High-Yield Z-Pinch Thermonuclear Neutron Source

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Introduction: Neutron beams are useful for many applications, from noninvasive imaging and characterization of materials to producing medical isotopes and detecting hidden explosive devices. Some applications require high-energy neutrons created in fusion nuclear reactions between deuterium (D) and tritium (T). To achieve thermal fusion, deuterium or DT plasma must be heated to about 10^8 K, which is a challenging task. One of the pathways to controlled thermonuclear fusion is inertial confinement fusion (ICF). High-energy ICF lasers, such as OMEGA at the University of Rochester and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, as well as ICF pulse power facilities, such as the Z accelerator at Sandia National Laboratories, compress and heat deuterium or DT-filled capsules by strong laser or X-ray radiation. The highest thermonuclear DD neutron yield of the pre-NIF era is about 3×10^{11}, obtained by direct capsule illumination with laser beams on OMEGA and by X-ray compression on Z. In the future, NIF will deliver ~180 kJ of X-ray energy to the capsule. DT neutron yield corresponding to "breakeven" (the same energy input as released in a DT reaction) is 6×10^{16}. Neutron yields above 6×10^{16} can only be produced when the fusion energy release exceeds the input, indicating ignition and fusion energy gain. On the other hand, a DD plasma at the same temperature and density would produce a fusion neutron yield about two orders of magnitude less due to lower reaction cross section, that is, about 6×10^{14}. Deuterium fusion neutron yields of this magnitude could only be expected from ignition-scale ICF facilities, only one of which, NIF, has been built so far.

Z-pinch Neutron Sources: A DD fusion neutron yield of about 3×10^{13}, exceeding the previous ICF record by two orders of magnitude, has recently been obtained on Z without a capsule implosion. A deuterium gas column was imploded in cylindrical geometry by a 15 MA, 100-ns-long current pulse, as illustrated by Figs. 1(a) and (b). The most powerful, fast, multi-MA current driver in the world, shown in Fig. 1(c), is much smaller and simpler to operate than ignition-class lasers.

Non-thermonuclear DD fusion neutrons have been produced in Z-pinch plasmas at pinch currents up to about 2 MA for many years. They were generated by relatively small quantities of "beam" deuterium ions accelerated in the strong electric fields accompanying the development of instabilities in the pinch. Their collisions with the cold "target" deuterium ions produced fusion neutrons. This "beam-target" mechanism of neutron production does not scale well to high currents and plasma densities, showing little promise for producing neutron yields above 10^{13}.

New opportunities for nuclear fusion in Z-pinch plasmas emerged at higher-current facilities. Analysis and modeling of the experimental results on Z done at NRL[1] led to an unexpected conclusion: a substantial part of the observed fusion neutrons must have been

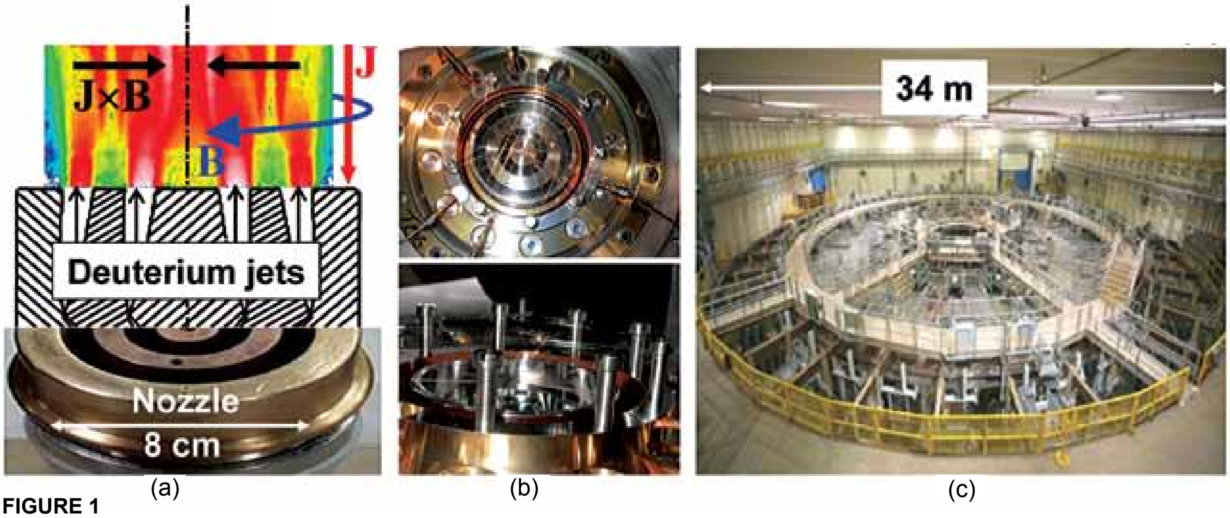

FIGURE 1
(a) An annular gas jet injected from a supersonic nozzle between the anode and cathode of the Z accelerator and then radially imploded by the **J×B** force to produce a tight, hot Z-pinch column on axis. (b) The nozzle installed on Z by L-3 Communications/Pulse Sciences. Thin wire mesh defines the anode. (c) Photo of the Z accelerator at Sandia National Laboratories, which after its refurbishment completed in 2007, can drive current pulses up to 26 MA and 100 to 300 ns.

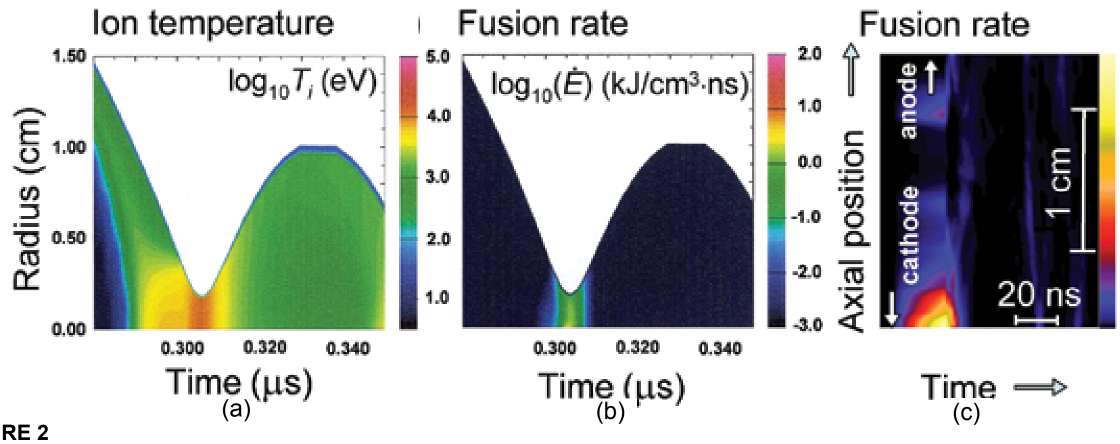

FIGURE 2
Simulated plasma heating and neutron production in deuterium gas-puff Z-pinch implosions on Z. Time histories of the ion temperature (a) and the DD fusion reaction rate (b) are from the 1D simulations. Radially integrated, time-resolved fusion rate (c) is from a 2D simulation.

of thermonuclear origin. Deuterium-pinch plasma imploded on Z by a 15 MA current is heated to about 10^8 K, has a sufficiently large mass, and is inertially confined long enough to produce over 10^{13} neutrons via the thermal mechanism. Figures 2(a) and (b) show the simulated time history of the ion temperature and the fusion energy and neutron production rate. The ions in the converging compressed deuterium plasma shell are heated by shock waves and adiabatically. As the ion temperature approaches 10^8 K, the fusion reaction starts producing neutrons. Figure 2(c) shows the axial nonuniformity of the neutron production in Z experiments, with most of the neutrons coming from near the cathode. The thermonuclear fusion mechanism implies that the neutron yield scales with the pinch current as I^4.

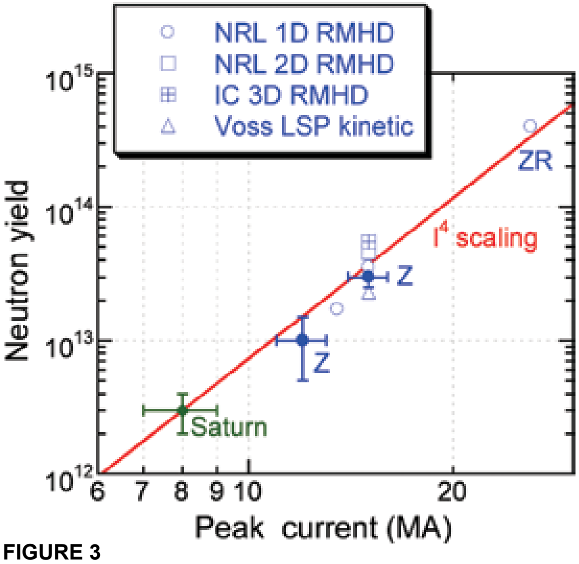

FIGURE 3
Neutron yield measured in gas-puff implosions on Saturn and Z accelerators at Sandia National Laboratories compared to the results of simulations of Z implosions done independently at NRL, Imperial College (IC, London, UK), and Voss Scientific, LLC (Albuquerque, NM). Radiative-magnetohydrodynamic (RMHD) simulations (NRL, IC) model only the thermonuclear contributions to the DD neutron yield, whereas the kinetic simulation (Voss) accounts for the beam-target mechanism of neutron production.

Figure 3 compares the results of experiments on two different high-current facilities at Sandia[2] with the I^4 scaling and simulation results. Radiation-hydro simulations take into account only the thermal mechanism of neutron production, which is seen to be sufficient to account for all observed neutron yield. Kinetic simulations done in 2009 with a code capable of capturing the contribution of the "beam-target" mechanism to the neutron production, estimate it to be about 50% of the total, the remaining 50% of neutrons being of thermal origin. Also shown is the predicted neutron yield in the new experiments with deuterium pinches designed at NRL for the refurbished Z facility, ZR. Our simulations predict DD neutron yields of about 4 × 10^{14}, that is, in the ignition-scale range. Extrapolating these results to higher driving currents, we can expect fusion ignition and energy gain in DT Z-pinch plasma at about 50 MA.

Summary: A deuterium Z-pinch can become the most powerful, cost-efficient, and energy-efficient laboratory source of thermal fusion neutrons, in the same way as fast Z-pinches are the most powerful laboratory X-ray sources. As stated in a *Nature Physics* "Research Highlights" article reviewing this work, the simulations and experiments "suggest that the technology has matured to a stage where useful fluxes [of neutrons] could soon be generated."[3]

Acknowledgments: The work presented here is part of a larger program on radiation effects and electronics survivability testing involving many scientists from NRL, Sandia National Laboratories, and industry.

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Rapid Air Traffic Modeling and Prediction

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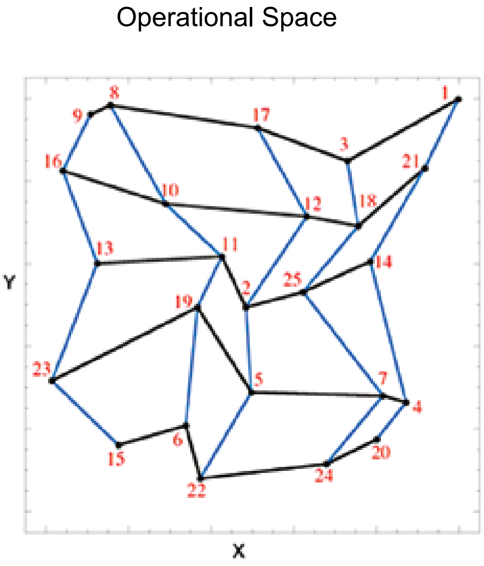
Introduction: Optimization and control of the air traffic system is vital to our national economy and homeland security. In order to develop strategies to design and control the increasingly complex aspects of air transportation, we must have a fast research tool for modeling all aspects of the air-traffic system, ranging from local groups of aircraft to global optimizations of entire traffic systems, including baggage, passengers, and aircraft. We are currently developing a dynamic global model, the Air Traffic Monotonic Lagrangian Grid (ATMLG), for simulating the air traffic flow as a platform for evaluating approaches to air systems control and optimization. ATMLG can be used to test control strategies for conflict prevention and traffic-flow management, or to evaluate the reaction of the system to local and global perturbations, such as weather. For example, ATMLG could be used to determine the most efficient way to reroute air traffic after local conditions, such as thunderstorms, have caused disturbances throughout the entire air-traffic system. This work is applicable to both military and civil aviation, as well as to other systems where many objects are moving in complex paths relative to each other, such as swarms of mobile sensors and space debris.

Monotonic Lagrangian Grid (MLG): The MLG was originally developed at NRL in the mid 1980s,[1] and has since been used as the underpinning for various particle dynamics simulations. The MLG is a data structure for storing the positions and other data needed to describe *N* moving objects, where *N* can be very large. The MLG algorithm sorts and orders objects on a grid structure in real (operational) space and indexing (computer memory) space. As an example, Fig. 4 depicts a small, two-dimensional (2D) MLG. The image on the left shows the 25 MLG nodes (objects) in operational space, while the table on the right shows the grid indices in computer memory of each node. Although the nodes are irregularly spaced (left figure), they are indexed regularly in the MLG by a monotonic mapping between the grid indices and the operational locations. A computer program based on the MLG data structure does not need to check *N*-1 possible distances to find which nodes are close to a particular node. Rather, the indices of the neighboring nodes are automatically known because the MLG node indices vary monotonically in all directions with the Lagrangian node coordinates. This is the major advantage of the MLG data structure for air traffic modeling. Extensive searches to find nearby aircraft are eliminated, allowing many more aircraft to be safely tracked on modest computers in real time.



Computer Memory Index Space

5	9	8	17	3	1
4	16	10	12	18	21
3	13	11	2	25	14
2	23	19	5	7	4
1	15	6	22	24	20
J/I	1	2	3	4	5

FIGURE 4
The figure shows a simple 2D MLG containing the x and y physical locations of 25 labeled nodes. The black (horizontal) lines show the x-links and the blue (vertical) lines show the y-links. The table shows the grid indices in computer memory of the nodes shown in the figure. That is, node 15 is indexed at I = 1, J = 1; node 6 is indexed at I = 2, J = 1, etc.

Conflict Prevention and Resolution Research: We have combined the MLG with algorithms for conflict prevention, circumventing restricted zones, and updating aircraft trajectories, for various test-case scenarios. Conflict prevention algorithms include those for preventing collisions and for maintaining adequate separation distance between aircraft. Figure 5 shows results from a simulation to evaluate "rules" to determine the best way to circumvent a restricted area with a minimum amount of flight delay time. The red square regions, which could, for example, represent an area of bad weather, were placed in the center of the computational domain, and aircraft approaching that area were required to avoid it according to the rules for that scenario. For example, in scenario (a), aircraft approaching the region from the northeast, entering the region at face a, are rerouted to the west (shown by the blue arrow). Aircraft approaching from the northwest are rerouted to the east (shown by the red arrow). In scenario (b), all aircraft are rerouted in a clockwise direction. In scenario (c), aircraft were routed to the numbered way-points. The bar chart in Fig. 5 indicates that the rules defined in scenario (c) result in the least delay time.

We have also used ATMLG to investigate ways to maintain a safe separation distance between many aircraft in complex airspace.[2] This is particularly important to the design of the Next Generation Air Transportation System, in which it is proposed that aircraft in high-altitude airspace will use automated self-separation maintenance methods. For a hypothetical problem, we tracked the total number of conflict-avoidance moves for each aircraft. This includes the initial primary maneuver when two aircraft first approach each other, and any subsequent secondary maneuvers required as a result of the primary maneuver. That is, after each aircraft is redirected to maintain a 3-km separation distance, we then check to ensure

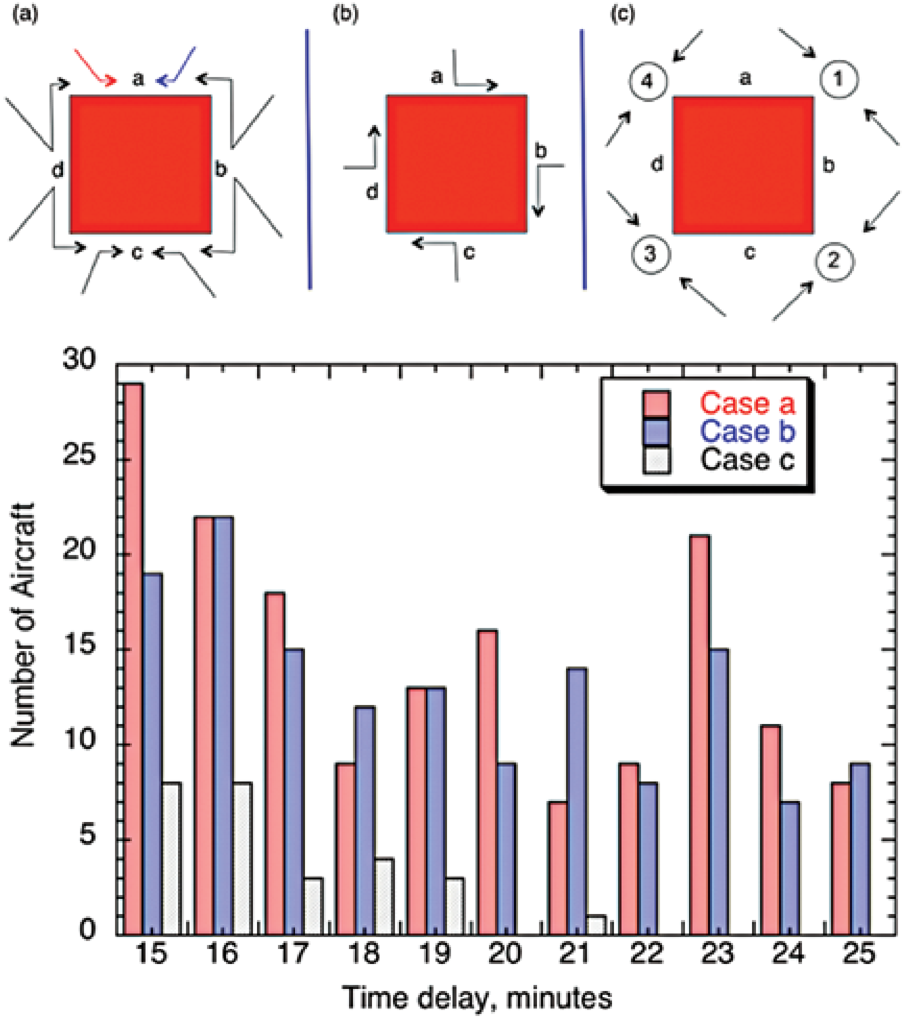


FIGURE 5
Simulation results to evaluate "rules" to determine the best way to circumvent a restricted area with minimum flight delay time.

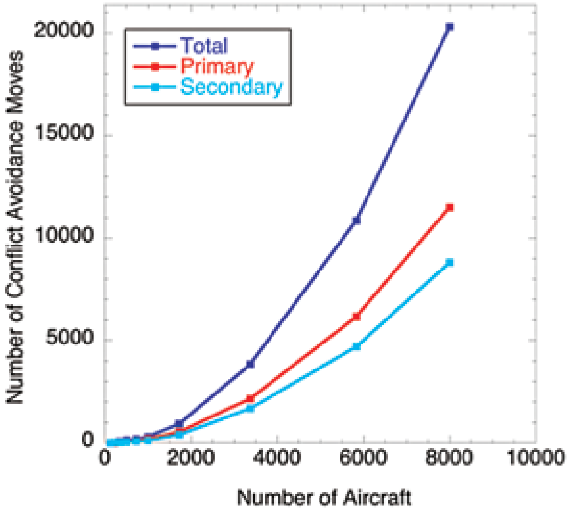


FIGURE 6
The number of moves to maintain a safe separation distance increases exponentially with the number of aircraft in the simulation.

that the modified trajectories do not create subsequent potential conflicts. Figure 6 shows that the total number of conflict avoidance maneuvers increases exponentially with the number of aircraft in the simulation, and that there are almost as many secondary maneuvers as primary maneuvers.

Discussion: We have developed ATMLG as a tool to rapidly test ideas and algorithms for preventing conflicts and maintaining adequate separation distance among aircraft. The fast sorting algorithm in the MLG enables rapid simulation of various air-traffic scenarios, and future implementations of ATMLG can be used as the basis for active design of the air transportation system.

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