Department of Aeronautics and Astronautics  
School of Engineering  
Massachusetts Institute of Technology  

Graduate Program (S.M., Ph.D., Sc.D.)  

**Field:** Space Propulsion and Plasmas  
**Date:** December 6, 2020  

**Introduction and Purpose**

The graduate program in the Department of Aeronautics and Astronautics at MIT provides educational opportunities in a wide variety of aerospace-related topics through academic subjects and research. The purpose of this document is to provide incoming masters and doctoral level students guidance in planning the subjects they will take during their graduate program. The suggestions outlined here are to be understood as guidance and not as a mandatory, rigid framework. The final decision as to which subjects are taken and in what sequence is to be decided between each student and their academic advisor and/or doctoral committee. In addition to these recommendations, the official S.M. and doctoral degree completion requirements must be taken into account during the design of a graduate program.

**What is Space Propulsion Engineering?**

Space Propulsion comprises the propulsion technology required to reach space, as well as that which can be used to maneuver in space. The first category (space access) remains confined to chemical rocketry, although some attempts continue to be made at electromagnetic or other alternative means of high-g propulsion. The in-space category, by contrast, has evolved towards the use of more mass-effective types of thruster, such as Electric Propulsion rockets, solar sails or electrodynamic tethers. The key difference in this case is the possibility of accumulating momentum for a long time, at the very low rate allowed by the limited supply of power available in space. Electric Propulsion (EP) has had a long laboratory maturation period, going back to the early 1960’s, and has now reached the practical application stage, to the point that essentially all new satellites, commercial as well as scientific or military, now feature some form of EP as their nominal propulsion system. An intermediate category, Nuclear Thermal propulsion, exists in principle, although environmental, economical and sometimes political obstacles have prevented its application so far.

Chemical launch engines develop thrust levels that are many orders of magnitude larger than their in-space counterparts, and therefore any improvement to their performance would appear to offer correspondingly larger returns in terms of payload capability. On the other hand, for missions that require substantial cumulative velocity increments after reaching orbit, any improvement on the performance of the in-space propulsion system will reduce the payload mass for the launcher, thus allowing a proportional reduction of the launcher mass and cost. Chemical rockets have nearly

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1 Refer to the S.M., Ph.D. and Sc.D. degree requirements in Aeronautics and Astronautics section of the MIT Bulletin, or to [http://aeroastro.mit.edu/graduate-program](http://aeroastro.mit.edu/graduate-program)
reached their technological maturity, with improvements mainly being sought in the areas of reliability, cost, diagnostics or controllability. Some exceptions are the potential for active control of combustion instabilities, or the possible miniaturization of these rockets.

In contrast, Electric Propulsion and its extensions continue to offer many opportunities for incremental and even revolutionary developments. Aside from immediate utilitarian considerations, students that specialize in this field have an opportunity to learn and use physics concepts that go beyond the usual Aero/Astro range, including plasma physics, micro- and nano-technology, high temperature fluid physics, etc, and can later access areas of technology that are also broader than usual, Figure 1.

Figure 1: Selected images from MIT Space Propulsion research Left: A vacuum tank for testing space propulsion devices. Center: Plasma plume from the Divergent Cusped Field thruster. Right: Microfabricated array of electrospray emitters. Bottom: MEMS Electrospray thrusters for small satellites.

Propulsion in general is a discipline that requires both, mastery of fundamentals and integration skills. A Space Propulsion specialist should be conversant with the requirements imposed by the overall mission goals (orbit dynamics, mass and power limitations, relative cost of time, etc), those imposed by the spacecraft itself (thermal isolation between thrusters and bus, plume impingement effects and limitations, like voltage limitations and EM noise bounds), and methods for rationally selecting overall parameters (specific impulse, thrust and power level, etc) for reliable and sometimes optimal mission performance. But in addition, the specialist should also be familiar with the basic physics of the devices, which can be fairly sophisticated and unfamiliar to non-scientists. This is true even for engineers whose job will be to integrate propulsion systems into spacecraft, and it becomes essential for those whose job will be to develop and refine those thrusters. An exciting new direction in the development of Space Propulsion technology focuses on their application to small spacecraft, including the now popular backpack-sized CubeSats. Providing these small satellites with high-performance on-board propulsion would enable them to do not only what their bigger counterparts can do in earth orbit, but also explore deep-space destinations, including near earth asteroids.
**Why is Plasma Science and Technology relevant?**

Some of the students selecting this field of study may choose to specialize in one of the fundamental disciplines that many in-space propulsion technologies depend on: Plasma Science. A plasma is defined as a collection of positively and negatively charged ions, negatively charged electrons and neutral species. The main characteristic of the plasma is that, when looked as a macroscopic average, it is electrically neutral, i.e., it has the same number of positive and negative charges. This neutrality eventually breaks down at the atomic scale, at the edges of the plasma or at the interface with a wall, as well as for very rapid perturbations (faster than the so-called plasma frequency). Because of this, it is said that a plasma is quasi-neutral. In a general sense, a plasma is like a multi-component fluid, and in many instances its behavior can be described with the same set of tools used to describe regular fluids, with one exception: plasmas react to electric and magnetic fields, and as such we need to consider stresses in addition to the hydrodynamic ones regular fluids experience. This response to electromagnetic fields enables the generation of propulsive forces that can be used for in-space applications. In addition, plasma chemistry is very rich and hence, in many cases, plasma has to be treated as a reacting flow, making plasmas extremely useful for a wide range of chemical applications such as combustion, fuel production, or CO₂ conversion.

Aside from space-propulsion, in the past few years, new interests in Plasma Physics and integration of plasma technology into aerospace applications has emerged, Figure 2. Some of these applications include plasma-based flow control including boundary layer actuation and shock modification; and plasma-assisted combustion, or the unlocking of new reaction pathways through electron impact reactions to tackle challenging combustion regimes such as lean and ultra-lean combustion (for interest in low NOx emissions) or supersonic conditions. In addition, a deep command of plasma science and gas discharge physics is required to protect and mitigate against the natural environment in which aircraft and spacecraft live, e.g. protection of aircraft and launch vehicles against lightning strikes (plasma arcs).

![Figure 2: Selected images from MIT Aerospace Plasma Group research. Left: Lightning initiation studies from a model aircraft. Center: Streamer corona discharge of relevance for atmospheric electricity studies and nonthermal plasma generation. Right: Different plasma regimes observed in a Dielectric Barrier Discharge operated with Pulsed Nanosecond Discharges. Bottom: Plasma-actuated mm-scale reactor showing different plasma regimes.](image)
A specialist in Aerospace Plasma Science and Technology should be well-versed in the fundamentals of plasma physics and be able to develop fundamental plasma models, computational techniques and algorithms as well as perform advanced experimental diagnostics, all of which are essential to advance the field. Given the interdisciplinarity of the field, the Aerospace Plasma specialist should also be familiar with the applications of interest, including aerodynamics, combustion or aircraft design.

Educational Goals in Space Propulsion and Plasmas

The educational goal of the MIT graduate program in Space Propulsion Engineering is to provide students with a foundational understanding and a working knowledge of the many technical issues surrounding the design, operation and integration of the propulsion systems used in space. This includes both, chemical and non-chemical types of propulsion systems, although the latter category is emphasized for its closer ties to research conducted at MIT.

The educational goal of the MIT graduate program in Plasma Science and Technology is to provide students with a foundational understanding and a working knowledge of both the fundamentals of plasmas, ionized gases and electrical discharges as well as the many technological applications that they can enable, both existing and emerging.

Successful graduates of the program will have:

- Acquired an understanding of propulsion system requirements and constraints, as dictated by the overall space mission goals.
- Gained a fundamental familiarity with the physical principles that underlie the production and control of the high-energy gas, ions or plasma jets used in space propulsion.
- Acquired and understanding of the technical advantages of plasma technologies, including kinetic-assistance (plasma chemistry) and dynamics.
- Gained a fundamental familiarity with the principles of plasma science, including analytical and numerical modeling as well as experimental diagnostics.
- Generated research contributions to the current space propulsion engineering or aerospace plasma engineering body of knowledge.

Educational Plan in Space Propulsion and Plasmas

The educational goals outlined above lead to a program of study based on a set of courses that provides the tools and knowledge required to support the objectives of the Space Propulsion and Plasmas graduate field:

A. Core Subjects
- 16.522 Space Propulsion
- 16.55 Ionized Gases
B. Additional Subjects

- 2.25 Fluid Mechanics
- 2.28 Fundamentals and Applications of Combustion
- 6.640 Electromagnetic Fields, Forces and Motion
- 8.311 Electromagnetic Theory I
- 16.346 Astrodynamics
- 16.512 Rocket Propulsion
- 22.611 Introduction to Plasma Physics I
- 22.612 Introduction to Plasma Physics II
- 22.67 Principles of Plasma Diagnostics

All students have to meet the departmental Mathematics Requirement (see separate document available from the graduate student office) with one graduate level mathematics course for the S.M. and two for the Ph.D. The department keeps a list of mathematics courses that are acceptable for fulfillment of this requirement.

While the structure of the graduate program is quite flexible, it is typical for students in the Space Propulsion and Plasmas field to be focused on one of three specific topic areas: Physics, Technology or Applications.

The Physics foundation courses support an in-depth understanding of the fundamental principles of the field. For example, an emphasis on continuum fluid dynamics is suggested for students attracted by chemical propulsion: Fluid Mechanics (2.25) and Compressible Internal Flow (16.120). A solid background in Plasma Physics is recommended for the student interested in electric propulsion and other aerospace technologies: Ionized Gases (16.55), Introduction to Plasma Physics I (16.611) and II (16.612), and Principles of Plasma Diagnostics (22.67). Those wishing to study novel thruster regimes should receive additional instruction in the interaction of fields with matter: Electromagnetic Fields, Forces and Motion (6.640) or similar subjects. Those interested in plasma-assisted combustion should receive additional instruction in reacting flows: Fundamentals and Applications of Combustion (2.28) or similar subjects.

The Technology foundation provides the student with the knowledge required to design and build propulsion systems or novel plasma technologies. For instance, Rocket Propulsion (16.512), which studies in detail the components of chemical propulsion engines and their interactions, and Space Propulsion (16.522), a comprehensive review of thruster technologies applied to move spacecraft once they leave the Earth’s atmosphere. Micropropulsion systems have benefited considerably on the development of Micro-Electro-Mechanical Systems (MEMS), this is why Design and Fabrication of MEMS (6.777) or similar subjects are relevant when studying miniaturized propulsion systems.

Propulsion sub-systems have an important influence on the design and operation of space missions. Application subjects such as Satellite Engineering (16.851) and Space Systems Engineering (16.89) allow the student to understand system-wide interactions and design accordingly. Astrodynamics (16.346) describes the tools required to calculate orbital elements and velocity changes for a particular mission or maneuver.

The SM degree subject requirement is 66 units, or a minimum of 6 courses. At least 21 should be from those offered by the Department of Aeronautics and Astronautics. The following are three examples of SM programs based on these guidelines:
While the program structure is flexible, students interested in doctoral work must take 3 subjects from sets A and B above, including at least one from the core A to fulfill the Field Evaluation requirements. In addition, doctoral candidates need to agree with their advisors on a set of 5 subjects for their major and 3 subjects for their minor field.

**Additional Courses related to Space Propulsion and Plasmas**

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<thead>
<tr>
<th>Course Code</th>
<th>Course Name</th>
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<tbody>
<tr>
<td>2.37</td>
<td>Fundamentals of Nanoengineering</td>
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<tr>
<td>2.62</td>
<td>Fundamentals of Advanced Energy Conversion</td>
</tr>
<tr>
<td>3.53</td>
<td>Electrochemical Processing of Materials</td>
</tr>
<tr>
<td>6.777</td>
<td>Design and Fabrication of MEMS</td>
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<tr>
<td>6.781</td>
<td>Nanostructure Fabrication</td>
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<tr>
<td>8.333</td>
<td>Statistical Mechanics I</td>
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<tr>
<td>8.624</td>
<td>Plasma Waves</td>
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<tr>
<td>16.540</td>
<td>Internal Flows in Turbomachines</td>
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<tr>
<td>16.120</td>
<td>Compressible Internal Flow</td>
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<td>16.89</td>
<td>Space Systems Engineering</td>
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<tr>
<td>MAS.859</td>
<td>Space technology for the Development Leader</td>
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<tr>
<td>5.68</td>
<td>Kinetics of Chemical Reactions</td>
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<tr>
<td>16.13</td>
<td>Aerodynamics of Viscous Flows</td>
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<tr>
<td>2.29</td>
<td>Numerical Fluid Mechanics</td>
</tr>
<tr>
<td>16.110</td>
<td>Flight Vehicle Aerodynamics</td>
</tr>
<tr>
<td>16.343</td>
<td>Spacecraft and Aircraft Sensors and Instrumentation</td>
</tr>
<tr>
<td>16.511</td>
<td>Aircraft Engines and Gas Turbines</td>
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Faculty and Staff with Interests in Space Propulsion and Plasmas

Paulo Lozano
*M. Alemán-Velasco Professor of Aeronautics and Astronautics*
37-401
(617) 258-0742
plozano@mit.edu
Electrospray propulsion, micro-fabrication, ion beam technology, small satellite mission design, space technology development

Carmen Guerra-Garcia
*Atlantic Richfield Career Development Professor in Energy Studies*
31-321
(617) 258-6762
guerrac@mit.edu
https://guerra.mit.edu
Plasma physics and aerospace applications, multiphysics modeling and experimentation, propulsion, combustion, lightning strike protection, nonthermal plasma technology

Please consult MIT Aero & Astro web-page for detailed faculty and staff interests:
http://aeroastro.mit.edu/faculty-research