Inertial Confinement Fusion and Fourth Generation Nuclear Weapons*

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Abstract

Starting with a brief review of the principles of boosting and two-stage thermonuclear explosives, the strong similarities that link inertial confinement fusion with thermonuclear weapons physics is emphasized. Recalling that micro-fission and micro-fusion explosions, as well as subcritical fission burn, are allowed by the comprehensive test ban treaty (CTBT), it is shown that the development of new types of nuclear weapons is possible for all parties to the treaty — including the non-nuclear-weapon States. These "fourth generation" nuclear weapons could make use of relatively standard technologies such magnetic compression, subcritical burn, or superlasers (i.e., ultrapowerful lasers with intensities higher than 10^{19} W/cm^2), or more advanced nuclear processes based on nuclear isomers, antimatter, superheavy element, etc. The cases of superlasers, antimatter-triggered nuclear weapons, and pure-fusion weapons is discussed in some details. The conclusion stresses the fragility of the current strategic environment, and the danger that would pose a new nuclear arms race in which all modern industrialized countries (e.g., Japan, France, China, Germany, etc.) would compete to become the second largest military power in the next century.

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Contents

1. H-bombs and boosting
2. Inertial confinement fusion (ICF) and simulation
3. Technological breakthrough: the “superlaser”
4. Fourth generation nuclear weapons
5. Subcritical burn and microfission explosives
6. Antimatter weapons
7. Pure fusion weapons
8. Conclusions

References

Tables

Figures

1 H-bombs and boosting

Despite the tight secrecy that covers the technical details of how nuclear and thermonuclear weapons are built, their principles are sufficiently well known to be described fairly accurately [1].

Using the wording of the U.S. Department of Energy, Office of declassification, the fundamental idea is that, “in thermonuclear weapons, radiation from a fission explosive can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel” [6]. This is the essence of the so-called “Teller-Ulam” principle that was declassified by the U.S. in 1979, and which is used in all modern fusion explosives.

Figure 1 is a simplified diagram of the U.S. MK-12A reentry vehicle. It was designed during the 1970s and mounted on the Minuteman III land-based ICBMs in th early 1980s.[1] The main nuclear components of its warhead are a fission bomb (also called the trigger, or the primary) that is producing the

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[1] Each Minuteman III carries three independently targetable (i.e., MIRVed) MK-12A reentry vehicles.

radiation (i.e., soft x-rays) necessary to compress and ignite the main stage (also called the secondary, or second-stage) that produces the major yield. The thermonuclear yield of the warhead is about 300 kt for a weight of about 200 kg. This corresponds to yield to weight ratio of 1.65 kt/kg, i.e., to an explosive power equivalent to 1650 times that of TNT.

The secondary consists of a U^{238} tamper containing the thermonuclear fuel (Li^6D) and possibly a "sparkplug" (a thin rod of U^{235} along its axis) to facilitate ignition. The radiation case enclosing the primary and the secondary is typically made of U^{238}. Its main characteristic is to be sufficiently heavy to contain long enough by its own inertia the x-rays emitted by the primary, in order that this radiation has enough time to compress and ignite the secondary.

I practice, in order to have been able to build such a weapon, i.e., to make it sufficiently small and lightweight to be deliverable by an ICBM, it was necessary to first miniaturize the primary. This miniaturization was achieved by using a small amount of tritium and deuterium, a thermonuclear fuel mixture, to enhance the performance of a fission bomb. This technique is called "boosting" because it was first developed in order to increase the yield of a fission bomb. Boosting is now primarily used to decrease the overall weight and size of nuclear bombs for a given yield, as well as to dramatically increase their safety. Since boosting is presently used in essentially all modern nuclear weapons (i.e., in all tactical or strategic weapons within all contemporary nuclear arsenals) it is important to explain this technique in some details.

The hollow spherical component at the top of Fig.1 is a simplified diagram of a tritium-boosted fission primary. Its core consists of a plutonium and/or enriched uranium shell (the "pit") surrounded by a stainless steel case and possibly a neutron reflector, and by chemical explosives. This corresponds to the present-day concept of sealed pits, with the fissile material permanently sealed within the high explosives. A short time before detonating the device, the pit is filled with a few grams of a deuterium-tritium (DT) gas mixture at a pressure of a few tens of atmospheres.

When the weapon is detonated, the pit and the case are imploded by the high explosives at the same time as the DT gas. As the pit collapses into a solid ball, the DT is compressed into a sphere of a few mm radius with a density tens of times greater than its solid-phase density. At the same time the fissile material is compressed to a few times its normal density — and the fission chain reaction starts.

As the chain reaction develops the fissile material warms up and begins to emit x-rays and neutrons which heat the DT at the center of the device. The temperature of this mixture of fusionable materials therefore rises at the same time as the temperature of the fissile material. This leads to a remarkable phenomenon which is the essence of the boosting process: the fusion fuel ignites *before* the fission chain reaction is terminated [1].

Therefore, at a time when the diverging chain reaction has generated a yield that is still negligible, the DT mixture burns out very quickly and generates a very intense pulse of high-energy neutrons by the thermonuclear reaction: $D + T \longrightarrow {}^4He + n$. These fusion neutrons interact with the fissile material, causing it to fission, and therefore to generate most of the yield of the explosion. In other words, with boosting, the yield of a fission explosive is controlled by the very fast neutron burst from the thermonuclear reactions, and the fissile material (apart from heating the fusion fuel to ignition) is essentially a passive neutron and energy amplifier in the final stage of the nuclear explosion. This leads to several important conclusions:

1) With boosting, it is possible to build a relatively high yield fission explosive which is fairly compact because it uses only a relatively small amount of high explosives to implode the fissile material. The device can also be made relatively light-weight because a thick neutron reflector surrounding the fissile material is not necessary. Moreover, since the fissile material is surrounded by a minimum amount of materials, electromagnetic radiation can flow out of it with only limited attenuation, and therefore fill the radiation case with x-rays.

2) In an actual weapon, before arming the device, the DT mixture, or just the tritium, is stored outside of the pit in a separate reservoir. This facilitates maintenance and insures that boosting will not happen in case of an accidental detonation of the high explosives. Since the amount of high explosives needed to implode a boosted-device is only on the order of a few kilograms, a boosted fission-weapon is extremely safe because an accidental nuclear explosion is almost impossible to take place. This increased safety is the most important single factor which enabled so many nuclear weapons to be deployed for so many years. It is also the main reason why threshold nuclear States such as India, Israel and Pakistan [3, p.195] rely on tritium-boosting technology to maintain a credible nuclear arsenal.

3) The most important technical aspects of boosting (e.g., that during the implosion the fusion fuel gets sufficiently compressed without mixing with the fissile material) can be tested *without* actually starting fission or fusion reactions. This can be done outside of the scope of the CTBT, and only

requires conventional equipments that are available in most high-explosive research laboratories.

Therefore, in summary, the very important advance in fission weapons constituted by boosting [4, p.312], and the fact that boosted bombs used as primaries are “lower-bounding the size and mass of hydrogen bombs” [4, p.313], confirm the tremendous importance of tritium for the operation of boosted-A-bombs, as well as of H-bombs, and therefore the importance of thermonuclear energy technology from the point of view of the non-proliferation of fission and fusion weapons.

Let us return to the design of a two-stage thermonuclear weapon. Its general principle, the Teller-Ulam method, was given at the beginning of this section, and is recalled in the caption of Fig.2. As with boosting, two conditions have to be satisfied: (a) the thermonuclear fuel has to be sufficiently compressed for the fusion reaction to be fast enough, and (b) the thermonuclear fuel has to be brought to a sufficiently high temperature for the fusion fuel to be ignited. Both conditions can be satisfied by using a boosted fission bomb as a powerful source of x-rays.[2]

Referring to Fig.2, the Teller-Ulam method is as follows: a fission bomb and a container filled with fusion fuel (the secondary) are placed within a common enclosure (the radiation case); while the radiation case and the envelope of the secondary (the pusher/tamper) are made of heavy materials opaque to x-rays, the remaining space within the radiation case (the hohlraum) is filled with light-weight materials transparent to x-rays; as the primary fissions, large amounts of x-rays are radiated ahead of blast and instantaneously fill the hohlraum; x-ray radiation trapped within the hohlraum rapidly turns the hohlraum filling into a hot plasma; radiation-driven thermalization insures that this plasma has very uniform pressure and temperature so that its effects on the secondary are the same from all sides; the plasma reradiates longer wavelength x-rays that are absorbed by the surface of the secondary; the surface of the secondary (the pusher/tamper) is heated to the point where it vaporizes and material is ejected from it; the material ablated from the pusher/tamper causes by reaction a pressure which pushes the tamper inwards, imploding the fusion fuel to very high densities. This satisfies condition (a).

Condition (b), ignition, is achieved by an optional element not yet dis-

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[2] This is why boosting is so important: the energy of the atomic explosion (which is mostly heat in the form of x-rays) can easily radiate away from the fissile core without being attenuated by a thick neutron reflector and large amounts of high-explosives.

cussed: the *sparkplug* at the center of the secondary in Fig.2. It consists of a subcritical amount of fissionable material compressed at the same time as the secondary. Because of the intense neutron background resulting from the explosion of the primary, a fission chain reaction starts in the sparkplug as soon as it becomes critical (in order to avoid a fizzle, the sparkplug is boosted by a small amount of DT). Hence, with a careful design, the sparkplug will explode just when the thermonuclear fuel is imploded to its maximum density. It will then provide, in the form of x-rays, neutrons, and additional compression from within, a large amount of energy sufficient to insure that ignition will start even in the worst case.

Consequently, when Edward Teller invented the sparkplug concept, soon after discovering with Stan Ulam in 1951 a means for achieving very high compressions, the whole scheme became thoroughly convincing. Indeed, as will be stressed much later (1983) by Carson Mark, the Los Alamos physicist who led the theoretical work on the first hydrogen bomb: "Almost immediately [the Teller and Ulam method] gave promise of a feasible approach to thermonuclear weapons, *provided only the design work be done properly*" [5, p.162]. Thus, a major feature of the Teller-Ulam design is that it provides a straightforward and intrinsically fail-safe method for making a thermonuclear bomb. In fact, this method is so good that *all* the first hydrogen bombs of the five nuclear weapon States worked the *first time*.[3]

The ignition mode in which a fissionable sparkplug is used to help ignition and improve the efficiency of thermonuclear burn is called the "Teller mode." In this mode, the design constraints are much less stringent than in the other possible modes. This is because, in the latter, heating of the fuel to thermonuclear ignition is achieved during compression by hydrodynamic conversion of kinetic energy into thermal energy.

For instance, the concept of central "spark ignition" relies on the formation of a hot spot in the center of the imploding fuel where the decelerating motion of the material is converted into heat. If the temperature is high enough, the hot spot ignites and initiates a thermonuclear burn wave that propagates to the outer cold fuel layers. To obtain such high central temperatures, the implosion has to be very symmetric and the time-dependence of the ablation pressure has to have a very precisely defined profile in order for compression to be adiabatic.[4] This is very difficult to achieve because

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[3] This is why there is no doubt that any technologically advanced country can build a militarily usable hydrogen bomb without nuclear testing [2, p.27].

[4] Adiabatic compression, i.e., without loss or gain of heat, minimizes the amount of energy needed to achieve a given compression.

the characteristics of the fission explosion which is at the origin of the whole process cannot be alterated at will.

In this respect, another hydrodynamic mode, the so-called "volume ignition" or "Wheeler[5] mode," is much less demanding: it consists of achieving compressions higher that those sufficient for the Teller mode, and let the fuel temperature rise by self-heating until it reaches a self-sustaining burn temperature. Then, provided compression is high and fast enough, it may be less symmetric and not necessarily adiabatic as is the case in spark ignition.

Hence, while the Teller mode of ignition was used in the first thermonuclear explosives, the Wheeler mode is certainly the one used in the more modern weapons (e.g., in the MK12-A, depicted in Fig.1). On the other hand, there is no unambiguous information on whether or not spark ignition is used in the most modern weapons. This is one reason why the mastering of this technique in the context of inertial confinement fusion (ICF) research with megajoule laser facilities may lead to further improvement in thermonuclear weapons technology.

2 Inertial confinement fusion (ICF) and simulation

The concept of inertial confinement fusion is that a sequence of tiny fuel pellets containing deuterium and tritium are projected towards the center of a reaction chamber where high-power laser or particle beam pulses strike each pellet, compressing and heating its fuel, and releasing thermonuclear energy by the reaction: $D + T \longrightarrow {}^4He + n + (2.8 \times 10^{-12}\mathrm{J})$. This energy is converted in an absorbing blanket into thermal energy which is coupled to a turbine to make electricity through a normal thermal cycle.

Since 1 g of DT produces about 340 GJ of energy, a nominal 1 GW (electric) fusion power plant with a thermal efficient of 30% would consume 10 mg of DT per second.[6] If we assume that one pellet is detonated each second, the explosive yield of each pellet would be 3.4 GJ, i.e., equivalent to about 810 kg of TNT.

Figure 3 is a simplified diagram of an advanced indirect-drive ICF target

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[5] John Archibald Wheeler worked on thermonuclear research at Princeton and Los Alamos in 1950-1951. He helped calculating the hydrodynamics of the first American thermonuclear device. In 1981 he applied similar ideas to ICF targets.

[6] This corresponds to a consumption of 0.5 kg of tritium per day.

of the kind that is extensively studied for future ICF reactors. Such a target consists of a hohlraum containing a $1-10\,\mathrm{mg}$ DT fuel pellet. The concept of *indirect drive* refers to the fact that in this type of target the driver energy is not directly deposited onto an outer layer of the fuel but is first converted into thermal x-rays confined in a hohlraum. In the U.S., this concept was declassified in 1979 at the same time as the Teller-Ulam principle (Fig.2), using a wording that is almost identical: "In some ICF targets, radiation from the conversion of the focused energy (e.g., laser or particle beam) can be contained and used to compress and ignite a physically separate component containing thermonuclear fuel" [6, p.103].

It is therefore not surprising that Fig.2 and Fig.3 are very similar, except for the technique used to generate the soft x-rays filling the hohlraum. In laser driven ICF, the hohlraum is generally a cylinder with openings at both ends to allow the laser beams to heat the inner surface of the hohlraum, causing emission of x-rays. In heavy-ion driven ICF, the heavy-ions are stopped in converters (i.e., small pieces of high-Z materials placed within the hohlraum) which are strongly heated. With other drivers, e.g., light-ion beams or antiprotons, the details would be different, but the result the same: strong heating of the radiation case or of the converters leading to x-ray emission into the hohlraum. Hence, any type of indirect drive ICF system will enable the simulation of H-bomb physics in the laboratory.

The problem, of course, it to succeed in compressing the pellet to a very high density[7] and igniting the fuel, either by "spark ignition," or by "volume ignition," as for hydrogen bombs. The difficulty of this task is enormous, and it would be advantageous to find a technique similar to Teller's "sparkplug" concept that considerably simplified the design of H-bombs. Apparently, such a technique has been found with the invention of the "superlaser": it will be discussed in the following section.

Ignition[8], however, is still an open question. For the time being, and for many years to come, the main practical applications of ICF are in the domains of thermonuclear weapons physics and effects.[9] Let us review them

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[7] The smaller the pellet radius R, the higher the density ρ, in order that the product ρR remains larger than the minimum of about 3 g/cm^2 that is required for a 30% burnup of the thermonuclear fuel.

[8] And all the potential applications that may derive from ignition, e.g., Inertial Fusion Energy (IFE).

[9] These implications have already been expounded in a number of publications See, e.g., [7, 1] and references therein. The other practical applications ICF, e.g., fundamental research in astrophysics [8], are generally dual purpose. A clear example of this ambivalence is the project to use the technology developped for the NIF as an Earth-based laser

in some details:

- *Nuclear weapon-effects research.*

ICF systems enable both nuclear and non-nuclear effects to be studied. The latter consists of the effects of low and high altitude single and multiburst detonation in the atmosphere. Such studies enable (a) prediction of the effects of subsequent bursts in a multiburst environment; evaluation of the spatial extent and duration of satellite communication interference; and (c) evaluation of radar shielding effects which hinder detection of secondary missions. Since 1964, because of the Partial Test Ban Treaty (PTBT), such problems cannot be studied with real nuclear explosions in the atmosphere.

The total radiation field of a nuclear explosion is composed of x-ray, gamma-ray, neutron and electromagnetic pulse (EMP) components. The intensity of each of these is strongly dependent upon the specific design and the yield of the weapon. Also, the presence or absence of some of these radiations depend on the environment in which the nuclear detonation occurs. For example, in an underground explosion some of the radiation (e.g., EMP) will be absent compared to an atmospheric or high altitude explosion.

Until the conclusion of the CTBT, synergistic testing was done through underground explosions, but ICF provides now an alternative method for carrying out such tests in the laboratory; an ICF exposure is expected to cost less than one percent of an underground experiment.[10] Furthermore, experiments with an ICF facility are much more convenient and reproducible. For example, meter-sized costly equipments such as reentry vehicles, missiles, satellites, can be exposed to neutron fluxes of 10^{13} to 10^{14} n/cm^2/s, or 3 to 30 cal/cm^2 x-rays, without completely destroying them. ICF systems can also be used for "nuclear hardening," and to "burn in" ready-to-field equipments by exposing them to radiations and replacing the weakest components that may have failed.

- *Nuclear weapons physics research.*[11]

After the discovery of the Teller-Ulam principle, and some major improvements during the 1960s, progress on thermonuclear weapons slowed down dramatically. In fact, despite more than 50 years of research and development, and after almost two thousand test explosions, the scientific un-

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to clear near-Earth space debris [9, p.15]: Such a device would also be an anti-satellite weapon.

[10] However, for countries such as India, because of the complexity and hugh cost of large ICF facilities, underground tests would be much less expensive than ICF simulations.

[11] For a more detailed development of this subject see, in particular, [1, Chap.3].

derstanding of the details of the secondary system is still incomplete.[12] If the CTBT would not have been concluded, the continuation of full-scale testing would probably never have changed this situation, given the great number of complex phenomena that occur simultaneously within the fraction of a microsecond of the explosion of an H bomb.

A major problem with full-scale testing is that the secondary of an actual bomb is buried deep inside the weapon, surrounded by a thick ablator and the radiation case. Therefore, most experimental data on the thermonuclear part of the explosion is indirect. In comparison, an ICF pellet is an almost naked secondary, and many configurations can be tested at will, with much better diagnostic capabilities than with underground nuclear tests. The promise of ICF is a complete description of nuclear weapons physics from first principles.

Charge-particle and laser beams are capable of concentrating large amounts of energy onto small targets. These targets may consist of non-nuclear materials, fissile materials, or fusion materials. The very high pressures and shock strengths possible with the kind of beams necessary to drive ICF systems, enable hydrodynamic behavior and material equations of state to be studied in a parameter range comparable to that existing within exploding nuclear weapons (see Fig.6 and Fig.7).

The large megajoule-scale ICF facilities currently under construction (see Tables 1 and 2) will be particularly well suited for this purpose [11]. But proton beams from high-power generators, such as, for example, the *Karlsruhe Light Ion Beam Facility (KALIF)* (see Table 1) in Germany enable similar measurement with power densities of up to 200 TW/g and energies densities of several MJ/g [12]. As can be seen on Fig.6, such energies densities, equivalent to 2×10^{-4} kt/kg, are only a factor of 100 less than for NIF (the *National Ignition Facility*, under construction in the U.S.A.) without ignition. Other pulsed-power beam generators, such as the *Saturn* electron accelerator [13] in the U.S.A., are also providing important nuclear weapons data, even though they are primarily advocated as fusion energy research tools.[13]

The complexity of ICF target experiments requires that they be analysed

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[12] "We do not completely understand the physical processes involved in the operation of a nuclear weapon" [10, p.24]. "We do not understand nuclear weapon processes well enough to calculate precisely the transfer of energy within a weapon" [10, p.30].

[13] Laser facilities, however, provide a much "cleaner" working environment, especially with respect to electromagnetic interferences from the pulsed power equipment, and much better energy deposition profiles because of the greater flexibility of time-shaping the laser pulses.

by simulating the experiment with two- and three-dimensional hydrocodes. Thus verification and improvement of weapon design code is an intrinsic part of ICF experiments. Since ICF research is done in non-nuclear weapons States, very sophisticated computer codes have been developed and published by scientists in such States. For instance, the two-dimensional hydrocode MULTI2D [14] developed at the *Max-Planck-Institut für Quantenoptik*, in Garching, Germany, is considered to be in several respects better and faster than LASNEX, the currently standard (and partially classified) U.S. two-dimensional hydrocode. These codes allow, in particular, the simulation of the dynamics and stability of implosion (of either passive or nuclear materials) driven by ICF or other types of drivers: chemical high-explosives, magnetic fields, electromagnetic guns, etc.

Considerable scientific data necessary for the design of fusion systems is also crucial for thermonuclear weapons. For example, the temperature- and pressure-dependent opacity functions for high atomic-number elements were classified until 1993 because this information is needed to make such weapons. Techniques for measuring these opacities are improving because of the availability of high-energy lasers. These can be used to measure opacities directly at laser frequencies, or indirectly by converting the laser radiation to x-radiation, and measuring opacities in the x-ray region which is the most relevant to nuclear weapons.

A last aspect of ICF which is of importance in weapons physics is that of rate-dependent processes. An ICF system can easily expose a recoverable target to neutron and x-ray fluxes comparable to those of a full size nuclear explosion.

- *Ignition, fourth generation nuclear weapons, and Inertial fusion energy.*

"Ignition" studies refers to the fact that macroscopic processes like thermonuclear plasma *ignition* are still not well understood. Special ICF targets which absorb the driver energy and convert it to x-rays enable H-bomb ignition physics to be studied directly. Moreover, ignition techniques different from the Teller-Ulam concept can also be studied, or discovered, using ICF. The fast ignitor using a superlaser is one example of such a new concept.

The important conclusion is that, whatever the details, successful ignition of thermonuclear micro-explosions in the laboratory will open the way to two types of applications which will most certainly remain in the military domain: new types of nuclear weapons, and Inertial fusion energy (IFE).

(i) *Fourth generation nuclear weapons.* Inertial confinement fusion is basically a continuous salvo of contained thermonuclear explosions. In a nominal

1 GW fusion power plant, the yield of these explosions will be equivalent to about 100 or 1000 kg of TNT, assuming a rate of ten or one detonations per second, or to about 10 tons of TNT, assuming a rate of one detonation every 10 seconds. The military significance of these yields is that the amount of conventional high-explosives (HE) carried by typical warheads or bombs is limited to a range of a few 100 kg to a few tons.[14] Since an ICF pellet weighs only a fraction of a gram, ICF based military explosives would revolutionize warfare. Combined with precision guidance, earth and concrete penetration, and other existing techniques, small and lightweight ICF based warheads would destroy virtually all possible targets, and render existing types of very-high yield nuclear weapons obsolete. The challenge, of course, is to replace the large laser- or particle-beam driver by some sufficiently miniaturised device. This problem will be discussed in section 7, were a number of chemical-explosive-driven drivers will be described.[15] However, it can already be said that a single-use device is usually much more compact and simple than a multi-purpose re-usable experimental facility, and that very-high energy-density technologies such as antimatter and superlasers are ripe to meet the challenge [1].[16]

(ii) *Inertial fusion energy* (IFE). Success with ignition, and a sufficient reduction of scale of the driver, would provide a very attractive substitute for the numerous nuclear reactors used by the military.[17] As for the possible *civilian* use of IFE, the prospect is bleak. Considering the bad image that nuclear energy has in general, it is unlikely that IFE will be found acceptable by the public in democratic countries. For one thing, development of IFE will come in parallel with fourth generation nuclear weapons which will use ICF pellets as their main explosive charge. A daily load of ICF pellets for a medium or full scale fusion power plant will consist of thousands of pellets, each of them equivalent to one or several tons of high explosives. If these pellets are not fabricated at the power plant, their shipment will have to be heavily guarded.

Tables 1 and 2 are compilations of the main characteristics of the major

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[14] The Scud ballistic missile warhead contains roughly 200 kg of HE and the Patriot anti-missile warhead roughly 40 kg. A Tomahawk long-range cruise-missile carries a conventional or thermonuclear warhead weighting about 120 kg, and a typical big air-dropped bomb weighs between 500 and 2000 kg.

[15] For a more extensive development of this question see, in particular [1, Chap.4].

[16] These considerations about radically new types of nuclear weapons should not minimize the potential of using ICF facilities for improving existing types of nuclear weapons [15].

[17] They are more military nuclear reactors at sea, under the sea, and in various military facilities, than nuclear power reactors producing electricity for civilian purposes.

operating or planned ICF-related facilities in the world. In the last column, “C” means that the facility is under construction, and “D” that it is in the design stage. The laser beam wavelength is in μm.

In these tables, the tabulated energy of the facility is the *nominal* maximum energy. This is because the beam-target coupling is a function of the nature of the beam (i.e., laser- or particle-beam) and of its energy, e.g., of the photon’s wavelength in the case of a laser beam. Hence, a comparison of the relative capabilities of ICF-related facilities is not trivial. Some convention is required. For example, the power of microexplosion fusion installations can be expressed as the total energy that the laser system is capable of delivering to the target at a given wavelength. At present, applying this convention to the shortest possible wavelength, the most powerful laser energy attains approximately 30 kJ for the United States, 10 kJ for Japan, 6 kJ for France, 2 kJ for Russia and China and about 1 kJ for the U.K. The nominal energy of LMJ will be the same as that of NIF, i.e., 1’800 kJ, which corresponds to an energy on the order of 600 kJ at the shortest wavelength.

In conclusion, the construction of large ICF microexplosion facilities such as NIF and LMJ (the *Laser Mégajoule*, under construction in France) will give the arms race a fresh boost. It must be understood that, as a result, there will be considerable follow-on effects within other countries. Japan and, to a lesser extent, Germany already possess ICF and other thermonuclear fusion facilities of comparable quality to that of the United States and France. These countries will certainly increase the power of their laser- and particle-beam ICF-drivers. India, Israel, and Korea are close behind. The world runs the risk that certain countries will equip themselves directly with fourth generation nuclear weapons, bypassing the acquisition of the preceding generations of thermonuclear weapons.

3 Technological breakthrough: the “superlaser”

“Superlasers” are ultra-short ultra-intense pulsed lasers with pulselengths in the range of 10^{-15} to 10^{-12} s, i.e., femtoseconds to picoseconds,[18] and beam intensities on the order of 10^{20} W/cm^2, i.e., sufficient to induce strong rela-

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[18] A femtosecond, i.e., 1 fs = 10^{-15} s is on the order of the time taken by an electron to circle an atom. This gives the order of magnitude of the minimum pulselength of an optical laser pulse.

tivistic, multi-photon, nonlinear, and nuclear effects [16, 17, 18].[19] They are the result of the combination of two inventions: One (a clever optical "pulse compressor") made by Oscar Eduardo Martìnez, an Argentinean working at Bell Laboratories as an external post-doctoral fellow, in 1984; the other (a scheme called "chirped pulse amplification") by Gérard Mourou, a French working at University of Rochester, in 1985. These inventions ended a twenty years long period over which laser intensity plateaued at a maximum of about 10^{14} W/cm^2, due to limitations caused by nonlinear effects (see Fig.4).

The potential military applications of superlasers are so impressive that their principles have been implemented on existing large laser systems built for inertial confinement fusion and weapons simulation, pushing their peak power by three orders of magnitude from 1 TW to 1 PW. For example, the Lawrence Livermore National Laboratory (LLNL) Petawatt laser is the result of transforming one of the ten Nova (see Table 2) laser beams into a superlaser beam [18, p.25]. As can be seen in Table 3, it is now the World's most powerful laser, overtaking the French 55 TW laser which was leading until June 1996. Since then, Japan has put a 100 TW laser in operation in April 1997, the United Kingdom a 200 TW one in January 1998, and Germany will soon have its own 100 TW laser [19, p.7].

Superlasers enable a two step approach to ICF similar to the "sparkplug" ignition of a cold compressed fuel in H-bombs[20, 21, 22]. The proposed "fast ignitor" scheme is as follows: First, a capsule is imploded as in the conventional approach to inertial fusion to assemble a high-density fuel configuration. Second, a hole is bored by a superlaser through the capsule corona composed of ablated material. Finally, the fuel is ignited by fast electrons, produced in the superlaser-plasma interactions, which then propagate to the center of the pellet. This new scheme enables a factor of 10–100 reduction in total driver energy; it also drastically reduces the difficulty of the implosion, and thereby allows lower quality target fabrication, and less stringent beam quality and symmetry requirements from the implosion driver [20, p.1626].

Fast ignition of ICF pellets and thermonuclear fuels is however only one of the many potential applications of superlasers with important military consequences.[20] Let us briefly review some them, following the rise in the curve shown in Fig.5, which gives the "electron quiver" energy (i.e., the oscillation energy of an electron in the laser electromagnetic field) as a function

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[19] They are called *super*lasers because their interactions with matter is qualitatively very different from those of ordinary lasers.

[20] There are of course many non-military applications of superlasers. Introductions to these can be found in several excellent review papers [16, 17, 18, 19].

of the laser intensity:

- *Generation of x-rays.* Superlasers can produce x-rays with submicron spatial resolution and sub-picosecond temporal resolution. Such ultrafast pulses can be used for x-ray tomography, imaging, and other diagnostics of fast processes such as the implosion and burn of ICF pellets.

- *Study of metallic hydrogen* [18, p.28]. Metallic hydrogen is potentially the most powerful chemical explosive conceivable [23].

- *Excitation of nuclear states.* Superlasers are needed to pump isomeric nuclear states for gamma-ray lasers, energy storage, and new military explosives [24].

- *Electron and ion acceleration.* Particles can be accelerated to MeV energy over extremely short distances. This effect has now been observed and opens the way to a number of applications: ultra-compact particle accelerators, electro-fission of fissile materials, heating of fusion pellets ("fast ignitor"), etc.

- *Hole boring and ultra-high magnetic field generation.* At an intensity of 10^{19} W/cm^2 the light pressure[21] of a beam focussed on a target, $p_L = 2I/c \approx$ 6 Gbar, is much higher than the material ablation pressure by an ordinary laser. The consequence is that the beam is boring a channel through the plasma by ejecting the electrons from it much faster than the matter (the ions) can move hydrodynamically. As relativistic electrons are set into motion by the pulse, magnetic fields up to 100 MG are generated [25].

- *Optically induced thermonuclear fusion.* The first thermonuclear neutrons in laser irradiation of matter were observed in 1968 in Russia by focusing a 20 J, 20 ps laser pulse on a lithium-deuterid target.

- *Optically induced nuclear fission.* The high energy electrons and the x-rays generate by focusing a superlaser pulse on a fissile target can induce electro-fission and photo-fission reactions [26]. This mechanism can be used to start a neutron chain-reaction, or to provide initial neutrons for subcritical burn, in a highly compressed pellet of fissile material.

- *Nuclear weapons physics and effects.* "At 10^{21} W/cm^2, the energy density of the pulse is over 3×10^{21} J/cm^3, which corresponds to a 10 keV blackbody and an equivalent light pressure of 300 Gbar [16, p.917]. These temperatures and pressures exist only within an exploding thermonuclear

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[21] The ponderomotive pressure of a light beam is given by momentum conservation as $p_L = 2I/c$ for completely reflected light, and $p_L = I/c$ for completely absorbed light.

weapon. [See, e.g., Fig.7.] Therefore, as can be read in the LLNL 1995 Annual Report: "Such high-energy fluxes [...] will allow researchers to measure in the laboratory important material properties at conditions similar to those that occur in the operation of a nuclear weapon" [27, p.29].

- *Production of positrons, pions and antimatter.* While existing superlasers are sufficiently intense to produce electron-positron pairs [28], they will be marginally capable to produce pions at their highest intensity. Future superlaser operating close to the laser intensity limit will produce copious amount of proton-antiproton pairs much more effectively that the huge particle accelerators that are used today for this purpose [29, 30].

The whole subject of superlaser research and development is presently a domain of very intense activity. New institutes and specialized laboratories have been created in several countries. For example, the *Center for Ultrafast Optical Science* at the University of Michigan, the *Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie* (MBI) in Berlin Adlershof, the *Centre d'Etude Lasers Intenses et Applications* (CELIA) in Bordeaux, or the *Advanced Photon Research Center* (APRC) near Osaka. As shown in Table 3, all the most advanced industrialized countries have now superlasers with powers of at least 10 TW, and 100-1000 TW superlasers under construction.

Superlasers are an example of a breakthrough that is the result of pure technological innovation. It was known since many years that one day a way would be found to go from the 10^{14} W/cm^2 standard laser intensity to the 10^{20} W/cm^2 range because there is no *fundamental* obstacle until the laser intensity limit of 10^{24} W/cm^2 is approached.[22]

The future will show if the development of the superlaser is really one of the most important invention of the past decade. In any case, as is suggested in a recent review, the superlaser may well be the signal that the industrial civilization has definitely entered, for better or for worse, the "Age of the photon" [19, p.7].

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[22] In contrast, technologies such as thermonuclear fusion for electricity generation are *already* at their scientific limit. No technological breakthrough is to be expected for them. This is why, assuming that all the details are worked out, whatever confinement scheme is adopted, it is already possible to compare these systems with other sources of electricity.

4 Fourth generation nuclear weapons

As science and technology advances, new weapons are conceived and developed all the time. However, since the advancement of science is a rather slow process, new types of weapons can be under consideration for quite a long time and come to public attention only after they reach the development or deployment stage. In the case of nuclear weapons, many different types — some of which are based on physical processes which differ from those used in current thermonuclear weapons — have been studied over a very long time. This is the case for pure-fusion bombs, antimatter bombs, laser-triggered bombs, thermonuclear shaped-charges, new explosives based on nuclear isomers, superheavy elements, metallic hydrogen, etc. So far, none of these concepts has led to an actual weapon. But this may be only a question of time, especially since considerable progress has recently been made on some of these concepts.

In this article we describe a few of the best documented such concepts and analyse their potential for becoming part of the new generation of nuclear weapons.[23] We shall restrict ourselves to those which may lead to new types of nuclear *explosives*. For instance, we leave aside developments such as high-energy beam weapons, x-ray or gamma-ray lasers, ICF-driven EMP weapons, etc. In this section, we begin with an overview of the main characteristics of the previous generations of nuclear weapons:

First generation nuclear weapons are all uranium or plutonium atomic bombs. The science and technology of these weapons is widespread, and their intrinsic simplicity is such that their successful development does not require nuclear testing. Today, these weapons constitute one of the main horizontal proliferation threats.

Second generation nuclear weapons are fusion-boosted fission-explosives ("boosted atomic bombs") and two-stage thermonuclear devices ("hydrogen bombs"). In hydrogen bombs, a tritium-boosted atomic bomb is used to implode and ignite a secondary system in which fusion reactions produce most of the yield. The development of these weapons required extensive testing and resulted in high-yield (100–500 kt) weapons with yield-to-weight ratios about twenty times larger than those of the best first generation nuclear weapons. Progress on these weapons has been slow, and the scientific understanding of the details of the secondary system is still incomplete.

From a strategic point of view, it is important to realize that modern

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[23] A more extensive survey and assessment can be found in [1, Chap.4].

second-generation nuclear weapons have all the necessary qualities to make them suitable for military use: they are simple, rugged, safe, reliable, relatively inexpensive, and highly lethal. It is therefore unlikely that they will disappear, unless they are banned by international law. For instance, the reduction, by almost half, of the number of arms in the American and Russian nuclear arsenals is mainly the result of the decommissioning of obsolete weapons, the elimination of weapons designed for outdated or doubtful military objectives, and the enormous problems associated with the aging of production facilities and the upkeep of large stockpiles of nuclear weapons.

Third generation nuclear weapons are "tailored" or "enhanced" effects warheads — such as the Enhanced Radiation Warhead (ERW), the Reduced Residual Radioactivity (RRR) or Electromagnetic Pulse (EMP) bombs, hot x-ray devices for antiballistic missile (ABM) systems, "clean" explosives for possible use in peaceful activities — or nuclear-driven "directed energy" weapons producing beams or jets of x-rays, electromagnetic waves, particles, plasmas, etc. Like many tactical nuclear weapons, these devices have never found any truly convincing military use.[24] Moreover, none of them has provided any decisive advantage (such as significantly reduced collateral damage, absence of radioactivity, etc.), and their development would have required a large number of nuclear test explosions. For these reasons, the development of this third generation of nuclear weapons is the most directly affected by the CTBT [33].

Fourth generation nuclear weapons are based on atomic or nuclear processes that are not restricted by the CTBT [34]. In contrast with second generation nuclear weapons, their development will be essentially science based, making use of many recent advances in fundamental or applied research and of very sophisticated computer simulation techniques that will allow deployment after only limited field testing. In common with first and second generation nuclear weapons, they could allow for rather simple and rugged designs, although the special materials they will use might be much more difficult to manufacture than plutonium or enriched uranium. Fourth generation nuclear weapons may provide significant military advantages (especially for tactical uses, since most of them will produce minimum residual radioactivity) and considerable political advantages, since their development will be restricted to the most technologically advanced countries.

Considering that existing high-yield thermonuclear weapons will remain the principal component of strategic arsenals for quite a long time, it is

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[24] A typical example is the so-called neutron bomb (ERW), which has not proved to be an effective anti-tank weapon [31, 32].

likely that the first fourth-generation nuclear weapons to be developed by the nuclear-weapon States will be highly miniaturized explosives with yields in the $1\,t$ to $1\,kt$ range, i.e., within the gap that today separates conventional from nuclear weapons. These "low-yield" nuclear weapons will not be considered as "weapons of *mass* destruction" and their construction will be possible for all countries, including the non-nuclear-weapon States. In the following sections we examine a number of concepts which are under active scientific investigation and which have a strong potential to be developed into such new weapons.

The so-called *Comprehensive* Test Ban Treaty (CTBT), which was adopted by the General Assembly of the United Nations on 10 September 1996, has put an end to *explosive testing* of nuclear weapons. However, since laboratory testing is not covered by the CTBT, the development of nuclear weapons will continue using a number of techniques perfected during the last forty years, which today can effectively replace field testing.

There are two major classes of nuclear tests allowed by the CTBT: *subcritical experiments* and *microexplosions.*[25]

During the CTBT negotiations, the five nuclear-weapon States met confidentially several times, either bilaterally or multilaterally, in order to clarify their interpretations of the words of the treaty, which only stipulates "not to carry out any nuclear weapon test explosion or any other nuclear explosion" (Article I of the treaty). In particular, they exchanged information on what they wanted to be allowed or forbidden by the CTBT, and negotiated a common understanding among themselves regarding "activities not treaty prohibited".

Although the exact terms of this understanding are confidential, a considerable insight is given by a report of the Department of State appended to a letter by President Clinton, transmitting the CTBT to the Senate for advice and consent to ratification. This report includes an article-by-article analysis of the CTBT [35]. In this analysis, "inertial confinement fusion (ICF) and other similar experiments" are explicitly mentioned as *examples* of CTBT-permitted activities "which, while not involving a nuclear explosion, may result in the release of nuclear energy." Therefore, it follows that all possible approaches to microexplosion are legal under the CTBT.

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[25] A legal and technical assessment of the nuclear tests allowed by the CTBT is the subject of [1, Chap.2]. This introductory evaluation does not attempt to challenge the nuclear-weapon-States's interpretation of the Treaty, something that should be done by professional lawyers.

Moreover, the Department of State analysis of the CTBT recalls the U.S. statement made at the 1975 NPT Review Conference which (by defining the size of "fissionable and/or fusionable" pellets) gave an upper limit to the yields of acceptable laboratory explosions. These maximum yields, which are on the order of 0.1 to 10 *tons* of high-explosive equivalent, have obvious military significance. They are also in the range of the microexplosion yields required for the efficient operation of the hoped-for future commercial ICF power plants. This is probably why, upon signing the CTBT on 24th of September 1996, Germany made the following declaration:

> "It is the understanding of the German Government that nothing in this Treaty shall ever be interpreted or applied in such a way as to prejudice or prevent research into and development of controlled thermonuclear fusion and its economic use" [36].

Therefore, neither the NPT or the CTBT are putting any restriction on ICF research and development, including the possibility of using drivers different from the huge laser or particle beam facilities that are currently used for this purpose. Moreover, even though the concept of "zero-yield" applies to "any nuclear weapon test explosion or any other nuclear explosion", the yield of microexplosions is not restricted by the NPT or the CTBT.

While this absence of restriction is clear for micro-*fusion* explosions, the situation is not as clear for micro-*fission* explosions. This is because — as will be seen below — the interpretation of the CTBT (i.e., by the U.S.) is such that only those experiments in which a self-sustaining nuclear fission chain reaction occurs are prohibited. It seems therefore that one will have to wait for the official justifications that might be given when the first micro-fission-explosion will be performed at the NIF or any other facility. However, since all information on ICF targets in which "fissile material [is] driven to criticality" [6, p.121] is classified, and since micro-fission and micro-fusion experiments can be made virtually indistinguishable, it is possible that such experiments will be made in secrecy.[26]

Considering subcritical experiments and subcritical fission burn, the fact that they are not forbidden by the CTBT was made clear in Spring 1997 already. This came after a controversy was started by the announcement of the U.S. Department of Energy to conduct a series of high-explosive-driven experiments with plutonium at the Nevada test site [37]. A first statement appeared in a JASON review of these subcritical experiments:

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[26] One of the reasons given for not including microexplosions into the scope of the CTBT is that their prohibition creates a very difficult verification problem.

> "The CTBT, in accord with its negotiating record, forbids explosions that produce any nuclear yield. The U.S. interprets this to mean that experiments in which conventional explosives assemble a critical mass of fissionable material are prohibited" [38, p.10].

This statement implies that the mere fact that criticality (and *a fortiori* supercriticality) is not reached is sufficient for consistency with the provisions of the CTBT. In other words, for the United States, "nuclear yield" is associated with energy released during a diverging chain reaction, suggesting that the kind of explosion forbidden by the Treaty is that in which the energy release is "uncontrolled". This is confirmed by a U.S. Department of Energy statement on subcritical experiments released shortly after the publication of the JASON review:

> "Subcritical experiments are fully consistent with the terms of the Comprehensive Test Ban Treaty (CTBT), signed by President Clinton last September at the United Nations. The treaty bans 'any nuclear weapon test explosion or any other nuclear explosion.' Subcritical experiments, on the other hand, are configured such that no self-sustaining nuclear chain reaction can occur even though special nuclear materials will be present. In other words, the configuration of each experiments guarantees that no nuclear explosion prohibited by the treaty can result" [39].

This official statement suggests that there can be nuclear *explosions* which are *not* forbidden by the CTBT: the only explicit restriction is that "no self-sustaining nuclear chain reaction" should occur. This leaves open the possibility of designing devices in which nuclear fission energy is released in a semi-controlled fashion, i.e., in a subcritical fission burn. The characteristics of these new types of fission explosives are discussed in the following section.

The US Department of State article-by-article analysis of the CTBT includes a "not all-inclusive but illustrative" list of activities allowed by the Treaty:

> "computer modeling; experiments using fast burst or pulsed reactors; experiments using pulsed power supplies; inertial confinement fusion (ICF) and similar experiments; property research of materials, including high explosives and fissile materials, and hydrodynamic experiments, including subcritical experiments involving fissile material." [35, p.6].

None of these activities constitute a "nuclear explosion": similarly "activities related to the operation of nuclear power and research reactors and the operation of accelerators" [35, p.6] are not prohibited by the Treaty. In performing these activities, a number of well known non-nuclear and nuclear processes and techniques are used. In the context of their applications to weapons technology, as well as for their use in military explosives, these physical processes can be classified according to the nature of the energy release, which is either of *atomic* or *nuclear* origin.

In Table 4, the most important *standard* physical processes that are currently used in existing military explosives (as well as for their development) are compared to the more *advanced* processes that may become part of new types of military explosives within a decade or two, as well as to more *exotic* processes that may become relevant in the more distant future. One can see that there is a relatively large number of physical processes available for the design of new types of military explosives — a confirmation that atomic and nuclear physics are relatively new sciences. Many surprising discoveries are still possible, with many implications for new types of nuclear explosives. The fact that international treaties such as the NPT and CTBT only take into account the more standard of these processes, without any provision constraining the potential military application of the more advanced ones, is therefore a serious reason for concern.[27]

To summarize this section, we give in tabular form an overview of the three classes of fourth generation nuclear weapons, one for each level of technological sophistication:

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[27] These considerations about radically new types of nuclear weapons should not minimize the potential of using ICF and other simulation facilities for improving existing types of nuclear weapons [15].

	Fourth generation nuclear weapons overview:
Standard processes:	Improved designs (e.g., spark ignition) Rugged designs (e.g., deep penetrators)
Advanced processes:	Subcritical burn (see section 5) Magnetic compression (see section 7)
Exotic processes:	Superexplosives Superheavy elements Nuclear isomers Antimatter (see section 6) Etc. ?

5 Subcritical burn and microfission explosives

To address the question of subcritical explosives, it is useful to recall some elements of neutronics.

If k_∞ is the average number of neutrons produced by fission (and possibly by other processes) per neutron absorbed in an infinite medium, and l the number of escaping neutrons leaking out of a finite assembly, the effective neutron multiplication factor, or criticality factor, is $k = k_\infty - l$.

When the criticality factor $k = 1$, the number of neutrons remains constant, and the assembly is called "critical." This is the normal operation mode of a nuclear reactor in which one has a stable chain reaction. When $k > 1$, the assembly is "supercritical," and the number of neutrons increases exponentially with time. The chain reaction is divergent and leads to the explosion of the assembly. Finally, when $k < 1$, the assembly is "subcritical," and the number of neutrons decreases exponentially with time, which implies that there is no self-sustaining chain reaction. This does not mean, however, that a subcritical assembly cannot be used to produce nuclear energy or to make a nuclear explosion. In effect, since at each generation of neutrons, the number n of neutrons in the assembly is multiplied by k, the total number neutrons produced by an initial number $n(0)$ is

$$n(\infty) = n(0)(1 + k + k^2 + k^3 + ...) = \frac{n(0)}{1-k} \quad . \tag{1}$$

This series converges for $k < 1$. Thus, for a subcritical assembly, the initial number of neutrons is multiplied by a factor $G = 1/(1-k)$. For k close to 1, this *gain* factor can become very large. Hence, by injecting a sufficient number of initial neutrons into a subcritical assembly, it is possible to generate a large number of fissions, and thus to release a considerable amount of nuclear energy. This technique is called *subcritical burn.*

Figure 8, which is adapted from Ref. [40], is the results of detailed computer simulations of the subcritical burn of small pellets of plutonium. These pellets have weights of 14, 70 and 700 milligrams, and the goal of the simulation was to determine (as a function of compression) the number of initial neutrons required for 100% burn, which corresponds to the release of 240, 1'200 or 12'000 *kg* of fission energy. Obviously, yields of between 0.24 and 12 *tons* of TNT are of considerable military interest. Moreover, in subcritical burn, the quality of the fissile material is of little importance: reactor-grade plutonium is just as good as weapons-grade plutonium.[28]

Figure 8 shows that with a fissile material density on the order of 10^3 to 10^4 g/cm^3, i.e., for compression factors on the order of 100 to 1'000, the number of initial neutrons required for complete burn is about 10^{18}. In that same range, the compression work to reach the necessary plutonium density is equivalent to the energy content of about 100 g of chemical explosives. Assuming a 10% conversion efficiency of the chemical energy into compression work, this means that with 1 kg of high explosives and less than a gram of plutonium, it is possible (in theory[29]) to produce a very compact fourth generation fission explosive with a yield of several *tons.*[30]

Looking at Fig.8 again, it can be seen that at a sufficient compression the number of initial neutrons decreases dramatically. This is because when $k \to 1$, the gain increases as the assembly approaches criticality where, in principle, a single neutron is enough to start a chain reaction. This leads to the idea of *microfission explosives* in which a small pellet of fissile mate-

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[28] All isotopes of plutonium are fissile for fast neutrons, and the problem of preinitiation is absent in subcritical burn.

[29] To turn this concept into practice, two major problems are the compression method and the initial source of neutrons.

[30] The yield of non-nuclear warheads of modern missiles and gravity bombs is limited by weight to a maximum of about 0.1 to a few tons of TNT.

rial is driven to criticality by laser or other means [41, 42, 43]. At first, it was thought that this method could be used to ignite fusion materials [42], and thus to provide an easy route to ICF and almost pure-fusion explosives for military purposes. But it was soon discovered that a major difficulty with microfission was the problem of the initiation of the chain reaction [44]. Indeed, in microfission, the stagnation time of a highly compressed pellet is so short that the probability of a spontaneous fission releasing an initial neutron is negligible. Moreover, the use of an external source of neutrons is almost impossible because it is very difficult to deliver and focus a stream of neutrons onto a very small target at just the right time.

Hence, it was suggested that the initial neutrons could come from DT fusion reactions produced in the center [45] (or in the reflector [46]) of the fissile pellet. However, as with ICF pellets surrounded by a heavy tamper to increase the confinement time [47], it is always better to work with a pure fusion target than with a hybrid fusion-fission target. This is because DT is easier to compress than any heavier material, and because the specific energy content of DT is higher than that of fissile materials. Therefore, it is much more attractive to develop micro*fusion* rather than micro*fission* devices. Nevertheless, a micro*fission* device would in principle be an extremely compact source of x-rays that could be used to implode a more powerful fusion device.

Compared to microfission, the practical problems of subcritical burn are less acute. For one thing, the compression work is ten to a hundred times less than the energy necessary to reach criticality. Moreover, since subcritical burn does not depend on a self-sustaining chain reaction, but on an external supply of neutrons, 100% fission burn efficiency can be achieved in principle. Finally, contrary to microfission, subcritical burn is not restricted by the CTBT.

In summary, a critical or subcritical microfission device can in principle serve as a low yield explosive or as a primary to compress a higher yield fission or fusion pellet. To do that, it is necessary to find a means to achieve the required compression, as well as a suitable source of neutrons to initiate the fission reactions.

The problem with compression is that the maximum pressure and the detonation velocity of existing chemical explosives are not high enough to compress fissile materials to the required densities [48, p.9–10].[31] This can

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[31] The smallest amount of plutonium that can be made critical in a fast assembly is about 100 g. This corresponds to a compression factor of about ten and requires a very

readily be seen by referring to simple high-explosive compression theory (see, e.g., [49]). For instance, in a detonation, the maximum pressure is $p \propto \rho Q$ and the detonation velocity $v \propto \sqrt{Q}$, where ρ is the mass density and Q the specific energy density. Thus, for a typical high-explosive with $Q = 10$ kJ/cm^3 and $\rho = 1.9$ g/cm^3, one has $v = 0.8$ cm/μs and $p = 0.4$ Mbar $=$ 40 GPa. Looking at a standard equation of state table [50], one finds that applying this pressure to uranium would increase its density by a compression factor of $\rho/\rho_o \approx 1.3$. Since the mass of critical assembly decreases with the square of this factor, such a compression is enough to make a rudimentary implosion-type atomic bomb critical, but totally insufficient for a micro-fission explosive. In fact, the required specific energy density can be estimated from the Thomas-Fermi model assuming that the compressed material is reduced to a degenerate electron gas. In this limit, the pressure and the density are related by the expression $p \propto \rho^{5/3}$ so that $\rho \propto Q^{3/5}$. Hence, assuming that a compression of 10 can be achieved using existing technology and explosives, to increase the density of uranium, or plutonium, by another factor of 10 would require a "super-explosive" at least 45 times more powerful than any existing high-explosive.[32]

Compression to about 100 times normal metal density would therefore require a system of laser or particle beams — or the use of magnetic compression [51]. Both techniques enable high compressions, $\rho/\rho_o \approx 100-10000$, and high implosion velocities, $v \approx 10-100$ cm/μs. However, standard lasers and particle accelerators would probably be too large to make a transportable weapon. But the use of a superlaser to compress the fissile material, or to generate the particle beam, might result in a sufficiently compact device. In the magnetic compression approach, the problem would be to miniaturize the system converting the energy content of high explosives into the energy of electrical currents and magnetic fields.

To generate the number of neutrons required by the subcritical burn, or by the initiation of the chain reaction, an external neutron source is not practical. However, by focusing a beam of charged particles (electrons, protons, antiprotons, etc.) on the pellet, fission reactions can be induced by various high-energy reactions. This requires a compact accelerator. In the case of electrons, a superlaser could accelerate them to an energy of about 20 MeV, which would be sufficient to produce neutrons by electro- and photo-fission reactions in the pellet. Moreover, if sufficiently intense, the superlaser beam

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sophisticated implosion technology.

[32] Assuming a density of 1.3 g/cm^3, the calculated energy density of metallic hydrogen would by ≈ 270 kJ/cm^3, i.e., about 27 times more than that of a typical high-explosive [23, p.5].

itself could be focussed directly on the pellet: high energy electrons generated on the surface would cause electrofission and photofission in the material surrounding the focal volume [26]. Finally, a solution that would dispense with the need for a superlaser or a MeV-energy accelerator would be to direct a small amount of antiprotons at the pellet to generate the required number of initial neutrons [51]. As seen in Fig.8, less than a microgram of antiprotons would be sufficient for such a purpose.

6 Antimatter weapons

Matter-antimatter interaction produces more energy per unit mass than any other means of energy production. For example, proton-antiproton annihilation releases 275 times more energy in the form of kinetic energy of charged particles than nuclear fission or DT fusion. Moreover, when antimatter is brought into the proximity of matter, annihilation starts by itself, without the need of a critical mass, as in fission, and without the high-temperature and high-pressure needed in fusion. In short, it is an ideal nuclear trigger, provided that methods to produce and manipulate sufficient quantities of antimatter be found.

It is therefore not surprising that the concept of using antimatter as an energy source has been in scientific literature for decades [52], [53, p. 833], [54, p. 85–86, 97]. Other practical applications of antimatter are under consideration. These include, for example, antimatter propulsion systems, space-based power generators, directed-energy weapons, cancer therapy, etc.[33] Finally, both Edward Teller [56, 57] and Andrei Sakharov[34] [58, 59], two key scientists in charge of the development of the H-bomb in their respective countries, show in their published scientific works a major interest in the annihilation properties of antimatter, the nuclear process that after fission and fusion was expected to lead to a new generation of nuclear bombs.

Briefly, antimatter is produced in the following manner: protons are accelerated close to the speed of light and then projected at a target. The ensuing collision is so violent that part of the energy is transformed into particle-antiparticle pairs. In order for this to be possible, the proton has to be accelerated to an energy of at least 4.3 GeV. Once the accelerator was

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[33] An extensive bibliography on antimatter science and technology has been published in 1988 [55].

[34] In a 1968 article, Sakharov remarked: "The annihilation of 0.3 g of matter with 0.3 g of antimatter has the effect of an atomic-bomb blast" [58, p.218].

built in 1955 at Berkeley, antiprotons were "seen" for the first time. By injecting them into a liquid-hydrogen filled detector, the energy liberated in the explosive encounter of an antiproton and a proton was seen to rematerialize into a scatter of other particles (essentially pions shooting off in all directions) that carryed away most of the annihilation energy. To the weapons scientists, this was a big disappointment.

But Edward Teller and his student Hans-Peter Dürr did not stop there [56]. In 1956, they proposed a hypothesis: if instead of annihilating with a simple hydrogen nucleus, the antiproton annihilated with a proton or neutron situated in the heart of a complex atom, such as carbon or uranium, the nucleus in question would literally explode. This would result in a very large local energy deposition, thus raising the possibility again, of many civilian and military applications for antimatter.

Thirty years passed before a complex of machines necessary to accumulate and slow down antiprotons was conceived. The only system of this type in the world is at the European Center for Nuclear Research (CERN), at Geneva, Switzerland. Finally, it became possible to study, on a large scale, the meeting of antiprotons with nuclei. As a result, it has been possible to demonstrate that the energy deposition, although less than Teller (or others more recently [60]) had hoped for, is sufficient to assure the feasibility of military applications of antimatter. On the other hand, due to its very high cost and the enormous amount of energy needed to produce it, it has also become clear that antimatter could never become a usable source of energy for a power plant.

Thanks to the results of CERN, it was possible to publish in August 1985, an estimation of the number of antiprotons needed to start thermonuclear reactions, be it to ignite an H-bomb or to trigger the microexplosion of a thermonuclear fuel pellet [61]. It turns out that it is possible to build an H-bomb, or a neutron bomb, in which the three to five kilograms of plutonium are replaced by one microgram of antihydrogen. The result would be a so-called "clean" bomb by the military, i.e., a weapon practically free of radioactive fall-out because of the absence of fissile materials. For such a military use to be realistic, a technology capable of producing enough antiprotons for at least one antimatter trigger per day is needed. This corresponds to a minimum production rate of 10^{13} antiprotons per second, six orders of magnitude higher than possible at CERN today (10^7 antiprotons per second). However, there are numerous ways to increase this rate [61, 62, 63].

Since the summer of 1983, stimulated by the prospect of the imminent availability of antiprotons, the RAND Corporation had been carrying out a study for the U.S. Air Force "examining the possibilities for exploiting the high energy release from matter-antimatter annihilation" [62]. The RAND study was completed in 1984. The version published in 1985 constitutes a serious evaluation of the development possibilities for such an undertaking in view of military applications. According to this document, a definitive evaluation of the possibility of producing and manipulating 10^{13} antiprotons per second, and of constructing transportable antiproton reservoirs, could be realized by the early 1990s. This was felt to be possible because many important technological problems can be studied with ordinary particles instead of antiprotons. This same report mentions four main categories of applications: *propulsion* (fuel for ultra-fast anti-missile rockets), *power generators* (light and ultra-compact generators for military platforms in orbit), *directed energy weapons* (antihydrogen beams or pumped lasers relying on very-short-duration energy release) and *classified additional special weapons* (various bombs triggered by antimatter).

On the night of the 17th to the 18th of July 1986, antimatter was captured in an electromagnetic trap for the first time in history [64]. Due to the relatively precarious conditions of this first successful attempt, it was possible to conserve the antiprotons for only about ten minutes. This was, nevertheless, much longer than the Americans scientists, working at CERN under U.S. Air Force sponsorship [65], had hoped for. This result was particularly important to the Americans because many experiments that can only be carried out with antimatter are necessary to investigate the feasibility of the military applications of antimatter. As long as antiprotons made in Europe (on Swiss Territory) could be bottled and brought back to the United States, the RAND Corporation concluded that a production/accumulation facility, such as the one at CERN, although desirable, would not in the near future have to be built in the United States [62, p.43].

The immobilization of the first antiprotons, and their strategic consequences were the subject of several papers [66, 67]. These were later reproduced in a collection of articles on the subject of antimatter technology for military purposes, together with an assessment by prominent physicists working in the fields of disarmament or arms control [68].

In the following ten years, from 1986 to 1996, an enormous amount of research, both experimental and theoretical, was done on the many problems which directly or indirectly pertain to the practical applications of antimatter. In particular, a major issue is the development of simple and compact antimatter storage techniques. For this, two major approaches are being considered. The first consists of making antihydrogen by combining antiprotons with positrons. The first atoms of antihydrogen were synthesized at CERN in 1996 [69]. The next step will be to form solid antihydrogen pellets [70] which could be stored and manipulated with the help of various electromagnetic and optical levitation techniques. Very high storage densities would be obtained — but only in cryogenic enclosures and extremely good vacuums.

The most appealing approach, however, would be to store the antiprotons in ordinary matter. In fact, if all antimatter particles have a tendency to spontaneously annihilate when coming into contact with matter (whether from the effects of electromagnetic attraction, in the case of positrons and antiprotons, or from van der Waals forces for antihydrogen), the existence of metastable states of antiprotons in condensed matter can not be ruled out *a priori* [71]. For example, if a very low energy antihydrogen atom is diffused into a solid, it moves about until its positron annihilates with an electron. The antiproton may then take the place of this electron, and under some conditions, remain confined at certain points within the crystalline structure. At present, the kind of substance that could be used is not known, but an enormous variety of chemical compounds and crystal types may potentially provide an optimum material.

As low energy antiprotons became routinely available, a number of physical quantities of military interest could be precisely measured at the Low Energy Antiproton Ring (LEAR[35]) at CERN. For example, about 16 neutrons are produced by stopped annihilation in uranium [72].[36] This means that a relatively small number of antiprotons would be sufficient to initiate a chain reaction in a highly compressed pellet of plutonium or uranium. This could solve the initiation problem of microfission explosions because, contrary to neutrons, antiprotons can easily be directed and focused onto a very small target. In the United States, this option is being studied at the Los Alamos [73] and Phillips[37] laboratories [74].

However, as explained is section 5, subcritical burn is potentially a much more promising method for making a very-low-yield nuclear weapon: directed onto a subcritical assembly, antiprotons can initiate subcritical burn of fissile materials. This opens the prospect of making very-low-weight fis-

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[35] LEAR was an 80-meter circumference ring that permitted the storage and slowing of antiprotons down to energies as low as 5 MeV. It was the first large machine ever built to decelerate, rather than accelerate, particles. Commissioned in 1980, LEAR was shut-down in 1996.

[36] In compressed uranium targets, the average neutron yield per antiproton annihilation increases from 16 to about 22.

[37] "Phillips Laboratory" is the new name of the "Air Force Weapons Laboratory" at the Kirtland Air Force Base near Albuquerque, New Mexico.

sion explosives with yields in the sub-*kiloton* range. Experiments are under way at the Phillips Laboratory to investigate this possibility [51]. The types of devices under consideration are based on plutonium pellets with masses between 0.014 and 0.700 gram which would have yields of 0.2 to 12 *tons* of high-explosive equivalent. In order to trigger these pellets, which are compressed by means of magnetic compression, much less than a microgram of antiprotons is enough (see Fig.8).

For these experiments, American researchers expect to use antiprotons produced at CERN. "Bottled" in an electromagnetic trap, they will be sent to the Phillips Laboratory by air.[38] The design and construction of this trap has been undertaken by the Los Alamos National Laboratory [73] and is being tested at CERN. In 1996, more than one million antiprotons from a single LEAR shot were captured and up to 65% of the captured antiprotons were subsequently cooled and stored for up to an hour [76].

Another important application of antimatter to fourth generation nuclear explosives is the triggering of ICF pellets [77, 78]. For this purpose, as we had found in 1985 [61], an important issue is to transfer as much of the annihilation-energy as possible to the *DT* or *LiD* plasma.[39] An attractive possibility — which Edward Teller must already have considered in 1956 [56] — is to annihilate the antiprotons in some special material that would "explode" into light fragments that in turn would heat the plasma. For this and other reasons, numerous measurements have been made in order to study the annihilation properties of antiprotons in various nuclei. The prospect is that what has been observed in explosive multi-fragmentation of heavy nuclei bombarded with light-ions [80] could happen with antiprotons [81]. For example, it is expected that a gold nucleus containing 197 nucleons may break up into 40 or more pieces, mainly small clusters and individual neutrons and protons [81].

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[38] Reference [75, p.1418] gives the following details: "The portable trap is one meter tall, 30 cm across, and weighs 55 kg. It operates at 4 ^{0}K temperature, supported by cryogenic nitrogen and helium reservoirs, and has as a unique feature that the confining magnet is made of permanently magnetic *SmCo* materials, which should prove to be robust. This trap will be tested at CERN in late 1995, then sent to CERN for a fill and demonstration journey across Europe. We plan to return a filled trap to the U.S. in 1996 for experiments planned under USAF sponsorship." However, due to experimental difficulties and the shut down of LEAR in December 1996, no antiprotons were yet shipped from CERN to the United States.

[39] In spacecraft propulsion applications, the same problem exists because the propellant to be heated is generally a low-weight substance, e.g., hydrogen [79], in order to maximize the specific impulse.

If antimatter is to be used to for *indirect drive* ICF, the problems are significantly less. For example, antimatter could simply be used to activate a small x-ray source that would take the place of the "A-bomb" in Fig. 3, where the secondary would be the ICF pellet itself. This x-ray source could be a pellet of fissile material that would be fissioned and brought to very high temperatures following the annihilation a small amount of antiprotons on its surface. Apart from the capsule containing the fission and fusion pellets (i.e the "primary" and the "secondary"), the only other major components of the device would be a system to store the antiprotons, and an injector to focus them on the fissile material at the moment of ignition. The result is a miniature thermonuclear explosive that could possibly be made sufficiently small and lightweight to make a weapon. Of course, there are many possible variations for designing such a device. Moreover, both the primary and the secondary could be made of more exotic materials than those used in contemporary microexplosion experiments.

At the present time, three main laboratories are involved in the production of antiprotons: CERN (Switzerland and France), FNAL (USA) and the Institute for High Energy Physics (IHEP) at Serpukhov (Russia). These laboratories use large accelerators to produce antiprotons in very small amounts.

The use of superlasers may result in conversion efficiencies one million times higher than those achieved with the use of accelerators [30]. For this purpose, high-energy superlasers with extremely short pulse durations are mandatory [57, p.9–10]. In effect, the first published estimates of laser production of proton-antiproton pairs showed that this process would need a superlaser with an intensity of at least 10^{18} W/cm^2 [29, 53] — a relatively modest intensity by today's standards. In this calculation, the actual generation of proton-antiproton pairs is by the so-called trident (or Bhabha) process. This requires the laser beam to be very precisely focused onto a 30×10^{-6} m radius solid hydrogen pellet. However, later estimates showed that this process would in fact need a more powerful CO_2 superlaser, i.e., a driving energy of about 1 MJ, a minimum intensity of 10^{23} W/cm^2, and a pulse length of about 0.3 ps [30]. These requirements are enormous, but "only" about a factor 100 or 1000 away from the LLNL "Petawatt" $Nd : glass$ laser design characteristics, i.e., 1kJ at 10^{21} W/cm^2 in 0.5 to 20 ps [16, 20].

Beside the trident process, there are other methods to produce antimatter with a superlaser. The most promising is to collide a powerful laser-beam with a high-energy particle-beam. For example, with an electron beam, positrons can be produced by the so-called "multi-photon Breit-Wheeler electron-positron pair production process". This method has recently been successfully demonstrated, using a tabletop superlaser generating 1.6 ps long pulses of 0.65 J energy and an intensity of 10^{18} W/cm^2, in collision with the 46.6 GeV electron-beam of the Stanford linear accelerator (SLAC) [28, 82]. Because real photon-photon pair-creation had never been observed before in the laboratory, this was "the first creation of matter out of light" [82]. To use this method for the production of antiprotons instead of positrons would need a much more powerful laser. It would also require a careful comparison with the trident and other processes that have the potential to make antimatter with superlaser systems.

In the near future, independent of the availability of superlasers, various experiments on the production of antimatter (i.e., electron-positron pairs) are planned at NIF [83].

At the end of 1996, CERN's LEAR facility was decommissioned as part of a major reorganization of the CERN accelerator complex in view of the construction of a new very large accelerator —the Large Hadron Collider (LHC) — which will be the highest-energy hadron accelerator ever built.[40] The construction of LHC will start in the year 2000 and last about five years. In order to continue its program of research on antimatter — which will be the only major physics research program at CERN in the years 2000 to 2005 — a new antiproton source, the Antiproton Decelerator (AD), is being constructed [84].

Beginning in 1999, there will be two major experiments at the AD, with participants from the United States, Germany, Denmark, Italy, Poland, the Netherlands, Korea, and Japan. Both experiments include participants which are supported in part by the U.S. Air Force antimatter technology program, e.g., [85, 76]. A third experiment will be by a Japanese-European collaboration to continue the search for metastable states of antiprotons in ordinary matter.

In the beginning of the next millennium, there will be enough antiprotons for more than these three antimatter experiments at CERN. Moreover, using antiprotons produced and trapped at CERN, numerous other experiments will be conducted in various American and European laboratories.[41] Apparently, the only competition will come from Japan, where low-energy antiprotons should become available around the year 2003.

Today, antimatter research is possibly the most important and vigorous of

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[40] For instance, LEAR will be used as a heavy-ion accumulation ring for the LHC.

[41] In this perspective, the AD system is optimized for antiproton transfer to the traps [84].

the fourth-generation nuclear weapons research and development programs.[42] The reason is because matter-antimatter annihilation does not pose any fundamental research problem anymore: its military use is now mostly a question of technological development.

7 Pure fusion weapons

In a June 1994 interview, the Russian Nuclear Energy Minister Viktor Nikitovich Mikhailov[43] made the following statement:

> “ a new generation of nuclear weapons could be developed by the year 2000 unless military research is stopped. [... This] fourth generation of nuclear weapons could be directed more accurately than current arms. [... The] new weapons could be programmed to wipe out people while leaving buildings standing. [... It is] a toss-up whether Russia or the United States would be the first country to devise the new arms” [86].

In 1980, the question of the links between ICF and pure-fusion weapons was raised by W.A. Smit and P. Boskma [87]. This publication — one of the rare well-informed publications on this subject to appear in the arms-control/disarmament literature in the period 1975–1990 — was based on a report published in 1978, see [7, Ref.6].

On 25 April, 1996, a few months after the CTBT negotiations were concluded, Hans Bethe, who directed the Theoretical division at Los Alamos during World War Two, wrote a letter to President Clinton — referring to the fact that pure-fusion explosive are scientifically feasible and militarily attractive — to ask the U.S. Government *to ban* “all physical experiments, no matter how small their yield, whose primary purpose is to design new types of nuclear weapons” [88], [89, p.438].[44]

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[42] This leading position is only challenged by inertial confinement fusion and superlaser research.

[43] V.N. Mikhailov is one of the scientists who helped develop the current generation of nuclear weapons. He is also the editor of the compilation *Nuclear Explosions in the USSR* (Khlopina Radium Institute, Moscow, 1994).

[44] Hans Bethe’s letter to President Clinton, and later President Clinton’s answer of 2 June 2 1997, were distributed by the Federation of American Scientists at the same time as an analysis of the question of pure fusion explosions under the CTBT [90]. See also [48, 91].

However, as for full-scale nuclear explosions, there is no way to distinguish between "military" and "peaceful" microexplosions at ICF facilities such as Nova, Gekko, NIF, LMJ, etc. Therefore, the acceptance by the U.S. Government of Bethe's proposal would be equivalent to recognizing that the Science Based Stockpile Stewardship (SBSS) program and powerful ICF facilities such as NIF could lead to a fourth generation of nuclear weapons. Moreover, Bethe's proposal would require to changing the official interpretation of the scope of the CTBT in such a way that microexplosions would be banned. This is almost impossible, especially since the SBSS program and the construction of the NIF were *accepted* by the U.S. Government in order that the nuclear weapons laboratories *accede* to the *Comprehensive* Test Ban Treaty (CTBT), signed in September 1996.

In fact, long before the CTBT, and even before the the *Partial* Test Ban Treaty (PTBT) of 1963, and in particular during the 1958–1961 moratorium on nuclear tests, there has been considerable research on pure-fusion concepts at all nuclear weapons laboratories. We will not review this work in detail[45] but will attempt to give an overview of the kinds of technologies that have been (and are still) considered as candidates for making pure-fusion (i.e., fission-free) explosives:

- *Chemical explosives* can be used to implode small amounts of fusion fuel (e.g., DD or DT gas), resulting in measurable production of fusion neutrons. In 1977, using a concentric explosion with an exceptional degree of symmetry, a group of Polish scientists were able to produce 3×10^7 neutrons by purely explosive means. The publication of this result in the journal *Nature* [93] prompted a letter from Russia, recalling that similar results had already been made public in 1958 at the Second international conference on the peaceful use of atomic energy in Geneva [94]. Moreover, as early as 1955, 10^8 neutrons per shot were generated in USSR. In 1963, for UD_3 and gaseous D_2 targets, this number increased to 3×10^{11}.

Similar research has been done in Western countries. But only few results have been made public. For example, in an experiment made in collaboration between a Canadian and an Israeli scientist, an explosive driven implosion facility was used to produce a few 10^3 fusion neutrons in a $D_2 - O_2$ mixture [95].

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[45] One should nevertheless mention that, as part of their respective PNE programs, both the American and Soviet laboratories developed very-low-fission-yield thermonuclear explosives. In the case of the Soviet program, a thermonuclear explosive was developed in 1970 which had less than 0.3 kt of fission-yield for a total yield of 15 kt, i.e., a "98% pure" fusion explosive [92, p.20].

At present, the largest published neutron yield from a chemical explosive driven device is $1 - 4 \times 10^{13}$ [96]. This result was obtained with a spherical chemical explosive device of 375 mm in diameter imploding a multilayered medium in order to achieve a higher energy cumulation level (compared to a homogeneous media). However, since this experiment used DT [97] (which under similar conditions produces about 100 times more fusions that DD), the progress relative to 1963 is not significant. This illustrates the considerable difficulty of initiating thermonuclear fusion with chemical explosives alone. In particular, while elementary consideration indicate that the temperature and pressure may reach infinity in the center (or on the axis) of a device, various imperfections and the onset of instabilities is usually limiting the amount of energy cumulation achievable in practice [98].[46]

In fact, since existing types of chemical explosives cannot create sufficiently fast and strong detonation waves, the temperature and the degree of compression achieved are always such that the thermonuclear yield is smaller than the energy of the chemical explosives used in the device. However, the results obtained in the Russian experiments show that the thermonuclear burn occurred at a temperature of about 0.65 keV [96] and that the device was only two orders of magnitude below the ignition threshold [97]. Therefore, the discovery of some powerful chemical super-explosive, or the synthesis of metallic hydrogen, may reverse this situation.

- *Impact fusion.* Instead of compressing a thermonuclear fuel by means of a spherical device (with or without velocity multiplication to increase the cumulation of energy) it is possible to take advantage of the possibility to accelerate a macroscopic object to high velocity and then to use its kinetic energy to compress and heat a target [100, 101]. This technique may deliver the few MJ of energy in a time period of about 10 ns into a volume of less than 1 cm^3 that is necessary to ignite a thermonuclear fuel. Since the target has often the shape of a conical DT region embedded in a heavy metal slab, the concept is sometimes called "conical target fusion" instead of "impact fusion". There are a number of variations for this technique: e.g., the thermonuclear fuel might be embedded in the projectile rather than in the fixed target, or two projectiles of opposite rectilinear motion might be fired against each other and around some fusile gas.[47]

The first significant result using a flat flyer plate accelerated by chemical explosives, i.e., the production of 10^6 DD-fusion neutrons, was published

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[46] A few interesting comments on the difficulty of initiating a thermonuclear explosion with nothing but high explosives can be found in [99, p.50-51].

[47] The same techniques could be used to compress a small amount of *fissile* material.

in 1980 [102]. In that experiment, the flyer was accelerated to a velocity of 5.4 km/s. Since then, little progress seems to have been made. Recently, however, a 5 g mass plate was accelerated to a velocity of 10.5 km/s, a world-class achievement, using $\approx$ 50 kg of explosives [103]. But this would not be sufficient to achieve much higher thermonuclear yields.

In fact, to reach ignition, impact fusion requires a projectile with an energy of about 10 MJ, which means accelerating a 0.5 g object to a velocity of about 200 km/s [104, p.iv]. To achieve such velocities, other techniques than high explosives have to be used: electron beam or laser beam acceleration, or electromagnetic guns [105]. However, as shown by a simulation published in 1987, a velocity of 25+25 km/s may in theory be sufficient to yield up to 10^9 DD-fusion neutrons per head-on impact of two colliding shells [106].

Further progress might be achieved by magnetizing the fuel within the projectile or the target.[48] Impact fusion with magnetized fuel targets has the advantage that much lower velocities ($\approx$ 10 km/s) could conceivably be used instead of the 200 km/s value usually quoted as necessary for small high-density unmagnetized pellet implosions [107].

Finally, high velocity impact could be used as an *indirect* driver for imploding an ICF pellet [108]. The idea is that instead of compressing a small amount of thermonuclear fuel, an impact fusion driver could be used to generated x-rays in a cavity containing an ICF pellet, or to compress a cavity containing a preexisting blackbody photon gas that is imploding an ICF pellet by ablative compression. Therefore, as high-gain ICF pellets will become available, impact fusion driver technology will provide a compact igniter for such pellets.

- *Magnetic Confinement Fusion (MCF)* research and development was long classified in Unites States under the code names *Sherwood* and *Matterhorn.* In particular, it was thought that some MCF schemes (e.g., "pinch effect" devices, the most widely and intensively approach studied at the time, e.g., [109]) could lead to pure-fusion explosives. In this technique, a large current is heating a narrow plasma column which is "pinched" by its own magnetic field. The plasma is compressed, and neutrons are produced. Unfortunately, the pinch is very quickly disrupted by instabilities, so that the concept can only be used as the basis for a pulsed device. In fact, after decades of improvements, it turned out that the pinch effect is possibly much more effective as a powerfull x-ray generator, rather than a thermonuclear fusion device, Therefore, its most promising application today is as an *indi-*

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[48] This concept is discussed below in a more general perspective.

rect driver for ICF [13]. For instance, at the Sandia National Laboratory, the Saturn pulsed-power-driven Z-pinch produces about 0.5 MJ of x-rays in 5–30 ns, and the Particle Beam Fusion Accelerator (PBFA-Z) about 1.5 MJ, also in 5–30 ns [13, p.1820]. Considering that the big megajoule lasers which are under construction will yield at most 1.8 MJ of low-energy photons, that still have to be converted into x-rays, the x-ray outputs of the pinch machines are enourmous. This is even more impressive considering that a Z-pinch machine is much smaller and less costly that a laser facility of comparable energy. In fact, implosion experiments with simple ICF targets containing deuterium fuel are planned for 1998 at PBFA-Z. They are expected to yield about 10^{12} DD-fusion neutrons per shot [91, p.19].

- *Magnetized fuel and magnetic compression* devices are based on the old idea that magnetic field can serve to thermally insulate the fuel from the walls and to localize α-particle[49] energy deposition in the fuel after ignition. This is of course what is done in MCF. But the same principle can be applied to a high density plasmas where the magnetic field also decreases thermal conductivity and improves energy deposition. These effects are particularly pronounced when very strong magnetic fields are generated, either by mechanically compressing a liner (i.e., a metallic receptacle) containing a magnetized fuel, or by magnetic compression of such a liner.

Magnetic compression can be driven by a capacitor bank [110] or by chemical explosives [111]. The technology of these energy cumulation devices is based on classical physics and has been under development for a long time [112, 113, 33]. It is a domain in which Russian scientists have invested a lot of effort since the early 1950s [113, 114]. Because self-destructive high-explosive driven experiments are in general less expensive than capacitor-bank experiments, the former has been preferred in Russia, whereas big reusable electromagnetic implosion facilities have become the speciality of the Western laboratories.[50]

In Russia, a concept called “MAGO,” proposed in 1979 by V.N. Mokhov [115], enabled the stable production of 4×10^{13} fusion neutrons from the magnetic compression of a 10 cm radius, 15 cm length, chamber filled with DT gas [116].

In the Unites States, the technique of magnetic compression is under investigation using non-destructive devices, such as the “Shiva-Star” facility

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[49] I.e., the He ions produced in DD or DT fusion reactions.

[50] But, of course, the high-explosive driven devices have a much greater potential to be made compact and light-weight.

at Philips Laboratory [117], or explosive devices, such as "Procyon" at Los Alamos. Procyon is an explosive pulsed-power system designed to drive 1-MJ plasma z-pinch experiments [118].

The concept of electromagnetic implosion of cylindrical plasmas shells (i.e., imploding plasma liners or hollow Z-pinches) has become a speciality of the Phillips Laboratory (formerly, *Air Force Weapons Laboratory* at Kirtland Air Force Base, New Mexico). These imploding liners can be used as intense sources of neutrons or x-rays. In 1980, for instance, neutron yields of $\approx 10^7$ and x-ray yields of > 1 kJ above 150 eV have been obtained[119]. This experiment used a 1.1 MJ facility. Today, the "Shiva Star" magnetic compression facility is the world's largest pulsed-power, fast-capacitor bank. It is activated by a 1.2 MA, 4.8 MJ electric capacitor discharge [120, 121]. In 1995, a Shiva Star experiment in which a 4 cm radius, 0.1 to 0.2 cm thick, aluminum shell was compressed to 16.8 g/cm^3, demonstrated the feasibility of electro-magnetically driven spherical liner implosion in the cm/μs regime [117]. This technique is being developed, in particular, for antiproton-driven subcritical microfission burn (see section 5).

The chemical explosive approach to magnetic compression is now the object of a major collaboration between Los Alamos and Arzamas-16 [111]. The first ever joint scientific publication of a team of American and Russian nuclear-weapon scientists was the result of this collaboration [122]: A hot plasma was produced and 10^{13} DT fusion reactions were observed — possibly the maximum ever in a high-explosive driven experiment performed outside of Russian territory. According to the authors of this publication, these experimental results are in reasonable agreement with computations suggesting that the technique could be used to yield 1 GJ of fusion energy, i.e., a yield equivalent to 250 kg of TNT. The prospect of a militarily useful explosive based on this concept has been examined in detail in a recent assessment of the arms-control implications of such type of pure-fusion devices [91].

In the future, much more powerful magnetic compression experiments will be conducted at the Nevada Test Site. A facility named "High-Explosive Pulsed Power Facility" is described in the Stockpile Stewardship and Management Programmatic Environmental Impact Statement. "In broadest terms, the facility could support experiments that could make 100 to 1'000 MJ of electrical energy available to power experiments. Typical proposed experiments could involve 4'536 kg (10'000 lb) or more of conventional high explosives in a variety of configuration" [123, p.A-15].

- *Beam-driven devices*, in which a powerful radiation (light or x-rays) or current (of heavy-ions, light-ions, electrons, or antiprotons) is used to evaporate the surface of a fusion- or fission-fuel pellet (resulting in a colossal reaction-pressure which implodes the fuel) are today's most important devices used to study primaries and secondaries of pure-fusion bombs. Whether or not very-compact lasers, superlasers, or particle-beam-generators can be designed (thus opening the possibility of *beam-triggered pure-fusion bombs*), beam-driven inertial confinement fusion enables the development of the technology of mini-secondaries for pure-fusion devices. Militarization of these devices will than be a matter a miniaturizing some kind of direct or indirect driver, e.g., of the kind we have described in this section.

To this list should be appended a number of other more or less promising concepts — and possibly some classified ones. Nevertheless, the progress made in at least two of these techniques (namely inertial confinement fusion and magnetic compression) is so impressive,[51] that "pure-fusion" and "subcritical microfission" explosives are today very close to becoming technologically feasible.

8 Conclusions

Let us summarize, in telegraphic style, the main conclusions of this study:

1) Technical conclusions

- ICF and pulsed power technologies are effective substitutes for underground nuclear tests.

- ICF and subcritical burn studies enable the development of new types of nuclear explosives.

- Chemical explosive driven pure-fusion devices are feasible: *They may have 1–100 tons of TNT equivalent explosive yield and weights in the 0.1–1 ton range.*

- Very compact low-yield two-stage devices are feasible: *The secondary could be 1–10 tons of TNT equivalent reactor-size ICF pellet and the primary a 0.1–1 GJ x-ray source driven by an exotic material such as antimatter.*

- Such devices could be built within the next few decades.

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[51] It is interesting to note that much of this progress happened in the few years that preceded the final negotiation and signature of the CTBT.

2) Political conclusions

- As emphasized by the critics of the CTBT, e.g., India, the development of new types of nuclear explosives is not stopped by this treaty.

- If the nuclear weapon States go ahead in developing fourth generation nuclear weapons, it is likely that countries like India will become declared nuclear powers.

- All modern industrialized countries are working on the science and technology related to these devices.

- The development of the most advanced types of fourth generation nuclear weapons is not restricted to the declared nuclear weapon States. For instance, Japan and Germany are working hard on all the technologies applicable to these weapons.

- This may lead to a nuclear arms race in which all modern industrialized countries (e.g., Japan, France, China, Germany, etc.) could compete to become the second largest military power in the next century.

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Particle beam driven ICF facilities						
Country	System name	Location	Energy [kJ]/[ns]	No. beams		
Particle beams						
USA	Saturn	SNL	400/5	36	—	
	PBFA-II-Z	SNL	1500/20	36	—	
	ILSE	LBL	6400/10	16	—	D
Germany	KALIF	Karlsruhe	40/40	1	—	
	HIBALL		5000/20	20	—	D

Table 1: Major operating or planned particle-beam driven ICF facilities. In the last column D means that the facility is in the design stage.

Inhaltsverzeichnis

aser beam driven ICF facilities

Country	System name	Location	Energy [kJ]/[ns]	No. beams	Wave length	
Glass lasers						
USA	Omega	LLE	3/0.6	24	0.35	
	Omega-UG	LLE	40/3	60	0.35	C
	Nova	LLNL	50/1	10	0.35	
	NIF	LLNL	1800/5	192	0.35	D
Japan	Gekko-XII	Osaka	20/1	12	1.06	
	Kongoh	Osaka	300/3	92	0.35	D
	Koyo	Osaka	4000/6	400	0.35	D
France	LULI	Palaiseau	0.5/0.6	6	1.06	
	Octal	Limeil	0.9/1	8	1.06	
	Phbus	Limeil	14/2.5	2	0.53	
	Mgajoule	Bordeaux	1800/15	288	0.35	D
China	Shen-Guang-I	Shanghai	1.8/1	2	1.06	
	Shen-Guang-II	Shanghai	6.4/1	8	1.06	
	Shen-Guang-III	Shanghai	60/1	60	0.35	D
UK	Helen	AWE	1/1	3	0.53	
	Vulcan	RAL	3/1	6	0.53	
Russia	Delfin	Moscow	3/1	108	1.06	
Italy	ABC	Frascati	0.2/2	2	0.53	
Israel	ALADIN	Soreq	0.1/3	1	1.06	
	Continuum	Soreq	0.07/7	1	1.06	
Germany		GSI	0.1/15	1		
		GSI	1/	1		D
Korea	Sinmyung-I	Taejon	0.08/0.5	1	1.06	
India		Bombay	0.05/5	1	1.06	
KrF lasers						
USA	Mercury	LANL	1/5	1	0.25	
	Nike	NRL	5/4	56	0.25	C
Japan	Ashura	Ibaraki	0.7/15	6	0.25	
	Super-Ashura	Ibaraki	7/22	12	0.25	C
UK	Sprite	RAL	0.09/60	6	0.25	
	Titania	RAL	0.85/0.5	1	0.27	
China	Tin-Guang	Shanghai	0.4/	1		
Iodine lasers						
Russia	Iskra-5	VNIIEP	15/0.25	12	1.30	
Germany	Asterix IV	Garching	2/5	1	1.30	
	Asterix IV	Garching	1/0.3	1	1.30	

Table 2: Major operating or planned laser driven ICF facilities. In the last column C means that the facility is under construction and D that it is in the design stage. The wave length is in μm.

Superlasers

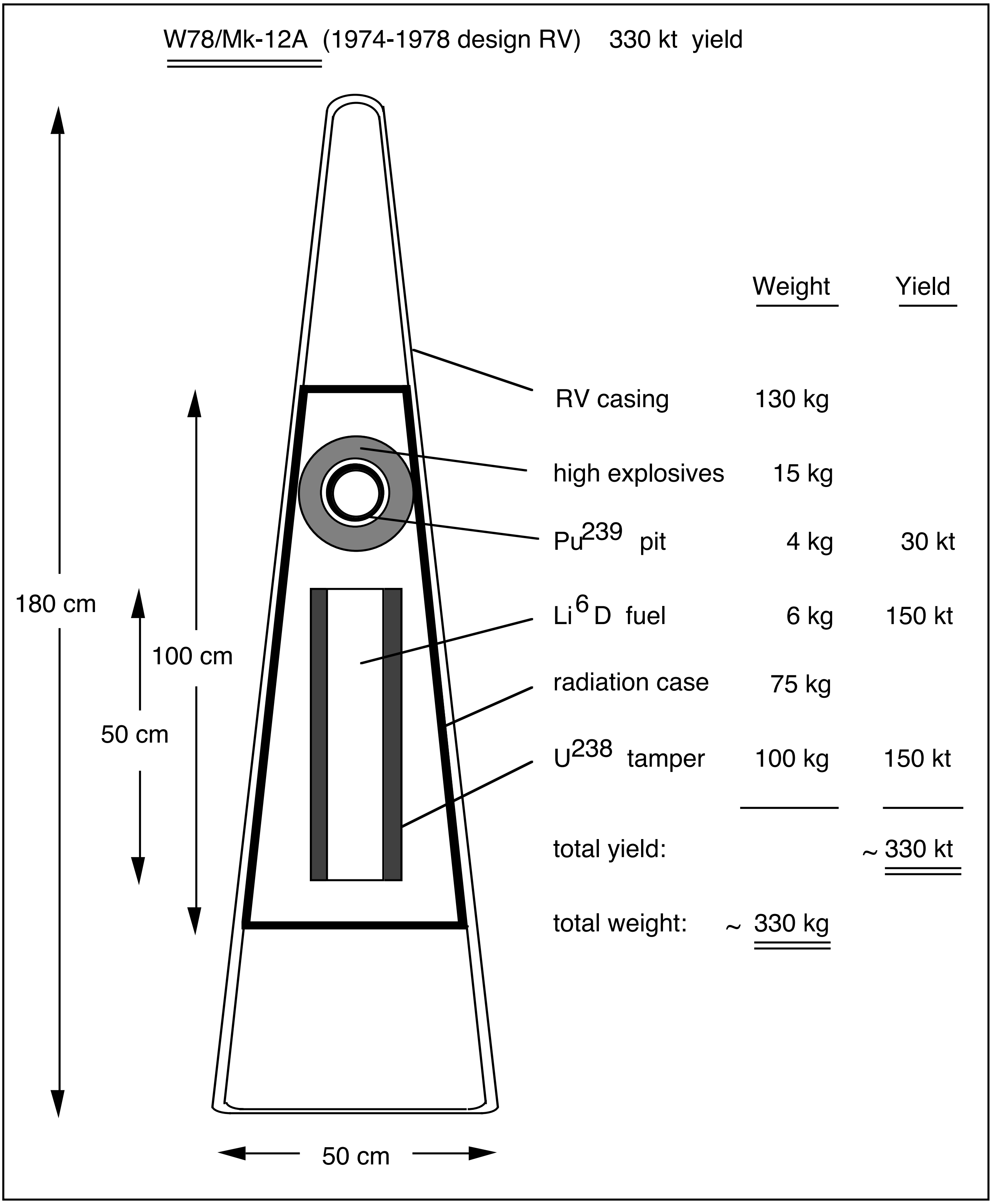
Name	Location	Energy [J]	Duration [ps]	Power [TW]	Intensity [W/cm^2]
USA					
Petawatt	LLNL	1000.00	20-0.500	1000.0	$> 10^{21}$
	UM, Ann Arbor	3.00	0.400	4.0	4 10^{18}
Trident	LANL	1.50	0.300	5.0	$> 10^{19}$
	UC, San Diego	1.00	0.020	50.0	
LABS II	LANL	0.25	0.300	$\sim$ 1.0	1 10^{19}
	UI, Chicago	0.15	0.500	0.3	1 10^{18}
	UM, Ann Arbor	0.07	0.025	3.0	
	WSU, Pullman	0.06	0.026	2.0	
	Stanford U.	0.06	0.120	0.5	$> 10^{18}$
UK					
Vulcan	RAL	180.00	1.000	200.0	1 10^{20}
Titania	RAL	1.00	0.400	$\sim$ 2.5	
Sprite	RAL	0.25	0.380	$\sim$ 0.7	4 10^{17}
Japan					
Petawatt	ILE	1000.00	0.500	1000.0	Design
	ILE	100.00	0.500	100.0	
Petawatt	APRC	30.00	0.030	1000.0	Design
	RIKEN	0.05	0.500	$\sim$ 0.1	1 10^{17}
France					
Petawatt	CESTA, Bordeaux	1000.00	1.000	1000.0	Design
P-102	CEL-V, Limeil	25.00	0.400	55.0	$> 10^{19}$
	LOA, Palaiseau	0.80	0.030	30.0	5 10^{19}
	LOA, Palaiseau	0.03	0.100	$\sim$ 0.3	1 10^{18}
ELIA	U. of Bordeaux	0.01	0.010	1.0	1 10^{18}
Germany					
	MBI, Berlin	10.00	0.030	$\sim$ 100.0	Constr.
Atlas	MPQ, Garching	1.50	0.150	$\sim$ 10.0	Constr.
	MBI, Berlin	0.30	0.032	$\sim$ 10.0	$< 10^{19}$
	MPQ, Garching	0.22	0.150	$\sim$ 1.5	$< 10^{18}$
Russia					
	St. Petersburg	0.50	1.500	$\sim$ 3.0	1 10^{17}
China					
BM				$\sim$ 3.0	

Table 3: Major operating superlaser facilities

	atomic processes	**nuclear processes**
standard processes	chemical detonation lasers	fission fusion acceleration
advanced processes	magnetic compression atomic isomerism x-ray lasers superlasers	subcritical fission nuclear isomerism γ-ray lasers muon catalysis antimatter
exotic processes	metallic hydrogen atomic clusters etc.	superheavy nuclei bubble nuclei halo nuclei etc.

Table 4: Major atomic and nuclear processes of importance to present and future military explosives

Inhaltsverzeichnis



	Weight	Yield
RV casing	130 kg	
high explosives	15 kg	
Pu^{239} pit	4 kg	30 kt
$Li^{6}D$ fuel	6 kg	150 kt
radiation case	75 kg	
U^{238} tamper	100 kg	150 kt
total yield:		~ 330 kt
total weight:	~ 330 kg	

Figure 1: The weight of the W78 warhead is about 200 kg for a total MK-12A reentry vehicle weight of 330 kg. This corresponds to a yield to weight ratio of 1.65 .

Inhaltsverzeichnis

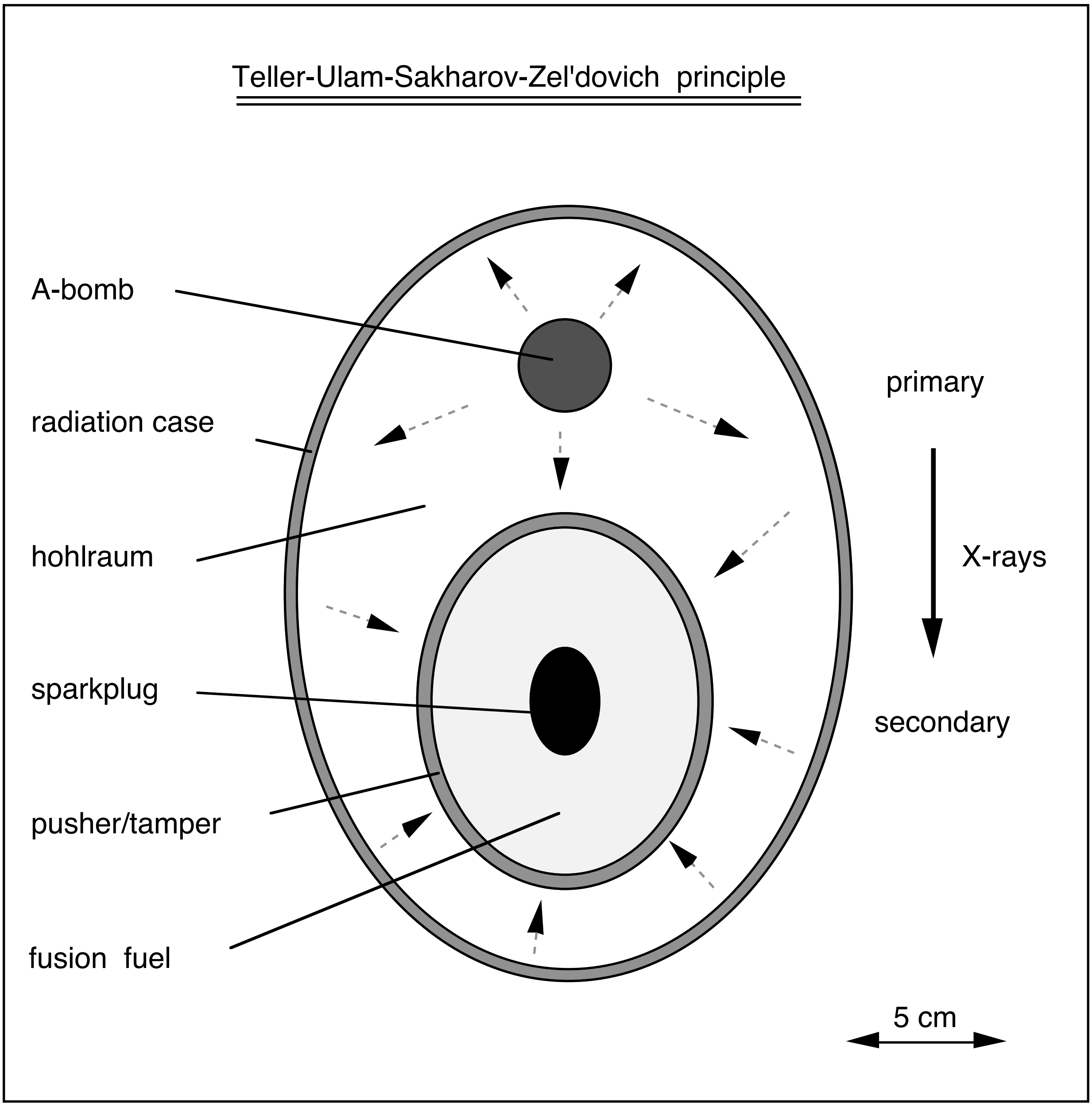


Figure 2: *"In thermonuclear weapons, radiation from a fission explosive can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel. (February 1979)"*.

Reference: U.S. Department of Energy, Office of Declassification, "*Drawing back the curtain of secrecy - Restricted data declassification policy, 1946 to present*", RDD-1, (June 1, 1994) page 94.

Inhaltsverzeichnis

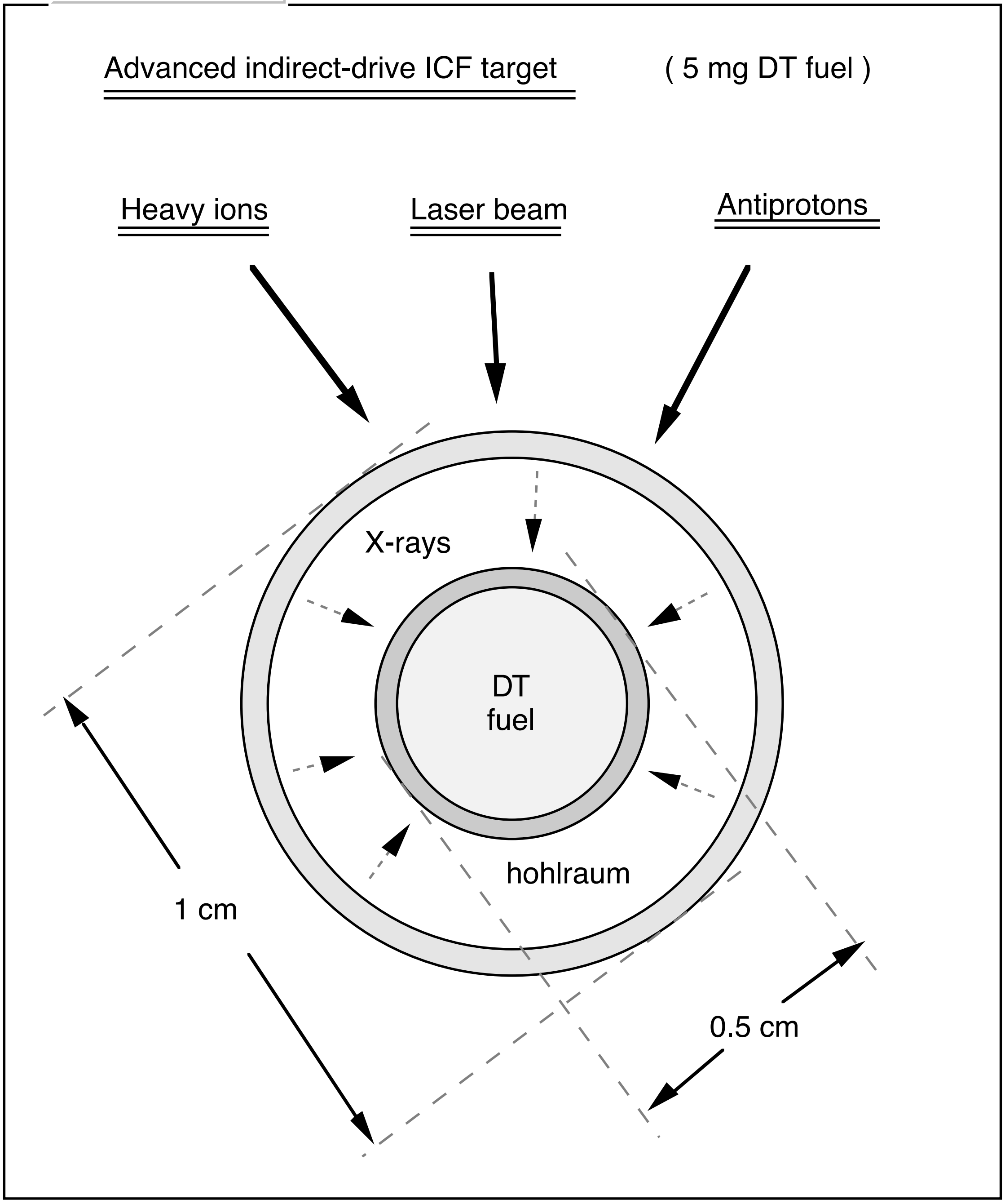


Figure 3: *"In some ICF targets, radiation from the conversion of the focussed energy (e.g laser or particle beam) can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel. (February 1979)"*.

Reference: U.S. Department of Energy, Office of Declassification, *"Drawing back the curtain of secrecy - Restricted data declassification policy, 1946 to present"*, RDD-1, (June 1, 1994) page 103.

Inhaltsverzeichnis

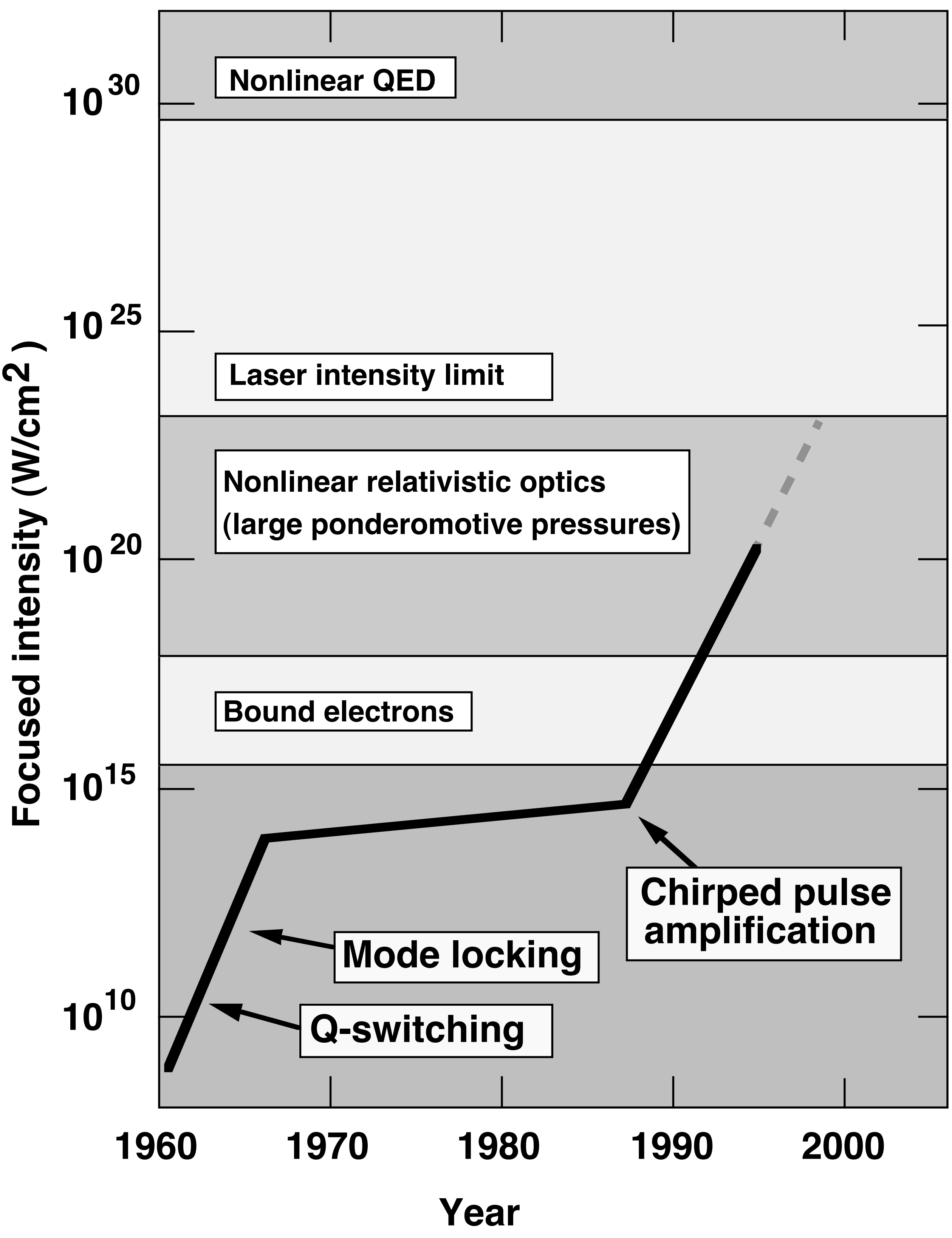


Figure 4. Laser intensity versus year for tabletop systems. Over the past decade the intensity has increased by a factor of one million. *Adapted from G. Mourou et al., Physics Today (January 1998) p. 25.*

Inhaltsverzeichnis

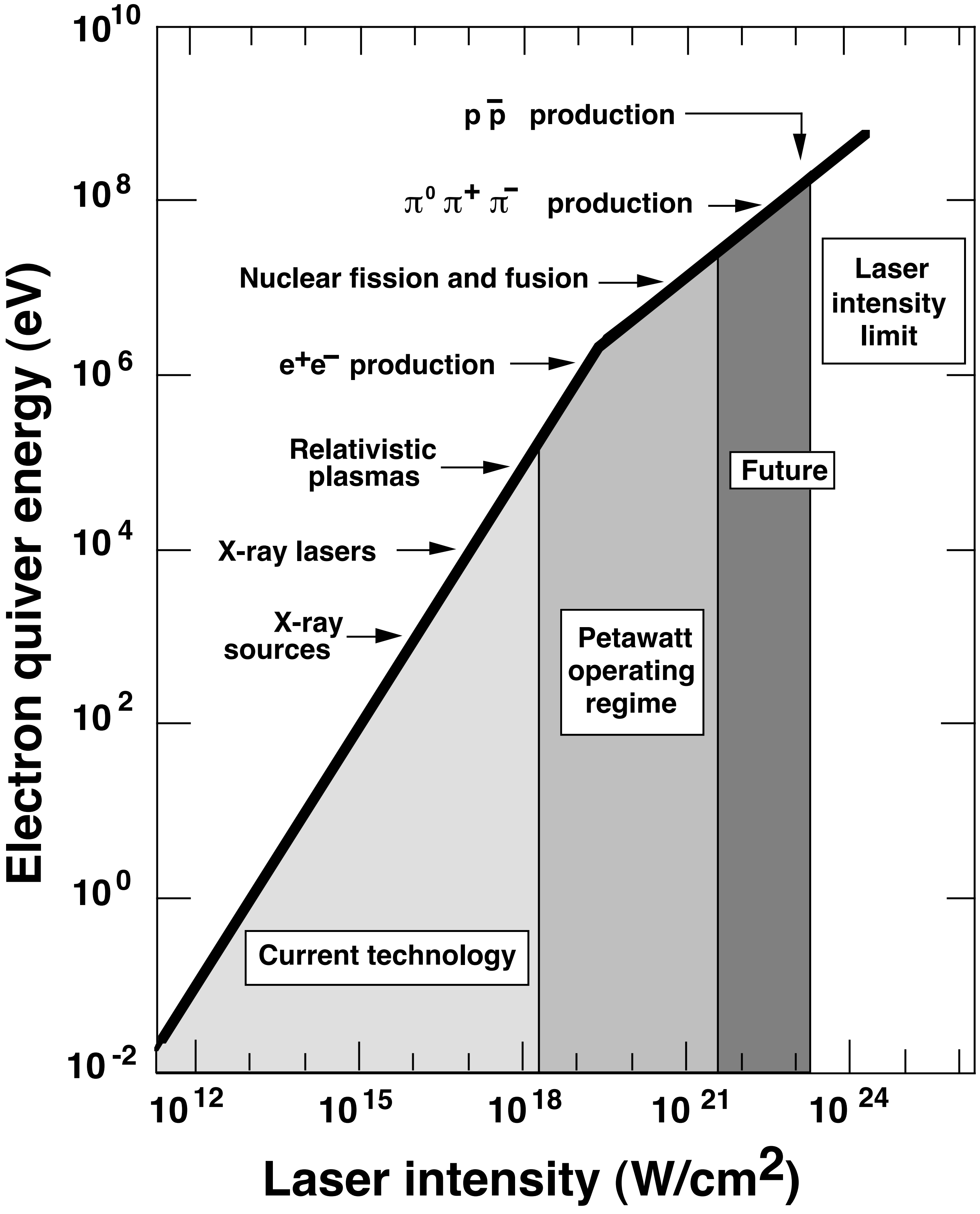


Figure 5. Electron quiver energy and accessible phenomena as a function of *Nd:glasss* laser intensity. The quiver energy is the cycle-averaged oscillatory energy of free electrons in the laser field. The break at 10^{19} W/cm^2 corresponds to quiver energies on the order of the electron mass, i.e., to the beginning of the relativistic regime characteristic of superlasers. The 10^{23} W/cm^2 threshold intensity for proton-antiproton pair production assumes a CO_2 laser. *Adapted from M.D. Perry and G. Mourou, Science (14 May 1994) p. 918.*

Inhaltsverzeichnis

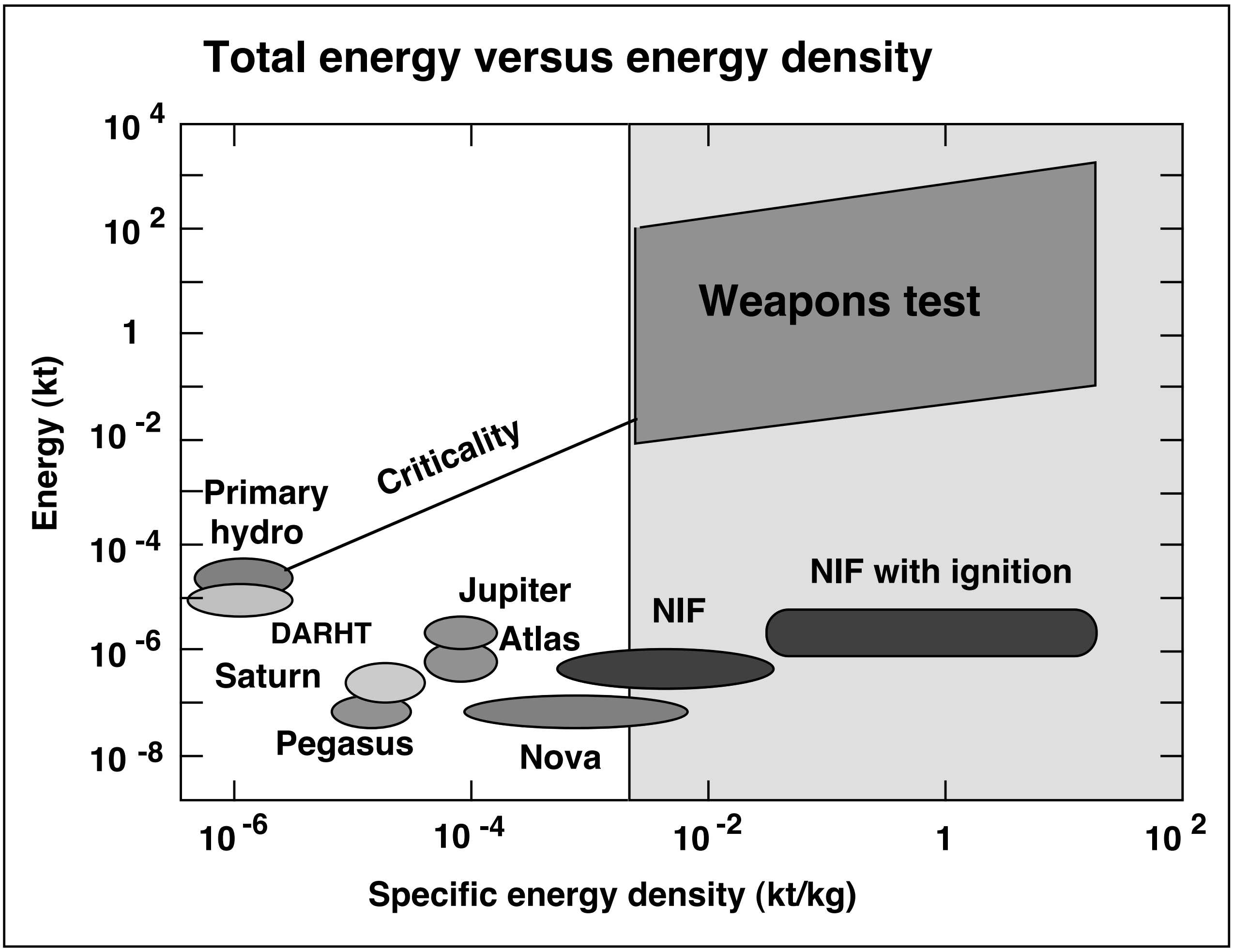


Figure 6. Total energy versus energy density for primary hydrodynamic tests (DARHT), pulsed power facilities (Saturn, Pegasus, Atlas and Jupiter), inertial confinement fusion facilities (NOVA and NIF, and weapons tests.

Inhaltsverzeichnis

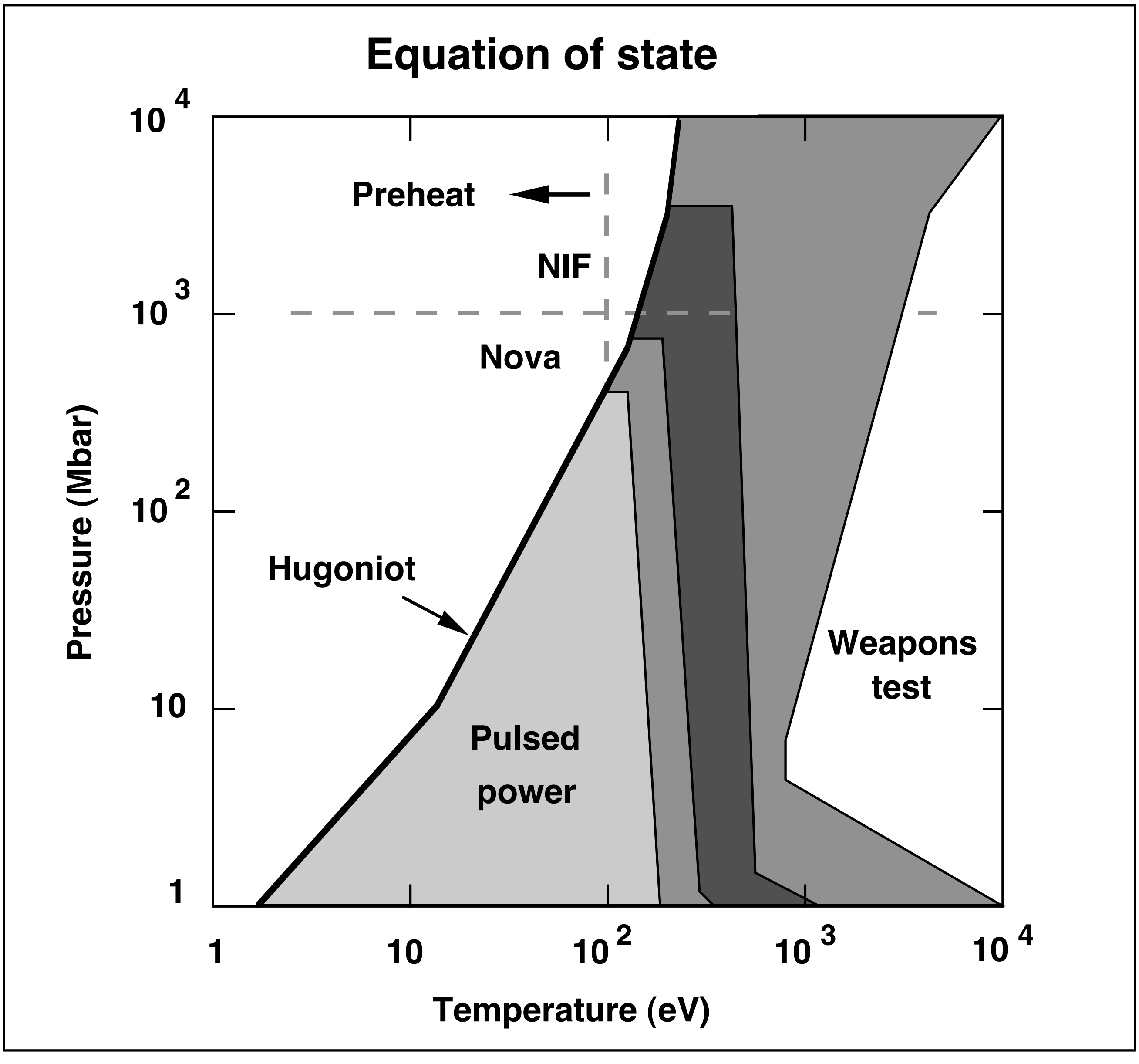


Figure 7. Equation of state measurements achievable on megajoule-scale facilities like NIF or LMJ overlap significantly the weapons-test regime.

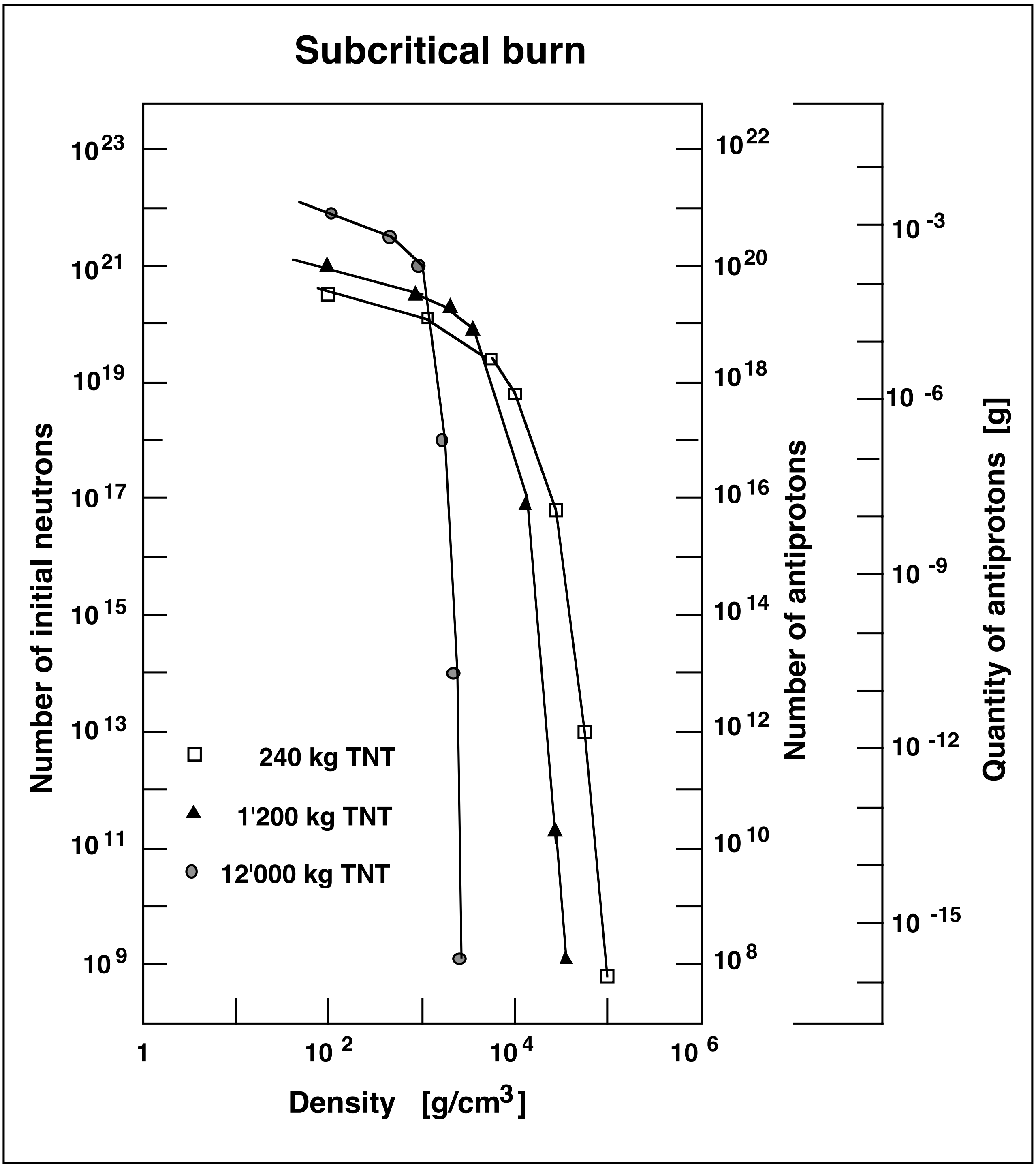


Figure 8. Dependence of the number of initial neutrons (or antiprotons) required for a 100% burn versus the final pellet density for three pellet sizes.

Adapted from R.A. Lewis et al., Nucl. Sci. Eng., Vol. 109 (1991) p. 413.