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The Next Generation of Fusion Energy Research

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Statement for the Record

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EXECUTIVE SUMMARY

Nuclear fusion powers the sun and other stars. Harnessing fusion energy has been a scientific quest since the 1950s. Inertial and magnetic confinement fusion are the main approaches to fusion energy pursued in the U.S. Both approaches use a 50-50 mixture of hydrogen isotopes (deuterium and tritium) as fuel. Like all advanced energy sources, inertial fusion requires a scientific demonstration of validity of the concept and a technology program to develop a viable power plant. The path to inertial fusion energy (IFE) involves three elements:

- The demonstration of the physics principles of controlled inertial fusion: thermonuclear ignition and burn of deuterium-tritium (DT) fuel
- The demonstration of high energy gain from DT fuel
- The development of the technology for an IFE power plant.

Demonstration of Ignition and Burn: *In the near future, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) is expected to achieve the first demonstration of thermonuclear ignition and moderate energy gain in the laboratory using lasers.* In the indirect-drive approach to inertial fusion, the laser is used to heat a small metallic enclosure (a "hohlraum") to high temperatures. The heated metal of the hohlraum wall emits x rays that irradiate a tiny pellet of cryogenic solid DT fuel. The pellet implodes, achieving extreme pressures and temperatures that turn the solid DT into hot dense plasma producing copious amounts of nuclear fusion reactions (what is called "a burning plasma"). Thermonuclear ignition is a thermal instability that causes the plasma to self-heat through a runaway process where fusion reactions increase the plasma temperature that in turn induces more fusion reactions. An ignited plasma can produce fusion energy that can greatly exceed the input energy required to produce the plasma. The process of laser irradiation, pellet implosion, thermonuclear ignition and energy gain is usually referred to as "target physics." Demonstrating thermonuclear ignition and energy gain in the laboratory has been a goal of fusion energy research for the past five decades, and is widely considered a milestone in the development of fusion energy, as well as a major scientific achievement.

The current status of IFE research in the US is dominated by the National Ignition Campaign (NIC). The NIC is funded for reasons of national security by the Stockpile Stewardship Program under the National Nuclear Security Administration (NNSA). In parallel to its national security mission, the NIC will be able to address many aspects of burning-plasma physics relevant to inertial fusion energy and will demonstrate the physics principles of IFE. The NIC involves many institutions (LLNL, LLE, LANL, General Atomics and SNL) and major NNSA facilities (NIF, OMEGA and Z). Many diagnostics and experimental setups are validated on smaller facilities (mostly on OMEGA at the Laboratory for Laser Energetics) before installation on the NIF.

> ***Recommendation:*** *It is crucial to provide adequate funding to the National Ignition Campaign. Achieving thermonuclear ignition in the laboratory is a milestone in the development of science and energy security. This goal should not be undermined by lack of adequate funding.*

Demonstration of High Energy Gain: The next step in target physics after ignition is the demonstration of high energy gain. For a viable IFE power plant, the fusion energy output must greatly exceed the input energy to the plasma. Energy gain is the ratio between energy output and input. It is unlikely that the NIF will achieve high gains (> 100) in the laser indirect-drive configuration.

The 2009 FESAC report[1] states that "Alternative IFE concepts [laser direct-drive, fast ignition, heavy ion fusion and others] funded through OFES and NNSA have the potential to generate the gains needed for IFE." *Present research in alternative IFE concepts is funded by DOE's Office of Fusion Energy Sciences (OFES) and NNSA, with NNSA providing limited access to their facilities. Limited access to the NNSA facilities constitutes a serious impediment to progress in this important area and to the achievement of high energy gains for inertial fusion energy*. While the NIF is currently configured to fully validate the scientific principles of the laser indirect-drive approach, it can also test the laser direct-drive approach with very modest changes to the existing laser system. The direct-drive approach is simpler since the laser directly irradiates the solid pellet. It is also more efficient since it eliminates the need for the intermediate process of conversion of laser light into x rays.

> ***Recommendation:*** *OFES and NNSA have already formed a joint program to support high energy-density physics research. This partnership should be strengthened to increase access to NNSA facilities for research in the area of high-gain inertial-fusion-energy concepts. Experiments on the NIF should be carried out to demonstrate ignition and energy gain with the laser direct-drive approach.*

Development of the Technology: *Achieving ignition and high gain does not imply that economically attractive fusion energy is just around the corner. Major technological and engineering challenges will still remain even after the demonstration of ignition. The development of a viable fusion power plant requires large scientific and financial investments.* Before launching a major energy development program, it is prudent to undertake an assessment of the different driver options. This can begin immediately with a small exploratory IFE technology program ("small" here is used for comparison with the "large" science program of the National Ignition Campaign that received $458M in the FY10 Appropriations bill).

Several drivers have been proposed: solid-state and Krypton-Fluoride (KrF) lasers, *Z* pinches and heavy ion beams. The driver compresses the pellet and is the most complex and expensive component of an IFE power plant. Drivers are part of an integrated system including a target chamber, injection systems and other components. Drivers must operate with relatively high repetition rates to produce enough average power output. *Lasers are the most developed drivers. Small-scale high-repetition-rate KrF and solid-state lasers have been built and operated. Research in target physics for laser drivers is also the most advanced. The current experimental campaign will explore ignition with lasers implying that the target physics issues will only be resolved for laser drivers. Other drivers will likely require longer development paths for both the technological development and target physics.* An exploratory IFE program should be started with the goal of assessing and selecting the most attractive driver option in order to move quickly towards an expanded energy development program once the NIF has completed the ignition campaign and reliably demonstrated fusion-energy gains. Such a program should also assess the viability of fusion-fission hybrid systems where a blanket of fissionable material surrounding the fusion reactor is used to amplify the fusion-energy output. Funding for research in IFE technology has been eliminated in 2009 and no plans are in place to support it in the near future.

> ***Recommendation:*** *It would be beneficial to immediately initiate an exploratory fusion technology program in parallel to the ignition campaign to assess the viability of the different driver options. If successful, such a program will select the most attractive driver by the completion of the ignition campaign on the NIF.*

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[1] Fusion Energy Science Advisory Committee (FESAC), *Advancing the Science of High Energy Density Laboratory Plasmas*, US Department of Energy, Office of Science, January 2009

Status of Inertial Fusion Energy Research and Vision for the Future

Nuclear fusion powers the sun and other stars. Fusion involves the merging (e.g. fusing) of light elements. Harnessing fusion energy has been a scientific quest since the 1960s. Inertial and magnetic confinement are the main approaches to fusion energy pursued in the US. Both approaches use a 50-50 mixture of hydrogen isotopes (deuterium and tritium). Deuterium is abundant and can be extracted easily from sea water. Tritium must be obtained by breeding with lithium, and lithium is a readily available light metal.

Like all advanced energy sources, inertial fusion requires a scientific demonstration of viability of the concept and a technology program to develop a viable power plant. The path to inertial fusion energy (IFE) involves three elements:

(1) The demonstration of the physics principles of controlled inertial fusion: thermonuclear ignition and burn of deuterium-tritium (DT) fuel
(2) The demonstration of high energy gain from DT fuel
(3) The development of the technology for an IFE power plant.

1. Demonstrating Controlled Thermonuclear Ignition and Burn

The demonstration of ignition and burn is the goal of the National Ignition Campaign (NIC). The NIC is funded for national security reasons by the Stockpile Stewardship Program under the National Nuclear Security Administration. The NIC involves many institutions (LLNL, LLE, LANL, General Atomics and SNL) and major NNSA facilities (NIF, OMEGA and Z). Many diagnostics and experimental setups are validated on smaller facilities (mostly on OMEGA at the Laboratory for Laser Energetics) before installation on the NIF.

Finding: *The National Ignition Campaign aims at demonstrating ignition and moderate fusion-energy gains in the next few years on the National Ignition Facility (NIF). Preparatory work is under way and the first attempts to ignition are set to begin at the end of FY10 on the NIF.*

Two recent highlights of the National Ignition Campaign are worth mentioning.

(1) Early experiments on the National Ignition Facility have shown good performance of the NIF laser and good coupling of the laser energy to the target. The NIF has already delivered energies exceeding one megajoule (1 megajoule = 1 million joules) and is on track to proceed with the first attempts to ignition using the indirect drive approach.

(2) Using the laser direct-drive approach, recent experiments on OMEGA have achieved world record performance in terms of DT plasma compression and attained the required densities for fusion. It is likely that, within the next few years, OMEGA will also demonstrate the temperatures that will scale to those required for ignition. If successful, OMEGA will validate many of the physics principles of the direct-drive approach (with the exception of ignition and burn).

The direct-drive approach is a straightforward alternative to indirect drive. First, it is simpler since the laser directly irradiates the solid pellet and the targets do not require metallic enclosures (hohlraums). Second, it is more efficient since it eliminates the need for conversion of laser light into x-rays. For these reasons, the direct-drive approach offers better prospects for energy applications. While the NIF is currently configured to fully validate the scientific principles of the laser indirect-drive approach, it can also test the laser direct-drive approach with very modest upgrades to the laser system.

Recommendation: *The results from OMEGA can and should be used to field experiments on the National Ignition Facility to demonstrate ignition and energy gain with the laser direct-drive approach. This is a necessary step that will resolve most of the target physics issues for the direct-drive scheme and will determine if laser direct-drive is a viable option for fusion energy.*

The NIC is currently funded at the level of $458M for FY10. To the best of my knowledge, some of the key institutions involved in the NIC are operating under very tight budgets. With the first demonstration of ignition expected within the next few years, this is not the time to underfund the ignition campaign. Even small budget increases could significantly improve the prospects for success.

Recommendation: *It is crucial to provide adequate funding to the National Ignition Campaign. Achieving thermonuclear ignition in the laboratory is a milestone in the development of science and energy security. This goal should not be undermined by lack of adequate funding.*

2. Demonstrating High Energy Gain

The next step in target physics after ignition is the demonstration of high energy gain. For a viable IFE power plant, the product of the efficiency of the driver (the ratio of the "wall plug" energy to driver energy produced) and the target gain should exceed 10, e.g. a 10% efficient driver requires a gain of 100. The target gain is the ratio between the energy output and the energy input on target. It is unlikely that the NIF will achieve high gains (> 100) in the laser indirect-drive configuration — and so an alternative approach may be required. The 2009 FESAC report[2] states that "Alternative IFE concepts funded through OFES and NNSA have the potential to generate the gains needed for IFE…. [The] alternative concepts in IFE will play a crucial role in the development of inertial fusion energy, since high gains and high driver efficiencies are required features of an economically viable IFE power plant." Present research in alternative IFE concepts is mostly funded by DOE's Office of Fusion Energy Sciences (OFES) and NNSA, with NNSA providing limited access to their facilities. Limited access to the NNSA facilities constitutes a serious impediment to progress in this important area and to the achievement of high energy gains for inertial fusion energy.

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[2] Fusion Energy Science Advisory Committee (FESAC), *Advancing the Science of High Energy Density Laboratory Plasmas*, US Department of Energy, Office of Science, January 2009

There are several options for achieving the gains required for IFE using lasers: direct-drive, fast ignition and shock ignition. Heavy ion fusion requires a heavy ion accelerator, and *Z*-pinch fusion requires a pulsed-power device.

Heavy ion accelerators are attractive drivers from the standpoint of wall-plug efficiency. Recent theoretical work has indicated that heavy-ion fusion (HIF) could achieve high gains through direct irradiation of the target. However, there is little or no experimental work on implosion physics with heavy-ion drivers. Since there are not existing HIF implosion facilities, it is not possible to easily acquire critical experimental data to make a valid assessment of the target physics requirements for HIF. An IFE development path for heavy-ion fusion will inevitably require both a target physics and a technology development program. With little available experimental data on heavy-ion fusion implosions and the lack of HIF implosion facilities, it is likely that an IFE development path based on heavy ion fusion will be lengthy and uncertain.

***Z*-pinch** fusion uses the indirect drive approach and requires high-gain targets (gains of 100 or more). Current *Z* pinches such as the *Z*-machine at Sandia National Laboratory have demonstrated reasonable single-shot performance and high x-ray yields. The rate of progress in target physics is mostly limited by the low shot rates of large *Z* pinches. Theoretical work indicates that it may be possible to design high yield targets that can satisfy the requirements for inertial fusion energy. *Z*-pinch fusion requires driving large currents through massive transmission metal lines that are partially destroyed at every shot. Since the cost of replacing the transmission lines would exceed the value of the fusion-energy output, a *Z*-pinch based IFE power plant will require recycling the large amounts of metal of the transmission lines. While some interesting ideas have been put forward to address this issue, a technology development path for *Z*-pinch fusion is highly uncertain.

Lasers are the most developed drivers and the target physics for laser fusion is the most advanced. Laser drivers are used for direct drive, fast ignition and shock ignition. **Laser direct drive** has been pursued in the U.S., Europe and Japan for over 30 years. According to theoretical analyses, laser direct drive offers the possibility of achieving high energy gains. Since existing laser drivers have poor efficiencies, gains in excess of 100 are required for fusion energy. The conventional approach to laser direct drive uses a single step with a single laser pulse driving the compression and the heating of the thermonuclear fuel. This approach is currently under investigation at two implosion facilities: the OMEGA laser at the Laboratory for Laser Energetics of the University of Rochester, and the GEKKO laser at the Institute for Laser Engineering of Osaka University in Japan. Both OMEGA and GEKKO use glass laser technology. Until recently, target-physics studies on laser direct drive were also pursued at the NIKE laser facility of the Naval Research Laboratory (NRL). NIKE is a Krypton-Fluoride (KrF) gas laser producing laser light with a wavelength shorter than the other large glass lasers. KrF lasers are more efficient than glass lasers. Their short wavelength light efficiently couples the laser energy to the target and allows operation at relatively high laser intensities. While short wavelength light improves several aspects of the target physics, it poses more severe technological constraints on the optical components of the laser system. The NRL

IFE program did not receive funding in the FY09 Omnibus Appropriations bill and its future is uncertain.

A wealth of experimental data is available on direct drive implosions. The data includes surrogate targets (mostly made of plastic shells) and cryogenic solid deuterium (D_2) and deuterium–tritium (DT) targets. The latter are the targets of most interest to inertial fusion energy. To date, cryogenic DT targets have only been used for implosion experiments on the OMEGA facility. Recent cryogenic implosion experiments on OMEGA have achieved high compression of thermonuclear fuel. While the required densities have been achieved, further progress needs to be made to raise the temperature (by about 50%-70%) and the fusion yield (by about 2 to 4 times) from the compressed DT fuel. Only when all these requirements (density, temperature and fusion yield) are simultaneously met in cryogenic implosions on OMEGA, can one achieve a full understanding of the target physics and full validation of the predictive capability. Achieving an experimental validation of the predictive capability is an important requirement for the design of robust high-gain targets. OMEGA is close to achieving such an experimental validation (with the exception of the validation of ignition and burn physics that requires experiments on the NIF).

Achieving gains in excess of ~100 with the conventional approach to direct drive requires very large lasers. An IFE laser driver should deliver a few megajoules of ultraviolet light to the target at a rate of about 10 shots per second. Krypton-Fluoride and advanced solid state lasers offer the promise of high efficiency and high repetition rates, but even in the most optimistic scenario, a power plant based on the conventional direct-drive approach will require large megajoule-class lasers and targets with gains above 100. The need for large high-repetition-rate laser systems is the main difficulty in the development of the conventional laser direct-drive approach to inertial fusion energy.

Fast ignition is a relatively new concept that separates the compression and the heating of the thermonuclear fuel. The compression is driven by a conventional system (laser or other driver), and the heating is induced by a beam of energetic electrons produced by the interaction of a short-pulse ultrahigh-intensity laser beam with the target. Fast ignition research is actively pursued in the U.S., Europe and Japan. Theoretical analyses indicate that fast ignition may lead to energy gains well above the gains of conventional direct drive. However, such theoretical calculations are incomplete and the physics principle concerning the interaction of intense light with matter and the transport of energetic electrons in plasmas are poorly understood. While fast ignition may require a relatively small compression laser (a sub-megajoule laser), it is likely that providing the necessary external heating power will involve a large high-power laser (~100 kilojoule petawatt-class laser – one petawatt = 1000 trillion watts). Presently, the largest petawatt lasers are the OMEGA EP laser (2.5 kilojoules) at the Laboratory for Laser Energetics and the FIREX laser (10 kilojoules) at Osaka University.

Since little experimental data on the target physics for fast ignition is available, it is difficult to make an assessment on its viability as an option for fusion energy. In the past, the lack of experimental facilities with a dual integrated laser system (the compression and heating lasers working together) has prevented the acquisition of the necessary data. However, the US and Japan have recently completed the construction of two integrated facilities that can explore the fast ignition concept. Such integrated laser systems are OMEGA at the Laboratory for Laser Energetics, and FIREX-I at Osaka University. A third integrated facility will soon be available at Lawrence Livermore National Laboratory. The OMEGA facility includes the OMEGA compression laser and the OMEGA-EP high-power laser, the FIREX-I facility includes the GEKKO compression laser and the FIREX high-power laser, and the NIF will soon include the ARC high-power laser. These three facilities have the potential to rapidly advance the target physics for fast ignition. The main obstacle to such advances is the very limited access granted to fast ignition studies on the US integrated facilities OMEGA and NIF. For example, only five days of the OMEGA facility were devoted to integrated fast ignition experiments in FY09. With such a limited time allocation, it is difficult to make meaningful progress in fast ignition. The reason for this limitation is that such facilities are funded by NNSA, whose primary mission does not include fusion energy development. Inadequate access to the integrated NNSA laser facilities is currently the main obstacle to acquiring the necessary experimental data required to validate the fast ignition scheme. The lack of experimental data on the target physics as well as the complexity of the scheme and targets renders highly uncertain the development path of fusion energy based on the fast ignition concept.

Shock ignition is a very new concept introduced in 2007. Similarly to fast ignition, shock ignition is also a two-step process where a strong shock wave is used to heat the thermonuclear fuel previously assembled by a compression laser. An advantage of shock ignition is that the shock can be launched by the same laser used for the compression, and therefore it requires a single laser. Much of the target physics for shock ignition is a straightforward extension from laser direct drive. However, launching strong shock waves requires relatively high laser intensities and there are concerns about the coupling of the laser light to the target and other negative effects that occur at high intensities. Most of the theoretical work on shock ignition to date comes from computer simulations carried out at the Laboratory for Laser Energetics, the Naval Research Laboratory, Lawrence Livermore National Laboratory and the Centre Lasers Intenses et Applications in Bordeaux (France). This work shows that high energy gains may be possible with shock ignition using a sub-megajoule driver. Recent experiments on the NIKE laser, target design work and computer simulations from NRL have indicated that Krypton-Fluoride lasers are particularly suitable for shock ignition because they provide a more effective drive for the shock and reduce the risks (to the target) of operating at high intensities. This interesting research stopped in 2009 when the NRL program did not received funding in the FY09 Omnibus Appropriations bill. While the simulation results are promising, there is not sufficient available experimental data on the target physics to make an assessment of shock ignition as a viable scheme for fusion energy. The only available implosion data on shock ignition comes from a few experiments on the OMEGA laser. Acquiring meaningful experimental data requires access to the NNSA laser implosion facilities OMEGA and NIF. Like fast ignition, access to these facilities for shock-ignition research is very limited. For example, only one day of operation of the OMEGA facility was devoted to shock ignition in FY09. Inadequate access to the NNSA laser facilities is currently the main obstacle to acquiring the necessary experimental data required to validate the shock-ignition scheme. Due to the lack of experimental data on the target physics, the development path for shock ignition is uncertain.

Finding: *Laser drivers are the most developed drivers for inertial fusion. The target physics for laser direct drive is also the most advanced. Because of the relatively low driver efficiency, laser-based inertial fusion energy requires high gain targets (with gains above 100). Laser direct drive, fast ignition or shock ignition may provide such high gains. A power plant based on conventional direct drive will likely require large and expensive megajoule-class lasers. Fast and shock ignition may require a significantly smaller driver than conventional direct drive. However, little experimental data is available for fast and shock ignition to make a valid assessment of their viability for fusion energy. Heavy-ion drivers are more efficient than lasers but little or no experimental data is available on implosion physics for heavy ion fusion and there are no plans to acquire such data in the near future. Z-pinch fusion uses the indirect-drive approach and requires high gains (about 100 or more). Z-pinch research has made progress in target physics but serious questions remain on the viability of Z pinches as fusion-energy drivers.*

Existing NNSA facilities have the capability of exploring the physics principles of direct- and indirect-drive laser fusion, as well as fast and shock ignition. Fast and shock ignition research is currently funded by the OFES. Access to the NNSA facilities for fast and shock-ignition experiments is currently very limited since NNSA's mission does not include fusion-energy development. This limited access is currently the main obstacle to acquiring the necessary experimental data required to validate high-gain IFE concepts.

Recommendation: *OFES and NNSA have already formed a joint program to fund high-energy-density physics research. This partnership should be strengthened to increase access to NNSA facilities for research in the area of high-gain inertial fusion energy concepts.*

3. Developing the Technology for Inertial Fusion Energy

Achieving ignition and high gain does not imply that economically attractive fusion energy is just around the corner. Major technological and engineering challenges will still remain even after the demonstration of ignition. The development of a viable fusion power plant requires large scientific and financial investments. Drivers compress the pellet and are the most complex and expensive component of an IFE power plant. The driver is part of an integrated system including a target chamber, injection systems and other components. Drivers must operate with relatively high repetition rates to produce enough average power output.

Finding: *Several IFE drivers have been proposed: solid state lasers, Krypton-Fluoride lasers, Z pinches and heavy-ion beams. Drivers are part of an integrated system including a target chamber, injection systems and other components. While the technology of some drivers is more advanced than others, none of them offers a development path free of major engineering and technological challenges.*

Therefore, before launching a major energy development program, it is prudent to make an assessment of the different driver options. This can begin immediately with a small exploratory IFE technology program ("small" here is used for comparison with the "large" science program of the National Ignition Campaign).

In the past ten years, the High Average Power Laser Program, funded by NNSA under congressional mandate, was engaged in IFE technology development for KrF and solid state lasers. This program was not funded in the FY09 Omnibus Appropriations bill and no funding is currently provided for IFE technology.

Lasers are the most technically advanced drivers. Small-scale high-repetition-rate KrF and solid-state lasers have been built and tested. Research in target physics for laser drivers is also the most advanced. Furthermore, the current experimental campaign will explore ignition with lasers implying that all the target physics issues will only be resolved for laser drivers. Other drivers will likely require longer development paths for both the technological development and the target physics. An exploratory IFE program should be started with the goal of selecting the most attractive driver option in order to move quickly toward an expanded energy development program once the NIF has demonstrated ignition and energy gains.

Because of the engineering and technological difficulties involved with fusion energy, it is important to assess/explore all possible schemes including fusion–fission hybrids. A fusion–fission hybrid power plant consists of a fusion reactor (the "engine") surrounded by a blanket of fissionable material. This concept has been recently promoted by the Lawrence Livermore National Laboratory (LLNL). The fissionable material is depleted uranium or spent nuclear fuel, while the fusion engine is based on the laser indirect-drive approach. Since the fission blanket amplifies the energy output from the fusion engine, a relatively low-gain laser indirect-drive (or direct-drive) scheme may suffice in its role as neutron source. Advocates argue that the LLNL approach to fusion-fission hybrids offers the shortest development path for inertial fusion energy since the target physics and the required target gains are essentially the same as the ones explored by the NIF within the next few years.

In light of these possible advantages, an exploratory IFE technology program should also assess the viability of fusion–fission hybrid systems and make a determination on the benefits of such systems and the possibility of a shorter development path.

Recommendation: *It would be beneficial to immediately develop an exploratory fusion technology program in parallel to the ignition campaign to assess the viability of the different driver options. If successful, such a program will select the most attractive driver by the completion of the ignition campaign on the NIF.*

Additional technical information, findings and recommendations can be found in:

- Fusion Energy Science Advisory Committee, *Advancing the Science of High Energy Density Laboratory Plasmas*, (Chapters 7, 9, 11), US Department of Energy, Office of Science, January 2009

- Fusion Energy Science Advisory Committee, *Review of the Inertial Fusion Energy Program*, US Department of Energy, Office of Science, March 2004

BIOGRAPHY

Dr. Riccardo Betti – is currently Professor of Mechanical Engineering & Physics and Astronomy at the University of Rochester. He is also Director of the Fusion Science Center for Extreme States of Matter, Senior Scientist and Assistant Director for Academic Affairs at the University of Rochester's Laboratory for Laser Energetics.
Dr. Betti has conducted research in plasma physics, inertial and magnetic confinement fusion for over 20 years. He is Vice-Chairman of the Department of Energy Fusion-Energy-Science Advisory Committee (FESAC), and Steering Committee Member of the High-Energy-Density Science Association. He was Chairman of the Plasma Science Committee of the National Academies in 2006–09, and Chairman of the FESAC sub-panel on High-Energy-Density Physics in 2008–09. Dr. Betti is a Fellow of the American Physical Society for his pioneering work on ablative fluid instabilities in inertial confinement fusion and energetic particle instabilities in magnetic confinement fusion. He is a recipient of the Edward Teller Medal for his seminal contribution to the theory of thermonuclear ignition and implosion physics for inertial confinement fusion. Dr. Betti received a "laurea cum laude" degree in Nuclear Engineering from the University of Rome, and a PhD in Nuclear Engineering from the Massachusetts Institute of Technology. He has co-authored over 100 refereed articles in plasma physics, magnetic and inertial confinement fusion.