intersect the confined plasma with the focused beams of an electron–positron collider having enough energy to generate pairs. By replacing the electron mass with the muon mass in Eq. (7), and provided that the effective temperature of the $\mu^+\mu^-$ gas is high enough, one can create a situation in which $\lambda_{\rm eff} \simeq r_T$. This is analogous to muon catalysis, but it is hard to imagine that with few intersection points between the core of the confined plasma and the e^+e^-collider there will be enough heating power to ignite fusion, unless a confinement geometry in which the whole plasma and the e^+e^- beams coexist is designed.

4. ENERGY CONVERSION BY HADRON CALORIMETERS AND HIGH-EFFICIENCY PHOTOVOLTAIC CELLS

Since a D–D reactor does not need a lithium blanket, this allows for revising the conversion of the neutron energy into electrical energy. In particular, the traditional thermal cycles have an overall efficiency limited to about 30%. Recent developments in scintillating materials, decades-long experience with hadron calorimeters, and progress in photovoltaic conversion may allow for an alternative scheme bypassing the thermal cycle while achieving comparable efficiency. The idea is to mimic the solar energy collection. In the latter case, the Sun is emitting with a peak around the visible region of the electromagnetic spectrum, and the few eV of the photons in this regions are adequate to create electron-hole pairs in semiconductors. In our case, since fusion in reactors must occur at higher temperatures to reach reasonable amounts of power, a wavelength shifter of the produced photons is required. Therefore, neutrons emitted from half of the D–D fusion reactions are progressively absorbed in a calorimeter producing ionization and scintillation. A material scintillating with a light yield of 30% has been recently discovered [17] and third generation photovoltaic cells now under development are expected to reach 70% efficiency [18]. Therefore, combining the two technologies, efficiencies of the order of 20% seem within reach. The power of the reactor in this approach seems limited by the radiation damage induced by neutrons in the calorimeter, with detectors at the Large Hadron Collider at CERN representing a state of the art design in permissible neutron flux (estimated to 2×10^{17} neutrons/(cm^2 s) for an integrated luminosity of 3000 fb^{-1} [19]), and the light yield has been found to decrease with increasing neutron fluence [20].

Such a scheme can be feasible, in light of the maximum permissible neutron flux, for compact low and medium power fusion reactors, with applications to decentralized electricity production in regions requiring low power densities (for instance rural regions, and as a complement to intermittent renewable sources like wind and solar energy), and especially in the sector of maritime transport, with the prospect of a virtually unlimited range of the vessels. Container vessels, due to their emissions and sheer number, significantly contribute to air and water pollution [21]. Notice that, due to the compact design of a fusion reactor, the usual request for low-cost per unit of surface of a photovoltaic cell is not a priority as in extensive solar power plants. This could lead to the search for higher efficiency, i.e., more expensive photovoltaic cells, still convenient especially if many (now unaccounted for) environmental costs are considered.

5. CONCLUSIONS

We have discussed somewhat futuristic approaches to nuclear fusion both in enhancing reactivity of D–D fusion processes, and in delivering electricity without the use of a thermal cycle. It is possible that various aspects of this proposal may become more realistic with dedicated efforts, as no fundamental technological hurdle seems in sight. The production and control of κ-distributed energy for the plasma requires a kinetic approach related, for instance, to the dynamics of neutral beam injection heating. Exploiting quantum vacuum effects from existing e^+e^- pairs at temperatures one order of magnitude higher than usually achieved in tokamaks, or from intersecting e^+e^- beams with the plasma to produce $\mu^+\mu^-$ pairs for efficient Coulomb shielding, will require a radical revision of the design of current fusion experiments. Calorimetry and photovoltaic panels need to be integrated into the unique goal of energy conversion to bypass the limitations in efficiency intrinsic to the thermal cycle, opening up a vast spectrum of applications for fusion energy through compact, low-power plants.

This project could be developed in parallel to the existing ITER-DEMO plan on D–T fusion, with no subtraction of human and financial resources to these existing and already planned facilities. By now, the margins of safety for embracing a sustainable, continuous, controllable and clean source of energy before irreversible climate changes are extremely limited. As such, the ITER-DEMO project and similar ones under development need to be developed at the maximum speed and extent.

Apart from obviously requesting more resources to the society at large, we believe that extra-resources on parallel designs as the one sketched here could be available once a consistent part of the scientific community will acknowledge where the most urgent, impactful priorities are. In this regard, it is reasonable to expect that the currently disproportionate emphasis on quantum information technologies—mainly driven by military and finance secrecy issues—will fade away, especially once researchers will recognize the large ratio between promised and delivered results [22]. A balanced transfer of human and financial resources from quantum information technology to research in controlled plasma fusion will be highly beneficial for our unique and irreplaceable Planet Earth.

It is a special honor to contribute to the Festschrift for colleague and friend Lev Petrovich Pitaevskii, whose outstanding contributions to some of the themes discussed in this note, plasma physics, quantum field theory, and statistical physics, will continue to be inspirational for many generations to come.

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