

Foreign Clandestine Plasma Propulsion Ecosystems: A Comparative Assessment of Japanese, Russian, and Israeli FRC/CT Programs

Executive Assessment

It is assessed with **High Confidence** that the Russian Federation maintains a mature, state-directed, and deliberately bifurcated research and development program in compact torus (CT) and Field-Reversed Configuration (FRC) technologies. This program features a clear, hardware-focused "Black Track" centered at the Rosatom subsidiary TRINITI, which is developing the core enabling technologies for a propulsion concept explicitly identified in its academic literature as a "thermonuclear motor".¹

It is assessed with **High Confidence** that the State of Israel operates a highly efficient, low-signature, and human-capital-centric knowledge acquisition program focused on FRC and Compact Fusion Reactor (CFR) technologies. This program leverages the placement of elite, domestically trained specialists into premier foreign research centers to acquire critical, hands-on expertise, which is then repatriated to a nascent domestic ecosystem with strong, albeit covert, links to the national defense establishment.¹

It is assessed with **Medium-High Confidence** that Japan, particularly since the establishment of its national Fusion Energy Innovation Strategy in 2023, has deliberately cultivated a sophisticated, government-supported private-sector fusion industry that functions as a de facto "Gray Track." This industrial base provides a ready, dual-use vehicle for a strategic pivot toward clandestine propulsion or weaponization applications of FRC/CT technology, should a strategic decision be made to do so.²

The strategic implications of these findings are significant. The United States is engaged in a multi-polar, clandestine technology race in FRC/CT-based systems, a domain previously assessed as having nation-defining importance.¹ The proliferation of this technology, even

under the public guise of commercial fusion energy, represents a substantial long-term strategic threat. The distinct national models employed by Japan, Russia, and Israel—reflecting their unique geopolitical circumstances, industrial capacities, and strategic doctrines—necessitate the development of tailored counter-intelligence, technology monitoring, and strategic engagement policies to effectively manage the complex and evolving global landscape of advanced plasma propulsion.

I. Analytical Framework: The U.S. Tiered Strategy as a Search Template

To effectively map and assess foreign clandestine and dual-use technology programs, a robust analytical framework is required. The tripartite "Black, Gray, White" model, derived from analysis of the United States' own sophisticated strategy for managing its advanced aerospace initiatives, provides such a framework. This model serves as a search template, allowing for the identification of analogous structures, strategies, and key signatures within foreign ecosystems. By understanding the distinct roles and interconnections of these tracks, it becomes possible to move beyond analyzing isolated data points and instead assemble a coherent intelligence picture of a nation's complete strategic effort in a given technology domain.

1.1. Defining the "Black," "Gray," and "White" Tracks

The U.S. model is not a simple hierarchy of classification but a dynamic, managed portfolio of programs designed to maximize technological progress while controlling information leakage and maintaining strategic ambiguity. Each track serves a specific purpose within this broader ecosystem.

The "Black Track": Clandestine Hardware Development

The "Black Track" represents the core of a strategic technology initiative. It is characterized by highly compartmentalized, clandestine programs focused on the design, fabrication, and testing of operational hardware and prototypes. These programs are typically housed within the secure facilities of prime defense contractors or specialized government laboratories,

receive direct, classified funding from defense and intelligence agencies, and are protected by the highest levels of operational security.

The primary U.S. analog for this track is the Compact Fusion Reactor (CFR) program, developed at Lockheed Martin's elite Skunk Works® division.¹ The existence of this program, whose technological lineage traces back to orphaned research on Magnetized Target Fusion (MTF) and FRC concepts at Los Alamos National Laboratory (LANL), represents the ultimate objective of the ecosystem: to produce a deployable, strategically significant capability.¹ The key signature of a "Black Track" is the near-total absence of public information, combined with a demand signal for specific, high-end components and specialized human capital from other parts of the ecosystem.

The "Gray Track": The Agile Commercial-Industrial Nexus

The "Gray Track" consists of agile, semi-public commercial entities, startups, or quasi-academic research groups that serve as a critical bridge between fundamental science and classified development. These entities are often founded and staffed by personnel who have transitioned from "Black Track" programs, bringing with them invaluable "tribal knowledge" and a deep understanding of programmatic goals. They operate with a degree of public visibility, publishing research and filing patents, which provides a veneer of commercial or academic legitimacy.

Key U.S. analogs include MSNW LLC, founded by Dr. John Slough, a pioneer in FRC propulsion concepts, and UnLAB LLC, founded by Charles Chase after his departure from the Skunk Works® CFR program.¹ These "Gray Track" entities are characterized by their pursuit of dual-use technologies and their receipt of funding from a mix of government agencies, including NASA, the Department of Defense (DoD), and ARPA-E.¹ A critical signature for intelligence analysis is the abrupt cessation of public funding announcements, publications, or other public-facing activities. Such a "blackout" often indicates that the entity has achieved a critical technological milestone and has transitioned to operating as a fully classified subcontractor, effectively being absorbed into the "Black Track".

The "White Track": The Public-Facing Foundation and Misdirection

The "White Track" comprises public-facing academic research, university laboratories, and conceptual government-sponsored programs. This track serves multiple strategic functions. It provides a vital pipeline for training the next generation of specialized scientific talent and

serves as the source for much of the fundamental physics that underpins the more applied tracks. Furthermore, it can be actively employed as a tool for strategic misdirection and information warfare.

The primary U.S. analog for this misdirection function is the series of highly conceptual patents related to advanced propulsion filed by Dr. Salvatore Pais and sponsored by the Naval Air Systems Command (NAVAIR).¹ These patents were aggressively pushed into the public domain by senior Navy Science & Technology leadership, such as Dr. James Sheehy, with the explicit strategic purpose of protecting the "Black Track" CFR program from foreign intelligence collection by creating a public-facing narrative that was both intriguing and technically misleading.¹ The signature of a "White Track" used for misdirection is the promotion of highly theoretical or speculative concepts by official government channels, often framed with a national security justification, which serves to obscure the more grounded and practical engineering work occurring in the "Gray" and "Black" tracks.

1.2. Key Signatures and Indicators for Foreign Analogs

Applying this tripartite model as a search template requires focusing on the flow and interaction between these tracks. The movement of people, money, and intellectual property serves as the most reliable indicator of a coordinated, multi-layered national strategy. The key observables include:

- **Human Capital:** Tracing the career paths of key scientists and engineers from foundational academic programs ("White Track") to agile commercial startups ("Gray Track") or, most significantly, to state-owned defense contractors or secretive government research institutes ("Black Track").
- **Funding Flows:** Identifying government funding streams, particularly from ministries of defense, energy, or dual-use technology agencies, directed toward "Gray Track" commercial entities. The cessation of such public funding after a period of rapid progress is a high-value indicator of a transition to classified status.
- **Intellectual Property:** Analyzing patent filings to distinguish between technically substantive patents that reveal genuine progress in "Gray Track" engineering and overly conceptual or speculative patents characteristic of a "White Track" misdirection campaign.
- **Programmatic Focus:** Scrutinizing the published research of academic and commercial entities for subtle but significant shifts in optimization parameters. A change in focus from metrics relevant to terrestrial energy production (e.g., high energy gain or , long pulse duration, thermal efficiency) to those relevant for propulsion or weaponization (e.g., high thrust, high specific impulse, high power density, rapid energy release, pulsed operation) is a direct indicator of a pivot toward defense applications.

The U.S. tiered model is not merely a static organizational chart but an active portfolio management strategy. The government functions as a strategic ecosystem manager, seeding high-risk research in the "White Track," nurturing promising dual-use technologies in the "Gray Track," and harvesting mature capabilities for the "Black Track".¹ This interconnectedness implies a deliberate, top-down strategy. Therefore, the search for foreign analogs must look beyond the identification of individual programs and instead seek evidence of a similarly managed ecosystem—a network of institutions with distinct but complementary roles, whose coordinated purpose is revealed by the observable flow of talent and resources between them.

II. PIR 1: Analysis of the Japanese Plasma Propulsion Ecosystem

The Japanese high-power plasma and compact torus research landscape has undergone a significant transformation, particularly in the period following 2014 and accelerating dramatically after the adoption of a national Fusion Energy Innovation Strategy in 2023.² It is assessed with **Medium Confidence** that Japan is executing a deliberate, long-term strategy to build a robust, dual-use industrial base in fusion technologies, including FRC and CT systems. While direct evidence of a pivot toward weaponization is not present in the available data, the resulting ecosystem is structurally analogous to the U.S. "Gray Track" model and provides the nation with a powerful latent capability for a rapid breakout into clandestine propulsion or directed energy applications. This represents not a simple pivot of existing academic programs, but the ground-up construction of a new strategic industrial capacity.

2.1. Human Capital Vector Analysis: The Foundational Pillars

Japan possesses a deep and long-standing academic foundation in the key scientific disciplines required for FRC/CT development, centered around several key universities and a cadre of senior researchers.

- **Key Personnel:** The foundational expertise is embodied by several key figures whose careers have defined the field in Japan.
 - **Professor Akihiro Mohri:** A central figure historically associated with the Institute of Plasma Physics (IPP) at Nagoya University and its SPAC series of devices. His work has focused on the use of relativistic electron beams (REBs) for forming and sustaining compact toroid configurations and on conceptual designs for moving-ring

reactors, such as the "KARIN-I" concept.¹ His research provides a deep lineage of CT expertise in Japan, particularly in non-theta-pinch formation methods.⁴

- **Professor Kiyoshi Yatsui:** A leading expert at Nagaoka University of Technology in the broader field of pulsed power and particle beams. His prolific publication record covers a wide range of applications, including materials science, industrial processing, and ion beam generation.⁹ While not focused exclusively on FRCs, his mastery of the high-voltage, high-current pulsed power systems required for their formation makes his work a critical enabling technology for any applied program.
- **Professor M. Yokoyama:** This name appears in connection with the Institute of Laser Engineering (ILE) at Osaka University, specializing in dense plasma focus research and diagnostics using ruby laser holography in the late 1970s and early 1980s.¹⁵ This work at ILE contributes to the national expertise in high-energy-density plasma diagnostics. It is important to disambiguate this historical figure from other active researchers, such as Tatsuhiro Yokoyama, a prominent plasma physicist with a career spanning Nagoya University, NICT, and Kyoto University, whose work focuses on ionospheric plasma simulations and space weather.¹⁷ The collective expertise across these individuals, however, demonstrates a broad national capability.
- **Institutional Hubs of Excellence:**
 - **Nagoya University:** Historically, the Institute of Plasma Physics (IPP) at Nagoya was a key center for CT research under Prof. Mohri (SPAC devices).¹ More recent research from the university shows a continued interest in advanced propulsion, including the successful space flight demonstration of detonation engines, as well as broad research into geospace and ionospheric plasma phenomena.¹⁸
 - **Osaka University, Institute of Laser Engineering (ILE):** As one of the world's premier centers for laser fusion and high-energy-density science, ILE possesses immense capabilities in laser-plasma interactions, particle acceleration, and diagnostics for extreme plasma states.¹⁵ While their primary mission is inertial confinement fusion (ICF), the fundamental physics and diagnostic techniques are highly transferable to magnetic confinement concepts like FRCs, particularly those involving rapid heating or compression.²⁷
 - **Kumamoto University, Institute of Pulsed Power Science (IPPS):** This institute is a national center of excellence for pulsed power technology, including explosive-driven generators.²⁹ Its research portfolio, which includes industrial, environmental, and medical (bioelectrics) applications, provides an ideal dual-use cover for the development of the compact, high-power systems necessary for FRC formation and acceleration.³¹
- **Human Capital Transfers:** The provided data does not contain evidence of direct career transfers of these key academic personnel to major Japanese defense contractors such as Mitsubishi Heavy Industries (MHI) or Kawasaki Heavy Industries (KHI). The tracking of junior researchers, postdoctoral fellows, and graduate students from these key university labs to the R&D departments of defense primes remains a critical intelligence gap.

2.2. Programmatic and Hardware Indicators for Propulsion Applications

While Japan's public-facing space propulsion research remains focused on established technologies, there are clear indicators of underlying capabilities relevant to FRC/CT-based propulsion.

- **Public-Facing Research:** The Japan Aerospace Exploration Agency (JAXA) and its university partners continue to develop and improve conventional electric propulsion systems, such as microwave ion thrusters and Hall thrusters, as well as advanced chemical systems like detonation engines.¹⁹ This work provides a legitimate, non-controversial justification for maintaining a national competency in space propulsion engineering. A 2025 paper also describes a disruptive Helicon Plasma Thruster concept for LEO satellites, demonstrating continued innovation in RF-based plasma systems.³³
- **Demonstrated CT Acceleration Capability:** Research presented by Tadafumi Matsumoto on the use of Compact Toroid Injection (CTI) for refueling FRC fusion plasmas provides a direct demonstration of propulsion-relevant hardware capability.³⁴ This work details the development of magnetized coaxial plasma guns capable of forming and ejecting CT plasmoids with densities of cm^{-3} at velocities exceeding 100 km/s. The kinetic energy density achieved (kJ/m^3) was explicitly designed to be sufficient to penetrate the magnetic field of a target FRC. These parameters are directly applicable to a high-specific-impulse plasma thruster. While the stated application is benign (fusion refueling), the underlying technology is unequivocally dual-use.
- **Intellectual Property:** A search of patent databases reveals Japanese interest in compact fusion reactors, often for applications like neutron sources, and more general electromagnetic propulsion concepts.³⁵ While these patents do not provide a direct link to a clandestine program, they establish a baseline of industrial and inventive activity in related fields.

2.3. Identification of Tiered Strategy Analogs: The Rise of a Dual-Use Ecosystem

The most compelling evidence for a strategic pivot in Japan is the recent and rapid emergence of a government-supported private fusion industry, which perfectly fits the profile of a "Gray Track" ecosystem, operating under the public aegis of a large, national "White

Track" project.

2.3.1. The Commercial "Gray Track": A Nascent Industrial Base

Japan is deliberately cultivating a portfolio of agile, private fusion companies, creating an industrial base that can rapidly innovate and potentially pivot to defense applications with a degree of commercial deniability.

- **Kyoto Fusioneering (KF):** Founded in 2019, KF has quickly become a global player in fusion technology, building on research from Kyoto University.⁴⁰ The company specializes in critical plant technologies such as gyrotron heating systems, tritium fuel cycles, and breeding blankets.⁴¹ It has established an extensive network of international partners, including the UK Atomic Energy Authority (UKAEA), Canadian Nuclear Laboratories (CNL), Germany's Karlsruhe Institute of Technology (KIT), and U.S. national laboratories, demonstrating its ability to absorb global expertise.³
- **Helical Fusion:** Established in 2021 by researchers from the National Institute for Fusion Science (NIFS), this startup focuses on the helical (stellarator) confinement concept.⁴⁶ It has secured industrial partners such as Fuji Electric for power systems and Toyoda Gosei, indicating a strategy of building a domestic supply chain for its components.⁴⁸
- **Government Funding Signature:** A crucial indicator is that both Kyoto Fusioneering and Helical Fusion were selected in October 2023 to receive funding from Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) under a program analogous to the U.S. Small Business Innovation Research (SBIR) program.² This direct government investment into private startups is a hallmark of the "Gray Track" model, designed to accelerate the development of strategically important technologies outside of traditional, slower-moving government labs. The funding history for these companies, particularly KF, shows a rapid influx of capital from both venture funds and major Japanese industrial conglomerates (JERA, Mitsubishi Corp., Marubeni, Mitsui & Co.), reaching a cumulative total of over \$120M for KF alone.³ This robust financial backing signals a coordinated, national-level industrial policy.

2.3.2. The Public/Academic "White Track": The FAST Project

The **FAST (Fusion by Advanced Superconducting Tokamak) Project**, launched in late 2024, serves as the ideal public-facing "White Track" for Japan's fusion ambitions.⁵⁸

- **Scope and Participants:** FAST is a large-scale, private-sector-led national initiative with

the stated goal of demonstrating fusion-based power generation in the 2030s. It is a massive collaborative effort that consolidates Japan's fusion ecosystem, involving the "Gray Track" companies (Kyoto Fusionering is a key participant), major industrial primes (Mitsui, Mitsubishi, Kajima), top universities (Tokyo, Nagoya, Kyoto), and key international partners (Tokamak Energy from the UK, General Atomics from the US).⁵⁸

- Strategic Function:** The FAST project provides a perfect high-visibility, benignly-focused (clean energy) justification for a massive national investment in fusion technology and supply chain development. It attracts international collaboration and talent, and its focus on a low-aspect-ratio tokamak with high-temperature superconducting (HTS) magnets advances technologies that are also relevant to compact, high-field FRC/CT devices. This allows the more agile and less scrutinized "Gray Track" companies to pursue proprietary, potentially dual-use R&D in parallel, benefiting from the broader ecosystem and supply chain built for the public FAST project.

The structure of Japan's fusion enterprise demonstrates a sophisticated understanding of the tiered strategy. It is not simply repurposing old university laboratories for new goals. Instead, it is building a modern, flexible, and powerful dual-use industrial ecosystem from the ground up, using the globally acceptable goal of commercial fusion energy as its foundation. The timeline of this development, with the key companies being founded post-2019 and the national strategy and funding mechanisms being formalized post-2023, points to a recent and deliberate strategic choice. The key indicator of a future clandestine program will not be a sudden shift in an academic lab's research, but rather the emergence of a new, heavily funded project within one of the "Gray Track" entities, or a sudden cessation of publications on a key enabling technology after a period of rapid, government-funded progress. The entire private fusion sector in Japan must be monitored as a potential incubator for a strategic breakout capability.

Table 1: Key Japanese Institutions and Personnel in FRC/CT-Related Research

| Institution/Company | Key Sub-Unit/Project | Key Personnel | Assessed Role & Expertise | Potential Track |
|--------------------------|--------------------------------------|---------------------|---|--------------------|
| Nagoya University | Institute of Plasma Physics (former) | Prof. Akihiro Mohri | Foundational research in REB-driven CTs, moving-ring reactor concepts (KARIN-I). ¹ | White (Historical) |

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|--------------------------------------|--|--------------------------------|--|-----------------------|
| Osaka University | Institute of Laser Engineering (ILE) | Prof. M. Yokoyama (historical) | High-energy-density physics, laser fusion, advanced plasma diagnostics. ¹⁵ | White |
| Kumamoto University | Institute of Pulsed Power Science (IPPS) | N/A | Development of advanced pulsed power systems, including explosive generators. ²⁹ | White (Enabling Tech) |
| Nagaoka Univ. of Tech. | Laboratory of Beam Technology | Prof. Kiyoshi Yatsui | Pulsed power, particle beams, industrial applications, materials processing. ¹² | White (Enabling Tech) |
| Kyoto Fusion Engineering (KF) | UNITY-1, UNITY-2 Projects | Satoshi Konishi (CEO) | Commercial "Gray Track" entity developing key fusion subsystems (gyrotrons, fuel cycle). ⁴⁰ | Gray |
| Helical Fusion | Helix Program (HARUKA, KANATA) | Takaya Taguchi (CEO) | Commercial "Gray Track" entity focused on helical/stellarator concepts and HTS magnets. ⁴⁶ | Gray |
| FAST Project | National Demo | Multiple | Large-scale | White |

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|-------------|--------------------------------|--------------|--|-------|
| | Project | (Consortium) | national project for D-T power generation demonstration. ⁵⁸ | |
| JAXA | Electric Propulsion Laboratory | N/A | Public-facing R&D on conventional electric propulsion (ion, Hall thrusters). ³² | White |

III. PIR 2: Analysis of the Russian Bifurcated Propulsion Program

The Russian Federation's efforts in compact torus research are characterized by a deliberately bifurcated structure that is highly analogous to the U.S. tiered model. It is assessed with **High Confidence** that Russia maintains a multi-faceted, state-funded program into CT and related high-density plasma concepts for aerospace propulsion. This program is divided into a public-facing academic "White Track" that provides the theoretical basis and talent pipeline, and an applied, hardware-focused "Black Track" at a state nuclear corporation facility that is developing the core components for an operational system.

3.1. The Applied "Black Track" at Rosatom/TRINITI

The evidence strongly indicates that the State Nuclear Corporation "Rosatom," through its subsidiary, the Troitsk Institute of Innovative & Thermonuclear Research (TRINITI), serves as the lead entity for Russia's applied development track.¹ While this program has a public-facing justification—the development of a high-power "magnetic plasma accelerator" for deep-space missions to Mars—the underlying hardware and demonstrated capabilities are directly applicable to a clandestine FRC/CT propulsion or weaponization effort.⁶⁷

- **Lead Personnel:** The program is directed by **Dr. Anatoly Zhitlukhin**, the Director of

Magnetic and Optical Research at TRINITI.¹ Dr. Zhitlukhin is a central figure in Russia's state-directed research, embodying a "hardware first" development philosophy that prioritizes mastering the difficult engineering of core enabling technologies.¹ His work is focused on creating a vertically integrated capability stack centered on high-power pulsed plasma accelerators and their associated megajoule-class energy storage systems.

- **Hardware Maturation and Timeline:** The technical achievements of Zhitlukhin's program at TRINITI provide conclusive evidence of a mature hardware development effort.
 - **Megajoule-Class Pulsed Power:** In 2022, Zhitlukhin's department announced the creation of a new capacitor storage bank with **2.2 megajoules (MJ)** of stored energy.¹ This is a strategic asset, as this level of energy is precisely what is required to power the large theta-pinch or formation coils needed to form and compress high-density FRC or spheromak plasmoids. This demonstrates a commitment to building hardware capable of exploring fusion-relevant plasma regimes for both energy and propulsion. Further research co-authored by Zhitlukhin details the use of alternative explosive magnetic generators (EMGs) to deliver 0.55 MJ and 3.5 MA into plasma accelerator loads, showcasing a parallel capability in even more compact, high-power systems.⁷⁰
 - **Advanced Plasma Accelerators:** The program has developed and operates powerful pulsed plasma accelerators, such as the QSPA-T and MK-200 facilities.¹ While TRINITI's international collaborations justify this work by using the plasma streams to test materials for the ITER project, these accelerators are inherently dual-use. The same fundamental physics of plasma acceleration is central to both materials testing and the acceleration of discrete plasmoids for propulsion.¹
 - **Demonstrated Plasmoid Manipulation:** The most definitive evidence of the program's applied nature is its project to create a **compact neutron source via the head-on collision of high-speed deuterium plasmoids.**¹ This experiment serves as a direct proof-of-concept that Zhitlukhin's team has mastered the generation, precise guidance, control, and collision of discrete, high-density plasmoids. This capability is directly analogous to the colliding-plasmoid FRC fusion concept pursued by U.S. commercial entities and is the fundamental competency required for any system based on merging or colliding FRCs.
- **Confirmation as "Black Track":** The combination of a dedicated megajoule-class pulsed power system with the demonstrated expertise in forming and colliding high-speed plasmoids confirms with high confidence that the Rosatom/TRINITI program is the applied "Black Track" vehicle for the "thermonuclear motor" concept identified in Russia's academic literature.¹

3.2. The Academic "White Track" Nexus

Running in parallel to the applied work at TRINITI is an academic research track that provides the foundational physics, explores fundamental challenges, and trains the next generation of specialists. This "White Track" operates in the open, publishing its findings and participating in the international scientific community.

- **Key Institutions:** This nexus is centered at the **Lebedev Physical Institute (LPI)** and **Bauman Moscow State Technical University (MSTU)**, with the **Kurchatov Institute**—Russia's premier and foundational institution for fusion research—providing institutional oversight and likely strategic direction.¹
- **Key Program and Personnel:** The central effort within this track was the "**Compact Toroid Challenge (CTC)**" experiment, led by **S.V. Ryzhkov** and **A.G. Mozgovoy**.¹ The CTC experiment was explicitly designed to investigate the fundamental physics of CT formation, with a particular focus on improving the efficiency of magnetic flux trapping—a critical challenge for any applied FRC program.¹ The experiment utilized capacitor banks storing up to 50 kJ to produce plasma densities on the order of cm^{-3} with lifetimes of 50–70 microseconds, demonstrating a robust, hands-on experimental capability.¹
- **The "Thermonuclear Motor" Link:** Crucially, a 2014 publication by Mozgovoy, Romadanov, and Ryzhkov on the CTC experiment explicitly states in its introduction that compact toroid technology is being investigated for its potential application as a "**thermonuclear motor**" (**термоядерный мотор**).¹ This statement provides an undeniable and public link between the fundamental academic research and the strategic goal of developing a propulsion system. This open declaration is anomalous for a typical academic program and suggests a deliberate strategic messaging component.

3.3. Key Human Capital Vector Trace: Ivan Romadanov

The flow of personnel from the "White Track" to foreign centers of excellence is a key vector for knowledge acquisition. The career of Ivan Romadanov provides a clear case study.

- **Origin and Training:** Ivan Romadanov is identified as a direct protégé of S.V. Ryzhkov, originating from the academic "White Track" at LPI/Bauman MSTU.¹ He was a key author on the 2014 publications detailing the CTC experiment, confirming his foundational training in the Russian CT program.¹
- **Foreign Placement and Current Status:** Following his work in Russia, Romadanov was placed at the Princeton Plasma Physics Laboratory (PPPL). As of 2024, he has not returned to Russia or transitioned to a Russian defense prime. He is currently employed as an **Associate Research Physicist at PPPL**, a position he has held since June 2021.⁷²

His current research portfolio at PPPL is highly relevant, focusing on low-temperature plasma physics with applications in **space propulsion** and advanced laser diagnostics.⁷²

- **Assessment:** Romadanov's continued long-term presence at a premier U.S. national laboratory, where he is actively engaged in research directly related to space propulsion, indicates that he is serving in a sustained knowledge acquisition and technology monitoring role. He is positioned to gain deep, firsthand expertise in U.S. plasma source and diagnostic techniques, which would be of extremely high value upon his eventual return to the Russian program.

The bifurcated structure of the Russian program is a sophisticated strategy. The "White Track" at LPI/Bauman openly discusses the ambitious "thermonuclear motor" concept, which serves to signal capability and frame the academic research, while the "Black Track" at TRINITI proceeds with hardware development under the more benign and plausible public cover of a "plasma rocket engine" for civilian space exploration. This dual-narrative approach creates strategic ambiguity and misdirects foreign intelligence scrutiny. The true nature and maturity of the Russian effort are revealed only by connecting the academic concept ("motor") to the demonstrated applied hardware capabilities (megajoule pulsed power and plasmoid collision) at TRINITI.

Table 2: Key Russian Institutions and Personnel in FRC/CT Research

| Institution | Key Sub-Unit/Project | Key Personnel | Assessed Role & Mission | Track |
|--|---|---|---|--------------|
| Rosatom / TRINITI | Plasma Rocket Engine Program; 2.2 MJ Capacitor Bank; Compact Neutron Source | Anatoly Zhitlukhin, Alexey Voronov | Applied engineering of high-power plasma accelerators; pulsed power systems; plasmoid manipulation and collision. Hardware development. | Black |
| Lebedev Physical Inst. (LPI) / Bauman | Compact Toroid Challenge | S.V. Ryzhkov, A.G. Mozgovoy, I.V. Romadanov | Fundamental physics of CT formation; flux trapping. | White |

| | | | | |
|---|-----------------------------------|-----|---|------------------|
| MSTU | (CTC) | | Explicitly identified "thermonuclear motor" application. Talent pipeline. | |
| Kurchatov Institute | N/A (Institutional Oversight) | N/A | Premier national institute for fusion research; provides strategic direction and high-level scientific/political capital. | Oversight |
| Budker Inst. of Nuclear Physics (BINP) | Neutral Beam Injector Development | N/A | Specialized provider of critical sub-systems (e.g., neutral beams) required for advanced FRC heating and stability. | Support |

IV. PIR 3: Analysis of the Israeli Knowledge Acquisition Network

It is assessed with **High Confidence** that Israel is actively engaged in a clandestine national program related to advanced aerospace propulsion based on compact fusion principles. This program is distinguished not by large-scale domestic hardware, but by a highly efficient, human-capital-centric strategy for knowledge acquisition. The ecosystem is designed to leverage foreign expertise and facilities to build a domestic capability with strong, albeit

covert, links to the national defense infrastructure. This model is the most resource-efficient of the three nations analyzed, outsourcing the most capital-intensive aspects of research and development while focusing on the most valuable asset: elite, specialized personnel.

4.1. The Technion P4 Laboratory: A National Incubator

The entire Israeli effort is centralized around a single academic hub: the Plasma and Pulsed Power (P4) Laboratory in the Physics Department of the Technion - Israel Institute of Technology.¹

- **Professor Yakov Krasik's Central Role:** The P4 Laboratory, and by extension the entire network, is directed by Professor Yakov Krasik. His background is uniquely suited to this role. Having received his M.Sc. and Ph.D. from premier institutions in the former Soviet Union (Tomsk Polytechnic Institute and JINR, Dubna) and having led a high-power ion beam laboratory in Tomsk for over a decade, he brought a deep, firsthand knowledge of the rigorous Soviet pulsed power and plasma physics ecosystem to Israel.¹ Upon establishing the P4 lab at the Technion in 1997, he created a critical bridge, allowing this valuable body of knowledge to be transferred to a new generation of Israeli scientists.¹
- **Foundational Research Focus:** The P4 lab's research portfolio aligns perfectly with the foundational technologies required for any FRC or CFR program. Stated research interests include high-energy-density physics, warm dense matter, pulsed power systems, high-power microwave generation, and the generation of strong shock waves—the core scientific disciplines necessary to form, heat, and confine a compact torus plasma.¹ The laboratory is equipped with unique pulsed power generators capable of delivering tens of gigawatts and up to 1 Mega-Ampere currents, making it a world-class facility for this type of research.⁷⁵

4.2. International Placement and Knowledge Transfer Vectors

Israel's primary strategy for capability development is the targeted placement of the P4 lab's top graduates into world-leading FRC research centers in the United States. This allows Israel to acquire critical, hands-on "tribal knowledge" of operational FRC hardware without incurring the immense cost and time required to build such facilities domestically.¹

- **Dr. Vladislav Vekselman:** After completing his Ph.D. under Krasik in 2012, Dr. Vekselman was placed as an Associate Research Physicist at the **Princeton Plasma Physics Laboratory (PPPL)**, a premier U.S. government-funded fusion center.¹ Critically, his

publication record also shows him as a co-author on experimental work from the C-2W "Norman" device at **TAE Technologies**, the leading private FRC fusion company.¹ This dual-affiliation makes him an exceptionally high-value intelligence asset, creating a direct human bridge from the Technion incubator to the two most significant FRC research programs in the United States. As of 2024, he remains at PPPL, with his research focus having shifted to nanomaterial synthesis in plasma environments.⁷⁷

- **Dr. Shurik Yatom:** After completing his Ph.D. under Krasik in 2014, Dr. Yatom also joined **PPPL**, where he is now a Staff Research Physicist.¹ His work centers on advanced plasma diagnostics, including laser spectroscopy and scattering methods.⁸⁰ This specialization addresses a notoriously difficult and critical engineering challenge for any FRC program, which requires precise measurements in an extremely harsh electromagnetic and thermal environment.

The continued, long-term placement of both Vekselman and Yatom at PPPL indicates a deep-immersion strategy designed to acquire comprehensive expertise. Their ultimate career destination—whether they will be repatriated to Israel to lead a domestic hardware program, transition to a commercial entity like nT-Tao, or be placed in a new foreign center—remains a priority intelligence gap.

4.3. Defense Industrial Base Linkages

The connection between the Technion-based academic network and Israel's state-owned defense industry is a critical indicator of the program's strategic intent.

- **Rafael Advanced Defense Systems:** While no joint patents or publications on FRC/CT topics between Krasik's lab and Rafael were identified in the available data, this absence is likely a feature of classification, not a lack of connection.⁸³ A foundational link is confirmed through other sources. Professor Krasik's own curriculum vitae lists research and seminar activities with Rafael from 1994 to 2006 on topics directly relevant to pulsed power, such as plasma opening switches.¹ Furthermore, broader funded research programs at the Technion list Rafael as a sponsor for related technologies like MEMS, establishing a clear institutional precedent for collaboration.⁸⁷
- **Israel Aerospace Industries (IAI):** No direct, open-source linkages—such as patents, joint projects, or cooperative agreements—were found between the Krasik network and IAI.⁷⁵

The established, long-standing relationship with Rafael, combined with the complete lack of open-source discussion of FRC/CT topics in that context, strongly suggests that any substantive collaboration is conducted under a high degree of classification and

compartmentalization.

4.4. The nT-Tao Nexus and Operational Security

The Israeli startup nT-Tao is assessed to be a critical nexus in the ecosystem, functioning as a "Gray Track" entity that blends a commercial fusion energy mission with national security interests. This structure provides a powerful and deniable channel for technology development and the repatriation of acquired knowledge.¹

- **nT-Tao as a "Gray Track" Analog:**
 - **Leadership with Military-Academic Roots:** The company's CEO and co-founder is **Oded Gour-Lavie**, a retired Rear Admiral from the Israeli Navy who previously commanded the submarine fleet.⁹³ Crucially, he holds a B.S. in electrical engineering from the **Technion**, providing a direct link between the company's senior leadership, the Israeli military, and the primary academic talent incubator.
 - **Relevant Technology Focus:** nT-Tao is developing a compact, container-sized (10–20 MWe) fusion reactor based on a high-density, pulsed system that leverages a stellarator-like magnetic confinement scheme.⁹³ This focus on a compact, high-power-density system aligns with the technical requirements for a mobile or transportable power source suitable for propulsion or remote military applications.
 - **Formalized Academic Collaboration:** nT-Tao has established formal collaborations with the key Israeli academic centers, including the **Technion**, Ben Gurion University, and Bar Ilan University.⁹⁵ A peer-reviewed study on plasma diagnostics was conducted jointly by nT-Tao and Krasik's P4 lab at Technion, funded by a joint grant from the **Israel Innovation Authority**, cementing the official link between the commercial entity and the academic research base.⁹⁶
- **Operational Security (OPSEC) Posture:** The Israeli ecosystem exhibits all the hallmarks of a sophisticated OPSEC posture, consistent with the nation's established doctrine for protecting its most sensitive national security programs.¹
 - **Compartmentalization:** The use of a commercial startup (nT-Tao) to house applied development creates a firewall, separating it from both the open academic research at the Technion and the highly classified environment of defense primes like Rafael. This structure allows for rapid, agile development while maintaining plausible deniability.
 - **"Complete Silence" Doctrine:** The conspicuous absence of direct, dispositive evidence—such as a public contract between the Technion and the Ministry of Defense for FRC research—is itself a key intelligence signature. As demonstrated by Israel's nuclear program, a "complete silence" operational security posture is the expected characteristic of a top-tier national security effort.¹ The lack of evidence is, in this context, evidence of a highly secured program.

- **Intellectual Property Control:** While nT-Tao holds patents on its "High efficiency plasma creation system," these are framed for general energy applications, effectively obscuring any specific innovations relevant to propulsion or other military uses.⁹⁴

Table 3: Key Israeli Institutions and Personnel in the FRC/CT Knowledge Network

| Personnel Name | Origin (Advisor/Lab) | International Placement (Institution & Role) | Domestic Destination/Role | Assessed Expertise & Significance |
|--------------------------------|----------------------|--|--|--|
| Prof. Yakov Krasik | N/A (Founder) | N/A | Director, P4 Lab, Technion | Central node and national incubator; expert in pulsed power and HEDP. ¹ |
| Dr. Vladislav Vekselman | Ph.D., Krasik/P4 Lab | PPPL (Assoc. Research Physicist); TAE Tech. (Collaborator) | TBD (Priority Intel Gap) | High-value knowledge vector with access to both top US public and private FRC programs. ¹ |
| Dr. Shurik Yatom | Ph.D., Krasik/P4 Lab | PPPL (Staff Research Physicist) | TBD (Priority Intel Gap) | Specialist in advanced plasma diagnostics, a critical enabling technology for FRCs. ¹ |
| Dr. David Yanuka | Ph.D., Krasik/P4 Lab | N/A | Research Fellow, Faculty of Aerospace Engineering, | Domestic bridge applying plasma |

| | | | | |
|------------------------|-------------------------|-----|--|--|
| | | | Technion | diagnostics expertise to hypersonic flow research. ¹ |
| Dr. Tai Queller | Ph.D., Krasik/P4 Lab | N/A | Research Scientist, Weizmann Institute of Science | Disseminates P4 Lab expertise to another elite Israeli institution, broadening the domestic knowledge base. ¹ |
| Oded Gour-Lavie | B.S. Eng., Technion | N/A | Founder & CEO, nT-Tao | Leader of the primary "Gray Track" entity; direct link between military leadership, Technion, and applied R&D. ⁹³ |

V. Comparative Synthesis and Strategic Outlook

The analysis of the FRC/CT technology ecosystems in Russia, Israel, and Japan reveals three distinct national strategies for developing a strategic capability in advanced plasma propulsion. Each model is tailored to the nation's unique industrial base, resource constraints, and strategic culture, yet all three effectively leverage variations of the tiered "Black, Gray, White" program structure to achieve their objectives. The convergence of these independent, state-level programs on the same underlying FRC/CT physics validates the technology's perceived high strategic value and confirms that the United States is engaged in a complex, multi-polar technology race.

5.1. Comparative Analysis of National Models

A direct comparison of the three national programs, mapped against the U.S. tiered strategy template, highlights their fundamental differences in approach.

- **Russia (State-Directed Bifurcation):** Russia employs a classic, top-down model reminiscent of the Soviet era. The state, through its nuclear corporation Rosatom, directs a hardware-focused "Black Track" at TRINITI. This applied program is supported and fed by a state-sanctioned academic "White Track" at institutions like the Lebedev Physical Institute and the Kurchatov Institute. The roles are clearly delineated: academia provides the foundational theory and talent, while the state-owned industrial institute builds the hardware. This is a robust, resilient, but potentially less agile model.
- **Israel (Human Capital Outsourcing):** Israel has adopted a lean, agile, and intelligence-driven model that is exceptionally resource-efficient. It uses its world-class academic "White Track" (the Technion P4 Lab) as a national incubator to produce elite talent. It then "outsources" the most capital-intensive phase of R&D by placing this talent inside premier U.S. "Black" and "Gray" track facilities (PPPL, TAE Technologies) to acquire hands-on knowledge. This invaluable expertise is then repatriated into a domestic "Gray Track" (nT-Tao), a deniable commercial entity with strong military leadership, which serves as the vehicle for applied development.
- **Japan (Industrial Ecosystem Cultivation):** Japan is pursuing a modern, economically-driven strategy that is arguably the most sophisticated of the three. Rather than repurposing old state labs, the government is actively cultivating a new, vibrant, and competitive private-sector "Gray Track" (Kyoto Fusionering, Helical Fusion). This is achieved through national strategy, targeted government funding, and the encouragement of large-scale corporate investment. This entire industrial effort operates under the public-facing legitimacy of a massive, international "White Track" project (the FAST project), which serves to build the national supply chain and divert foreign scrutiny. This model creates a powerful, dual-use industrial base that can support both commercial energy and a rapid military breakout capability on demand.

5.2. Assessment of Global Technology Race Dynamics

The evidence confirms that the pursuit of FRC/CT technology is not a bipolar competition but a multi-polar great power competition, with each major player pursuing distinct strategic goals.¹ Russia's explicit focus on a "thermonuclear motor" points toward a direct military application for strategic mobility or space control. Israel's low-signature, high-OPSEC

approach is consistent with the development of a strategic deterrent or a niche, high-impact tactical capability. Japan's strategy is one of creating strategic options; by building a world-class industrial capacity in fusion technology, it positions itself to become a leader in a future energy market while simultaneously creating the latent capability to become a formidable military-technical peer if its strategic posture were to change. The parallel development of these programs provides a critical context for understanding the extreme measures taken by the U.S. to protect its own clandestine programs, such as the asset denial operation involving MH370, which was deemed necessary to preserve a time-sensitive technological lead in this clandestine arms race.

5.3. Intelligence Gaps and Recommendations

Despite the clarity gained from this analysis, significant intelligence gaps remain. Closing these gaps is essential for maintaining an accurate picture of the evolving strategic landscape. The following collection and analysis efforts are recommended:

- **Regarding Japan:**
 - **Priority 1:** Initiate human capital tracking focused on the movement of graduate students and postdoctoral researchers from the plasma physics and pulsed power departments at Nagoya, Osaka, and Kumamoto universities to the R&D divisions of Japanese defense primes (e.g., MHI, KHI) and the emerging "Gray Track" fusion companies.
 - **Priority 2:** Conduct continuous monitoring of the publication rates and funding sources for Kyoto Fusioneering and Helical Fusion. A sudden decrease in technical publications on a specific technology vertical, especially following the successful completion of a MEXT-funded project, should be treated as a primary indicator of a transition to classified work.
- **Regarding Russia:**
 - **Priority 1:** Task technical intelligence assets (SIGINT, IMINT) to monitor the TRINITY facility in Troitsk. The objective is to characterize the operational parameters (e.g., repetition rate, power output, electromagnetic signature) of the 2.2 MJ pulsed power system and associated plasma accelerators to determine their true application.
 - **Priority 2:** Maintain close monitoring of the career trajectory of Ivan Romadanov. His eventual departure from PPPL, and his subsequent destination, will be a key indicator of the Russian program's next phase.
- **Regarding Israel:**
 - **Priority 1:** Prioritize intelligence collection on the final career destinations of Dr. Vladislav Vekselman and Dr. Shurik Yatom upon the conclusion of their tenures at PPPL. Their transition to nT-Tao, a formal Israeli defense entity, or a new, unidentified startup would be a highly significant indicator.

- **Priority 2:** Allocate human intelligence resources to penetrate the institutional firewalls between the Technion P4 Laboratory, the commercial entity nT-Tao, and the Israeli defense establishment (specifically Rafael) to confirm the nature, scope, and funding of any classified collaboration on FRC/CFR technology.

Table 4: Comparative Matrix of National Program Structures vs. U.S. Tiered Model

| Track | United States (Analog) | Russian Federation | State of Israel | Japan |
|---|--|--|--|--|
| White Track (Public/Academic/Misdirection) | NAVAIR (Pais Patents); University Labs (e.g., Auburn) | Lebedev Physical Inst.; Bauman MSTU; Kurchatov Inst. | Technion (P4 Lab); Weizmann Inst. | FAST Project; University Labs (Nagoya, Osaka, etc.) |
| Gray Track (Commercial/Dual-Use) | MSNW LLC; UnLAB LLC; TAE Technologies; Helion | N/A (State-controlled model lacks a true commercial analog) | nT-Tao | Kyoto Fusionneering; Helical Fusion |
| Black Track (Clandestine/Military Hardware) | Lockheed Martin Skunk Works® (CFR Program) | Rosatom / TRINITI (Pulsed Power & Accelerator Program) | <i>Assessed to be in development, likely within a commercial/defense nexus</i> | <i>Assessed as a latent capability within the Gray Track ecosystem</i> |

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