EECS 517 / NERS 578: Physical Processes in Plasmas
Fall 2012 - TuTh 10:30 AM - 12:00 PM - 1012 EECS

Instructor: **Mark J. Kushner**
2236 EECS Building (734-647-8148)
Office Hours: Afternoons or by appointment
e-mail: mjkush@umich.edu

Goals of Course: This course addresses the fundamental science and technology of low temperature, partially ionized, non-equilibrium plasmas. This class of plasmas is used, for example, for etching and deposition of materials, surface treatment, lighting sources, flat panel displays, welding, laser ablation, lasers and biomedical applications. These plasmas are also naturally occurring, such as the aurora, shock waves and lightning. The objectives of this course are to first provide a foundation of the fundamentals of electron-atom collisions, electron and ion transport and the different ways in which low temperature plasmas are created. After providing this foundation, the course will apply those fundamentals to study of the technologies which use partially ionized plasmas, with examples taken from lasers, plasma materials processing, lighting sources and plasma medicine.

Grading Policy: The field of low temperature plasmas is intrinsically interdisciplinary. The linkages between the supporting fields are best appreciated by problem solving in a real-world context. As a result, one will not be able to fully benefit from the course without putting a good-faith effort into the homeworks. To acknowledge the importance of homework, it is being heavily weighted in the grading policy. The grading policy will be:

Homework	30%
Mid-Term Exam	30%
Final Project	30%
Instructor's discretion	10%

Instructor's discretion includes my qualitative assessment of students' effort towards the course (e.g., class attendance and participation).

Texts:

Required: M. Lieberman, Principles of Plasma Discharges and Material Processing, 2nd Edition (Wiley, New Jersey, 2005)

Optional Text: A. Friedman and L. A. Kennedy, Plasma Physics and Engineering (Taylor and Francis, New York, 2004)

Note that both of these texts are available electronically through a subscription by the UM Engineering Library.

It may interest you and your students to know that the library has purchased access to e-book versions of these texts.

"Principles of Plasma Discharges and Materials Processing" can be accessed online at http://mirlyn.lib.umich.edu/Record/009855464

"Plasma Physics and Engineering" can be accessed online at http://mirlyn.lib.umich.edu/Record/004721840

Alternate Meeting Time:

Prof. Kushner would like to schedule an alternate meeting time for classes that are missed due to travel. A signup sheet will be provided to indicate times that are good for you.

Course Website: A combination of CTools and a separate course website will be used to distribute materials and for class communications. The alternative course website is located at:

http://uigelz.eecs.umich.edu → Classes → EECS 517

The materials that will be posted on the website include:

1. Introductory materials
2. Homework assignments
3. Handout Packages (Note that some, but NOT ALL of the handouts can also be downloaded individually!)
4. Class announcements (such as cancellations, rescheduled classes, exam dates)

Course Map

"Gaseous Electronics is the study partially ionized gases and their application to technologically relevant devices."

MICROSCOPIC → **MACROSCOPIC**

Electron collisions

Cross sections, rate coefficients

Gas discharge theory
Electron production, loss
Sheaths
Electron distribution functions
Transport coefficients

Low pressure dc discharge devices

High pressure discharges and
e-beam pumped plasmas

rf and microwave discharges

Diagnostics

Applications:
Plasma etching
Toxic Gas Remediation
Special Topics

Syllabus and Reading Assignments (Version 03)

Reading assignments in Lieberman are required. Others are recommendations for background.

Unit	Topic	Class	Reading Assignments (Chapters or sections)	
			Lieberman	Fridman
I	Introduction	1	1	1
II	Electron Collisions	2,3	3,8, Appendix A	2,3
III	Cross Sections and Rate Coefficients	4,5	3,8	2,3
IV	Gas Discharges	6	2	7
V	Electron Continuity Equation, Diffusion, Production, Loss	7,8,9	2,5	4.5
VI	Sheaths	10,11	6.1-6.5, Handouts	6.1
VII	Electron Distribution Functions	12	2, Appendix B	4.1-4.2
VIII	Transport Coefficients	13	5	6
IX	Low Pressure DC Discharges	14	10,14	7.12-7.8
X	High Pressure Discharges and Electron Beam Pumped Plasmas	16	Handouts	12
XI	RF and Microwave Discharges	17,18	11,12	10.5-10.6, 10.9
XII	Fully Ionized Plasmas	19	4, Handouts	
XIII	Magnetic Fields in Discharges	20	4	6.2
XIV	Inductively Coupled Plasmas	21	12	10.7
XV	Diagnostics	22	6.6	
XVI	Atmospheric Pressure Plasmas	23,24		9
XVII	Plasma Chemistry	25	7	3.7
XVIII	Applications and Special Topics (to be selected by class)	26,27		
	a. Plasma Etching/Deposition/Surface Chemistry		9, 15, 16	
	b. ECR and Helicon		13.1,13.2	10.8
	c. Plasmas in Liquids		Handouts	
	d. Plasma Medicine		Handouts	
	e. Dielectric Barrier Discharges		Handouts	9.3

Required: M. Lieberman, Principles of Plasma Discharges and Material Processing, 2nd Edition (Wiley, New Jersey, 2005)

Optional Text: A. Friedman and L. A. Kennedy, Plasma Physics and Engineering (Taylor and Francis, New York, 2004)

Class Schedule (Version 03)

The class schedule is listed below. Due to my travel commitments this Fall, we have scheduled alternate makeup lectures. The times and locations of the alternate classes will be determined….

Alternate Classes:

Date			**Time**	**Room**
19	Oct.	Friday	12-1 pm	EECS 1008
26	Oct.	Friday	2-3 pm	EECS 1012
7	Dec.	Friday	1-2 pm	EECS 1012

Class Schedule: Tu/Th 10:30 am -12:00 noon, EECS 1012 (Version 03)

Class	Day	Date		Comment	Approximate (!) Topic (See Syllabus for Reading Assignment)
1	T	4	Sept.		Introduction
2	Th	6	Sept.		Electron Collisions
3	T	11	Sept.		Electron Collisions
4	Th	13	Sept.		Cross Sections and Rate Coefficients
5	T	18	Sept.		Cross Sections and Rate Coefficients
6	Th	20	Sept.		Gas Discharges
7	T	25	Sept.		Electron Continuity, Diffusion, Sources
8	Th	27	Sept.		Electron Continuity, Diffusion, Sources
9	T	2	Oct.		Electron Continuity, Diffusion, Sources
10	Th	4	Oct.		Sheaths
11	T	9	Oct.		Sheaths
12	Th	11	Oct.		Electron Energy Distributions
	T	16	Oct.	Fall Study Break	
13	Th	18	Oct.		Electron Energy Distributions and Transport Coefficients
14	F	19	Oct.	Alternate Meeting, 12-1 pm, EECS 1008	Low Pressure DC Discharges
15	T	23	Oct.		*Mid-Term Exam*
	Th	25	Oct.	MJK Travel	Low Pressure DC Discharges
16	F	26	Oct.	Alternate Meeting, 2-3 pm, EECS 1012	Low Pressure DC Discharges
	T	30	Oct.	MJK Travel	
17	Th	1	Nov.		High Pressure and e-beam pumped plasmas
18	T	6	Nov.		RF Discharges
19	Th	8	Nov.		RF Discharges
20	T	13	Nov.		Fully Ionized Plasmas
21	Th	15	Nov.		Magnetic Fields in Discharges
22	T	20	Nov.		Inductively Coupled Plasmas
	Th	22	Nov.	Thanksgiving Recess	
23	T	27	Nov.		Diagnostics
24	Th	29	Nov.		Atmospheric Pressure Plasmas
	T	4	Dec.	MJK Travel	
25	Th	6	Dec.		Plasma Chemistry
26	F	7	Dec.	Alternate Class, 1-2 pm, EECS 1012	Special Topics – or Project Presentations
27	T	11	Dec.		Special Topics – or Project Presentations
	F	14	Dec.	Final Project Due (5:00 pm)	

Supplementary Texts and References
****= On Reserve at UM Engineering Library**

J. R. Roth **Industrial Plasma Engineering. Vol 1 & 2** **
Practical view of low temperature plasma physics from an engineering perspective.

A. Fridman & L. A. Kennedy **Plasma Physics and Engineering** **
Comprehensive text on low temperature plasmas

A. Fridman **Plasma Chemistry** **
Physics of low temperature plasmas and application to gas phase and surface chemistry.

*C. K. Birdsall & A. B. Langdo*n **Plasma Physics via Computer Simulation** **
Introductory text on the use of Particle-in-Cell simulations for modeling plasmas.

P. Chabert & N. Braithwaite **Physics of Radio-Frequency Plasmas**
Recent monograph on RF discharges of the type used for plasma materials processing.

M. Mitchner **Partially Ionized Gases** **
Mostly for fully ionized plasmas but good treatment of sheaths, continuity equations, and electron-ion collisions.

G. Bekefi **Principles of Laser Plasmas**
Specialty items such as recombination, discharge stability and vibrational excitation.

L. M. Biberman, et al. **Kinetics of Nonequilibrium Low-Temperature Plasmas**
Good general reference but difficult to read. (Russian Translation)

S. C. Brown **Basic Data of Plasma Physics**
Classic but dated text for basic topics.

B. Chapman **Glow Discharge Processes**
Good “gut level” monograph. Good source for RF discharges.

F. F. Chen **Introduction to Plasma Physics**
Fully ionized plasmas with good treatment of Debye lengths, and magnetic field effects.

B. Cherrington **Gaseous Electronics and Gas Lasers**
Classic but dated text. Good basic introduction.

J. Cobine **Gaseous Conductors**
Classic, but dated test. Extremely empirical treatment of topics but good presentation. (You can learn something from this book on the first reading.)

L. Huxley **Diffusion and Drift of Electrons in Gases**
Advanced monograph on Boltzmann Equation and Transport Coefficients.

U. Kortshagen **Electron Kinetics and Applications of Glow Discharges**
Proceedings of NATO Workshop. Very good overview articles

L. Loeb **Basic Processes of Gaseous Electronics**
Classic and comprehensive text, but very dated.

D. Manos and *D. Flamm* **Plasma Etching: An Introduction**
Compilation on methods in plasma processing.

T. Mark **Electron Impact Ionization**
Thorough treatment of electron impact collisions producing ionization

E. McDaniel **Ion Molecule Reactions**
Advanced monograph on reactions between ions and neutral atoms/molecules. Good tables of reaction rate coefficients.

L. C. Pitchford, et al. **Swarm Studies and Inelastic Electron-Molecule Collisions**
Compilation of papers on fundamental studies in nonequilibrium electron transport and obtaining cross sections from swarm data.

Y. Razier **Gas Discharge Physics**
If you are going to buy a second text, get this one. It has all the material that's important, but is difficult to read.

Y. Razier **Radio Frequency Capacitive Discharges**
Exhaustive treatment of this important discharge device for plasma etching.

S. Rossnagel **Handbook of Plasma Processing Technology**
Compilation of papers on basics of plasma etching and deposition.

B. M. Smirnov **Physics of Ionized Gases**
Good general reference but difficult to read. (Russian Translation)

A. von Engel **Ionized Gases**
Collection of lectures given at Oxford. Considered a classic for introduction to field.

A. von Engel **Electric Plasmas; Their Nature and Uses**
Simplified view of gas discharges but good introduction.

J. Waymouth **Electric Discharge Lamps**
Defining text for fluorescent lamp physics.

M. Larousii et al. **Plasma Medicine**
Multi-author collection of basic concepts in plasma medicine.

Projects

Instead of a final exam, there will be a final project. The project should consist of developing a model for, or performing an in depth analysis of, a low temperature plasma or electric discharge system. Some possible choices of electric discharge systems are:

- Plasma processing reactors
- Fluorescent lamps
- He-Ne, excimer, CO_2 lasers
- Sputter deposition reactors
- E-beam pumped systems
- Arc jets and plasma thrusters

The project should include a literature search to provide you with background on how these devices operate and to see how other researchers have analyzed them. Some of the models which appear in the literature are quite involved and complex. The intent of the project is not for you to duplicate the complexity of those models. Rather, the intent is to give you some sense of how the device and the "final product" (e.g., laser power, deposition rate, etch rate) scales. Your model should have at least the degree of sophistication of our homework assignments but should include real device parameters. For example, use the actual gas pressures, gas mixtures, dimensions, cross sections, currents, and voltages. (Note, you can obtain the real cross sections for the majority of cases of interest by request from M. Kushner.)

Your final project deliverables will consist of the written report and, optionally, a presentation to the class. The limit on length is 25 pages, though 25 pages are not required. (Fewer pages of higher quality are preferred.) Please include a description of the discharge system, how you have analyzed it, the scaling laws you developed and a discussion of what you have learned. Generously use plots to display parametric results. Your analysis might include issues such as:

- Electron densities
- Electron and ion temperatures
- Current density, power deposition, operating E/N
- Etch or deposition rates
- Electron or ion energy distributions
- Efficiency of producing the "product"
- Densities of excited states.
- Spectrum of emitted light.

Due dates: Friday, December 14, 2011, 5:00 PM
Paper copy to: Prof. Kushner office
PDF copy to: mjkush@umich.edu

Units and Best Practice

Units prove to be a confusing aspect of this course. The units which are *commonly in use* in the field are the "standard" for this course. Unfortunately, the units are "mixed" (that is, a mixture of cgs and mks). Some useful conversion factors are listed below. Some best practices you should follow are:

1. ALWAYS perform a units analysis and perform a "sanity" check to determine that your answer is reasonable. In most cases, "unreasonable" answers are a result of unit problems. For example, if your answer is that the argon ion density in a plasma etching reactor is 10^{50} ions/cm^3, your answer is unreasonable and you probably have a units problem. You know your answer is unreasonable since if the density is really 10^{50} argon ions/cm^3, the mass of 10 cm^3 of the plasma would be equal to twice the mass of the earth.

2. **Never, ever be confused by expressing temperature in Energy Units (or vice-versa). Temperature in Energy Units ALWAYS Means**

$$T\ (eV) \equiv k_B T\ (eV)$$

3. Unless specified otherwise, you final answers in homework problems should be expressed in the following units.

Electron energies or temperatures	eV
Atomic or molecular energy or temperature	K or eV
Length	cm
Electron, atomic or molecular mass	AMU or g
Electron, atomic or molecular speed	cm/s
Cross section	cm^2 or A^2
Mobility	cm^2/V-s
Diffusion coefficient	cm^2/s
Rates coefficient ($1^{st,}$ 2^{nd}, 3^{rd} order)	s^{-1}, cm^3/s, cm^6/s
Electric fields	V-cm^{-1}
Normalized Electric Field	V-cm^{-2} or Td (10^{-17} V-cm^2)
Density	cm^{-3}
Power	W
Power deposition (specific)	W-cm^{-3}
Current density	Amps-cm^{-2}

Useful Conversion Factors

$k = 1.38 \times 10^{-16}$ erg/K = 1.38×10^{-23} J/K

1 eV = 1.6×10^{-12} ergs = 1.6×10^{-19} J $\equiv$ 11,594.2 K

$q = e$ = 1.6×10^{-19} C (coulomb) = 4.8×10^{-10} esu

1 V = 1 J/C = 10^7 erg/C

$\varepsilon_o = 8.85 \times 10^{-12}$ [F/m or C^2/m-J] = 8.85×10^{-14} [F/cm or C^2/cm-J]

m_e (electron mass) = 0.911×10^{-27} g = 0.911×10^{-30} kg

E/N: 1 Td (Townsend) = 10^{-17} V-cm^2 = 10^{-21} V-m^2 = 0.354 V/cm-Torr at (T = 273 K)

1 Å^2 = 10^{-16} cm^2 = 10^{-20} m^2

1 atm = 760 Torr = 1.013 bar

Gas Density: $N = \dfrac{P}{kT} = 9.654 \times 10^{18} \dfrac{P(\text{Torr})}{T(\text{K})}$ cm^{-3}

1 m^3 = 10^6 cm^3

Useful Relationships

Electron speed for energy ε : $v = \left(\frac{2\varepsilon}{m_e}\right)^{1/2}$ = 5.93 x 10^7 $(\varepsilon(\text{eV}))^{1/2}$ cm/s

Average electron thermal speed for temperature T_e: $v = \left(\frac{8kT_e}{\pi m_e}\right)^{1/2}$ = 6.69 x 10^7 $(T_e(\text{eV}))^{1/2}$ cm/s

Debye Length: $\lambda_D = \left(\frac{\varepsilon_o kT_e}{n_e q^2}\right)^{1/2} = \left(\frac{kT_e}{4\pi n_e q^2}\right)^{1/2} = 743\left[\frac{T_e(eV)}{n_e\left(cm^{-3}\right)}\right]^{1/2} cm$

mks cgs

Plasma Frequency:

ω_p (radian/s) $= \left(\frac{n_e q^2}{m_e \varepsilon_o}\right)^{1/2} = \left(\frac{4\pi n_e q^2}{m_e}\right)^{1/2} = 5.64\times 10^4\left[n_e\left(cm^{-3}\right)\right]^{1/2}\frac{radians}{s}$

mks cgs

Rate coefficient: $k\left(\frac{cm^3}{s}\right) = \langle \sigma \bullet v \rangle$ (e.g. (e.g. $\frac{\partial N}{\partial t} = n_e kN$))

σ = cross section cm^2 v = velocity cm/s

Conductivity: $\sigma = \frac{n_e q^2}{m_e \nu_m} = 2.81\times 10^{-4}\frac{n_e\left(cm^{-3}\right)}{\nu_m\left(s^{-1}\right)}\frac{1}{\Omega - cm}$

ν_m = electron momentum transfer collision frequency

Electron Mobility: $\mu_e = \frac{q}{m_e \nu_m} = \frac{1.756\times 10^{15}}{\nu_m\left(s^{-1}\right)}\frac{cm^2}{V-s}$

http://mipse.umich.edu

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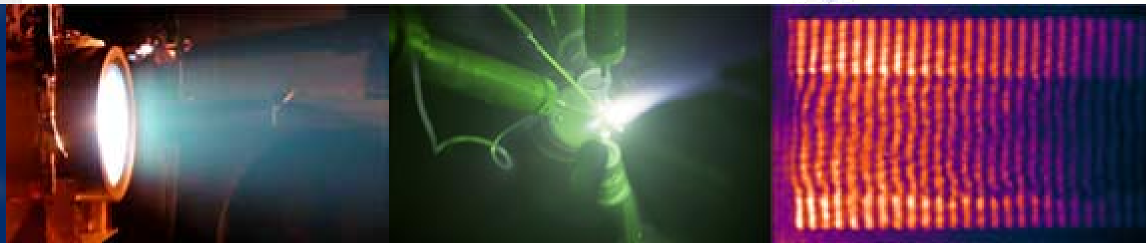

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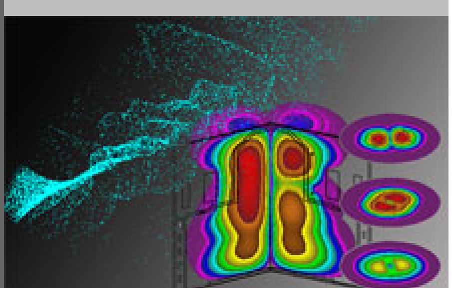
DOE Plasma Science Center



Michigan Institute for Plasma Science and Engineering

Welcome to the website of the Michigan Institute for Plasma Science and Engineering! MIPSE is a community of faculty, staff and students at the University of Michigan whose research and education programs are devoted to the advancement of the science and technology of plasmas. The breadth of research is impressive – from laser produced plasmas for particle acceleration to plasmas in the earth's magnetosphere. We take pride in the excellence of the research and in the resulting societal benefits.

Laser Driven Plasma Wakefield Accelerator

News & Events

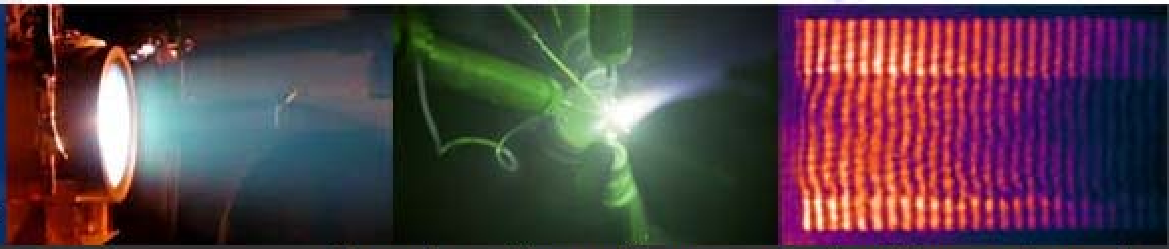
- MIPSE Graduate Fellows 2012-2013 Announced
- Jyoti Mazumder honored with Distinguished University Innovator Award
- Jyoti Mazumder elected to the National Academy of Engineering

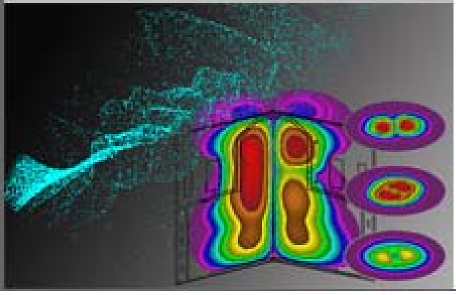
Being a focal point for university-wide activities in plasmas, MIPSE:

- Provides opportunities for faculty and staff to collaborate across disciplinary boundaries
- Supports student research by sponsoring competitive fellowships to graduate students
- Sponsors a seminar series, inviting leading international researchers to the UM campus
- Seeds research activities to attract center-level funding
- Provides educational opportunities through a graduate certificate program in Plasma Science and Engineering (PSE)
- Sponsors an annual Graduate Student Symposium
- Invites companies with technology interests in plasma science and engineering to join the MIPSE Indusrial Affiliates Program
- Provides consultation to companies, government agencies and foundations involved in the use of plasmas

Michigan Institute for Plasma Science and Engineering
Fall 2012 Seminar Series

Date, Time, Location	*Speaker (Affiliation)*	*Title, Abstract*
Tuesday **18 September 2012** 1:30 - 2:30 pm 1017 Dow, **U-M**	**Prof. David Graves** University of California, Berkeley	**Biomedical Applications of Ambient Gas Plasma: The Confluence of Redox Biology and Plasma Science** *Jointly sponsored by MIPSE and the Dept. of Chemical and Biomolecular Engineering*
Wednesday **19 September 2012** 4:00 - 5:00 pm 1311 EECS, **U-M**	**Prof. Chan Joshi** UCLA	**Shocks and Wakes in Plasmas**
Wednesday **3 October 2012** 3:15 - 4:15 pm 1345 Engineering Building, **MSU, East Lansing**	**Prof. Konrad Gelbke** Michigan State University	**From NSCL (National Superconducting Cyclotron Facility) to FRIB (Facility for Rare Isotope Beams) at MSU** *Special Seminar opening the 3rd MIPSE Graduate Student Symposium*
Wednesday **10 October 2012** 4:00 - 5:00 pm 1311 EECS, **U-M**	**Prof. Mounir Laroussi** Old Dominion University	**Plasma Medicine: Low Temperature Plasma as a Transformational Technology for the Healthcare Field**
Friday **12 October 2012** 4:00 - 5:00 pm White Auditorium (G906 Cooley), **U-M**	**Prof. John H. Booske** University of Wisconsin-Madison	**Back to the Future: 21st Century Instruction Innovations** *Jointly sponsored by MIPSE and the Dept. of Nuclear Engineering and Radiological Sciences*
Wednesday **7 November 2012** 4:00 - 5:00 pm 1311 EECS, **U-M**	**Prof. Howard Milchberg** University of Maryland	**The Extreme Nonlinear Optics of Air and Femto-second Optical Filamentation**
Wednesday **5 December 2012** 4:00 - 5:00 pm 1311 EECS, **U-M**	**Dr. Yevgeny Raitses** Princeton Plasma Physics Laboratory	**Complex Phenomena in Magnetized Plasmas in the Presence of Electron Emission**





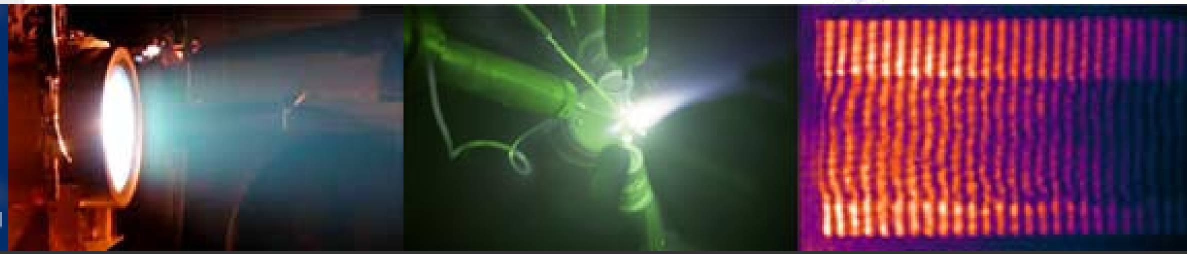
GRADUATE CERTIFICATE IN PLASMA SCIENCE AND ENGINEERING

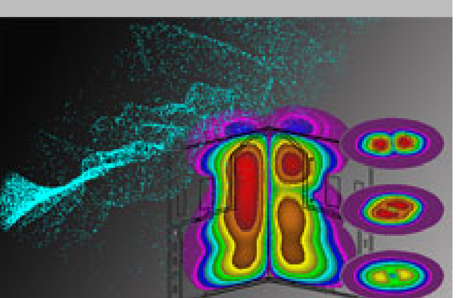
MIPSE is administering a graduate certificate in Plasma Science and Engineering (PSE). The graduate certificate provides an opportunity for students conducting research in the fundamentals or applications of PSE to both broaden and deepen that experience. The components of the graduate program include:

- Coursework in the fundamentals and applications of PSE.
- Co-advising to broaden the student's research.
- Participation in an annual research symposium.
- Research on a topic related to PSE.

Information for students interested in pursuing the graduate certificate in PSE

- Overview, Requirements and Admission Procedures
- Application for Admission





MIPSE GRADUATE STUDENT SYMPOSIUM

1st MIPSE Graduate Student Symposium - September 29, 2010

2nd MIPSE Graduate Student Symposium - September 21, 2011

3rd MIPSE Graduate Student Symposium - October 3, 2012

3rd Annual MIPSE Graduate Student Symposium - October 3, 2012

The 3rd Annual MIPSE Graduate Student Symposium will be held on Wednesday, October 3, 2012, 2-6 pm, at the Michigan State University, East Lansing. The Symposium will be an opportunity for graduate students involved in plasma research and students pursuing the Graduate Certificate in Plasma Science and Engineering to present the results of their investigations, learn about the research of their fellow students and network with MIPSE faculty and staff.

The symposium agenda will include a special MIPSE seminar by Prof. Konrad Gelbke (MSU) and three student poster sessions. All student presentations will be considered for the Best Presentation Award. Transportation from Ann Arbor to East Lansing and back will be provided.

Schedule

Abstract Submission

- **Deadline: August 31, 2012**
- To create an abstract, please use this Word template.
- Open the template using "Print Layout" view.
- The length of abstracts should be limited to one page.
- Send the abstract to juliafk@eecs.umich.edu

2nd Annual MIPSE Graduate Student Symposium - September 21, 2011