AIR FORCE INSTITUTE OF TECHNOLOGY

Plasma: Born in the Crest of a Wave & Rocked in the Cradle of the Deep….

PPPL SULI

Introduction to Fusion Energy & Plasma Physics Course

Plasma Waves

16 JUN 2021

CDR Royce W. James, Ph.D.

US Coast Guard Academy

Air Force Institute of Technology

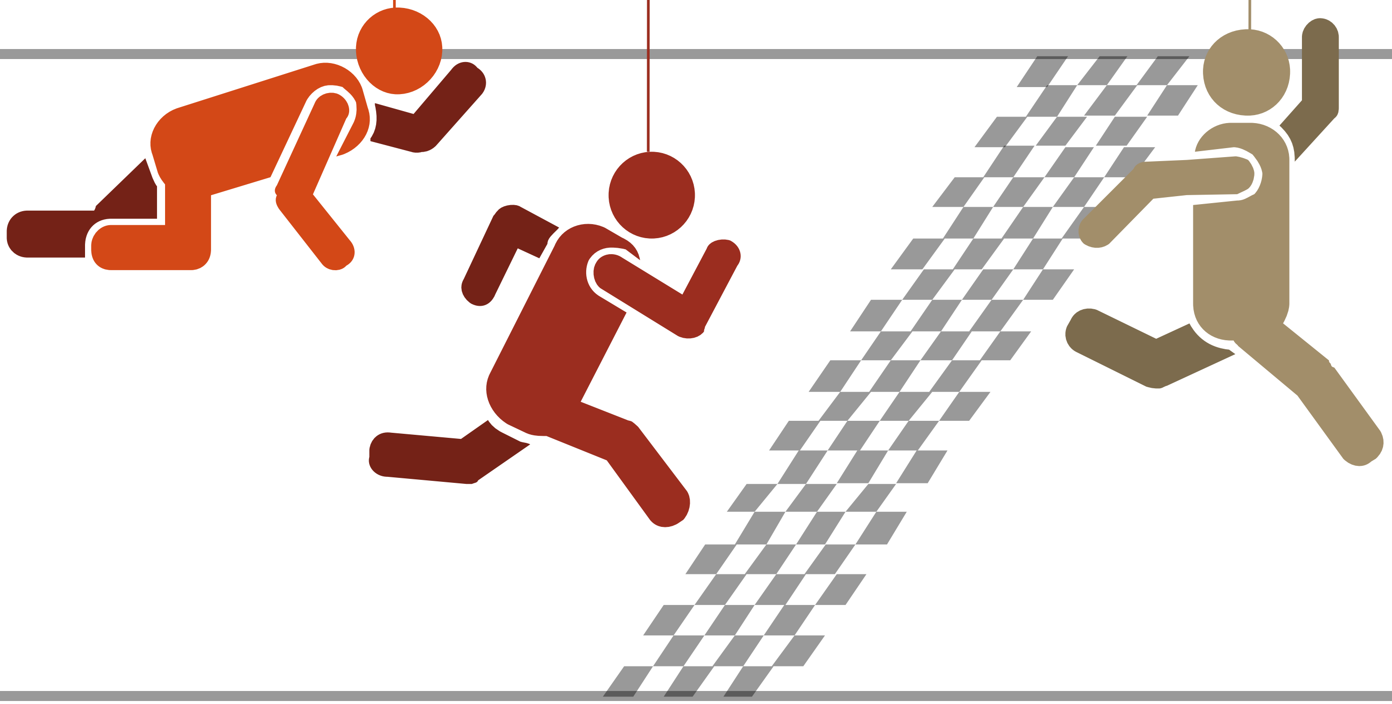
COAST GUARD ACADEMY PLASMA LABORATORY

CHECK-IN ACTIVITY

It’s Not My Day!
SCORE: 1 - 4

Doing Alright!
SCORE: 5 - 8

Best Day Ever!
SCORE: 9 - 10



Dessert Poll

COAST GUARD SPECTRUM

HERE & NOW….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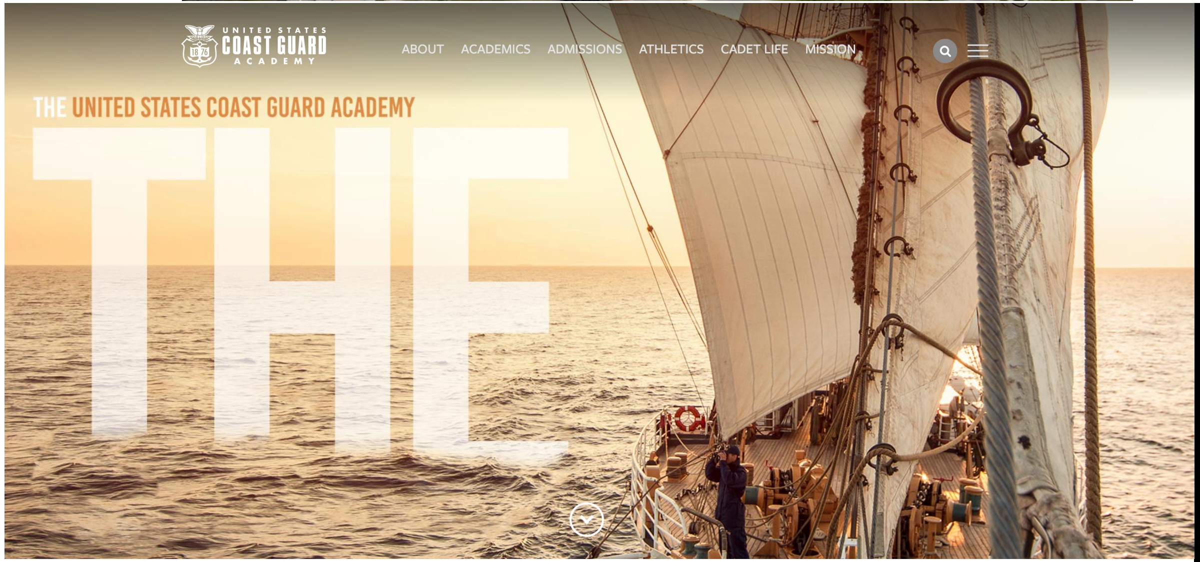
UNITED STATES COAST GUARD ACADEMY
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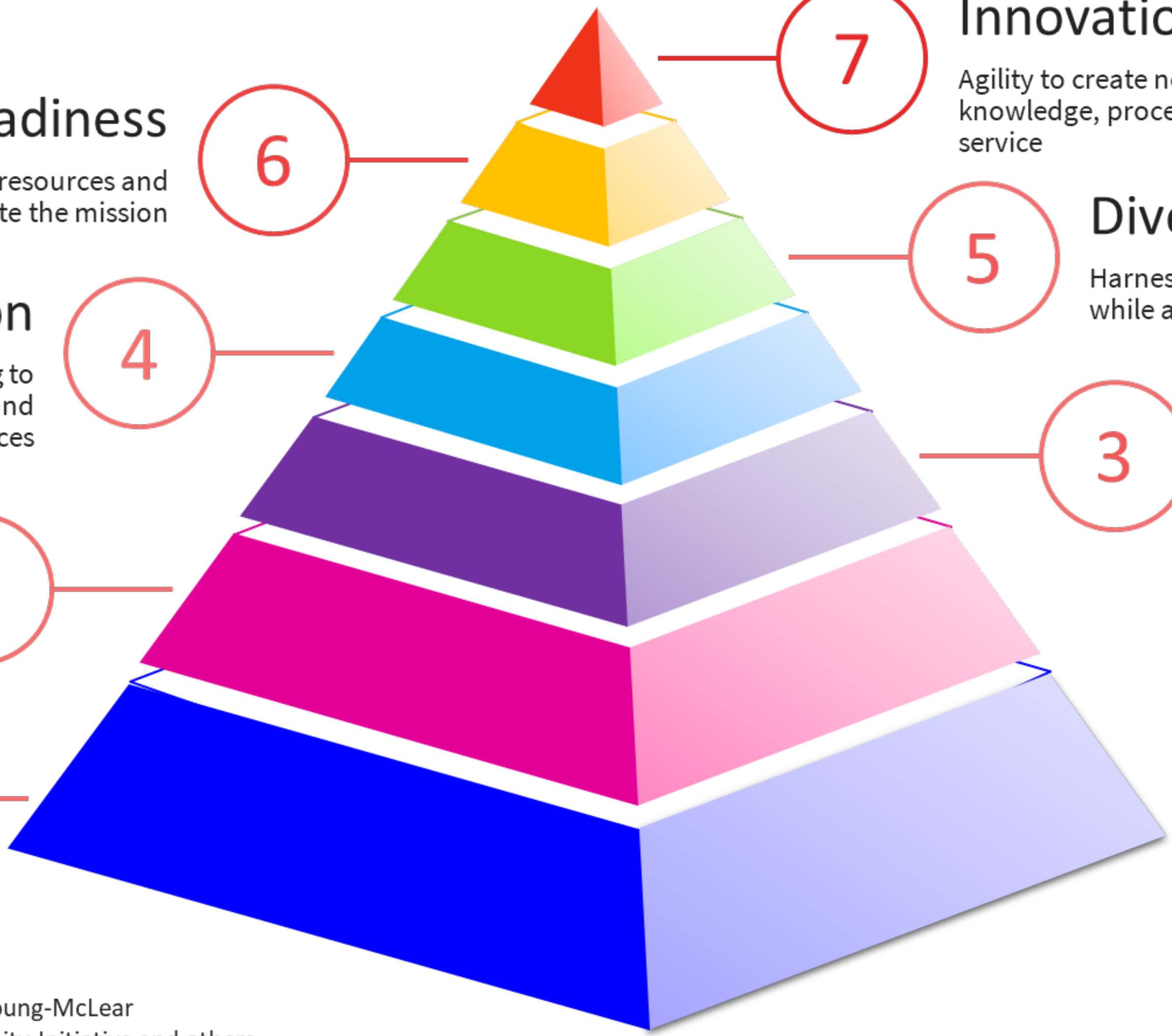
THE

‘HEALTHY TO INNOVATIVE’ FRAMEWORK

COAST GUARD SPECTRUM



7 **Innovation**

Agility to create new value, knowledge, process, product, or service

6 **Mission Readiness**

Prepared and have the resources and cohesion to complete the mission

5 **Diversity & Equity**

Harnessing the strength of differences while achieving equitable outcomes

4 **Inclusion**

Intentional continuous learning to treat others with fairness and provide equal access to resources

3 **Cultural Competence**

Effectively interact across norms, cultures, and values

2 **Moral Courage**

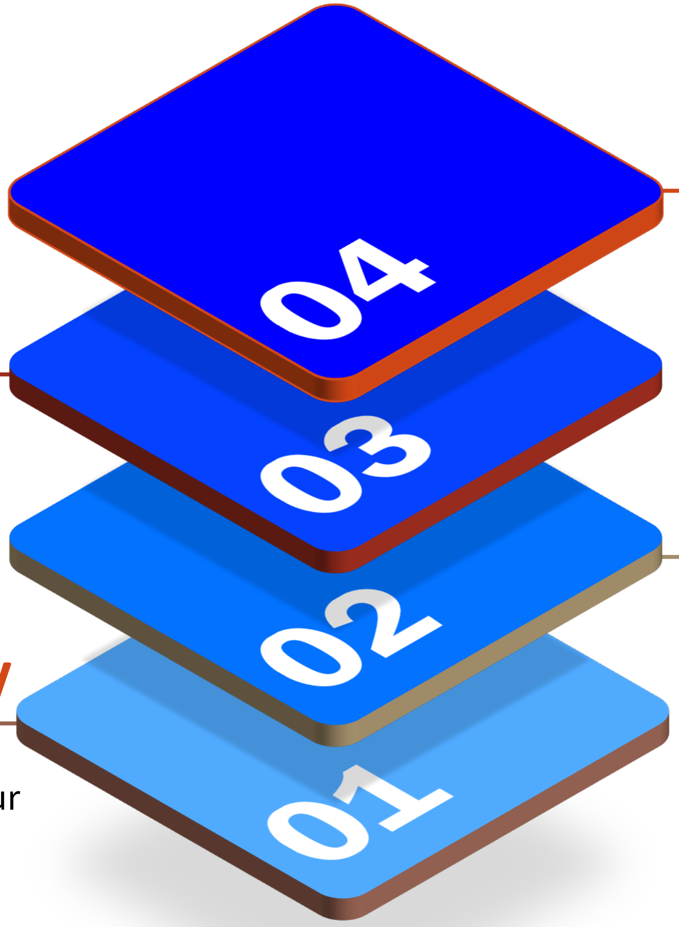
Speak up against unethical or immoral practices

1 **Psychological Safety**

Safe to be authentic, learn, contribute, and challenge

Reference: Framework developed by Dr. Kimberly Young-McLear
Adopted by CG Spectrum, USCGA ASEE Dean’s Diversity Initiative and others

FOUR STAGES OF PSYCHOLOGICAL SAFETY



Challenger Safety

You are safe to challenge the status quo or intervene against injustices

Contributor Safety

You are safe to exercise your judgement and contribute to work tasks

Learner Safety

You are safe to learn, ask questions, and make minor mistakes

Authenticity Safety

You are safe to explore your identity and are accepted as your full authentic self

Reference: Modified from The Four Stages of Psychological Safety by Timothy Clark
https://www.porchlightbooks.com/blog/changethis/2020/the-four-stages-of-psychological-safety

UNITED STATES COAST GUARD · SEMPER SUPERBIA ·
COAST GUARD SPECTRUM

LEVEL 01

PSYCHOLOGICAL SAFETY

FLORIDA STATE UNIVERSITY

FLORIDA STATE ARMY ROTC SEMINOLES

PERSHING RIFLES 1894

SINFONIA 1898

LEVEL 01

PSYCHOLOGICAL SAFETY

AMERICORPS NCCC

NSBE
NATIONAL SOCIETY OF BLACK ENGINEERS

NATIONAL SOCIETY OF BLACK PHYSICISTS

NM STATE BE BOLD. Shape the Future.
New Mexico State University
Department of Physics

LEVEL 01

PSYCHOLOGICAL SAFETY

STEVENS
INSTITUTE of TECHNOLOGY
THE INNOVATION UNIVERSITY®
1870

LEVEL 01

PSYCHOLOGICAL SAFETY

LEVEL 02

MORAL COURAGE

The lasting legacy of the Greensboro Four (above from left: David Richmond, Franklin McCain, Jibreel Khazan and Joseph McNeil) was how the courageous moment grew to a revolutionary movement. *(Wikimedia Commons)*

THE MOMENT WHEN FOUR STUDENTS SAT DOWN TO TAKE A STAND

One of the great monuments to the Greensboro Sit-In is at the Smithsonian's National Museum of American History

LEVEL 03

CULTURAL COMPETENCE

LEVEL 04

INCLUSION

Climate & Inclusion Town Hall, DPP 2020

This year the DPP Diversity, Equity, and Inclusion Organizing Collective Committee (OCC) is offering a workshop on evidence-based practices (EBP) that can help make the plasma science community more diverse, equitable, and inclusive. The workshop includes

- Introduction to the OCC
- Discussion of EBPs by Dr. Christine Clark
- Professionally facilitated EBP discussion sessions
  *****with Registration only*****
- Take-home EBP toolkit

Dr. Christine Clark
University of Nevada, Las Vegas
Senior Scholar in Multicultural Education
Founding Vice Pres. for Diversity and Inclusion

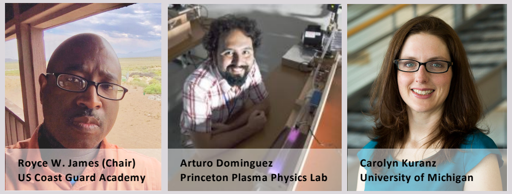
https://www.unlv.edu/news/expert/christine-clark

Register at:

https://rb.gy/7matra

Discussion slots are limited, so please register soon!

Members of the DEI OCC



Evidence Based Practices (EVPs)

Section 1 of 2

APS DPP DEI Town Hall Registration Form

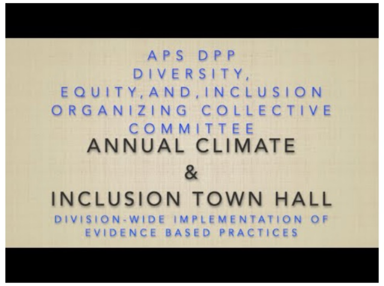
Please review the following video of our DEI Expert, Prof. Chris Clark, Ed.D. on Evidence-Based Practices (EBPs) below.

You may also want to follow Prof. Clark's presentation with this handout on EBPs: https://bit.ly/2TQfRDQ

The OCC with Prof. Clark has settled on the following 5 EBPs for the division to focus on.

1) addition of non-cognitive variables in graduate student admissions and in hiring industry and national laboratories personnel and faculty;
2) adoption of the Rooney Rule in hiring industry and national laboratories personnel and faculty;
3) establishment of a human relations code;
4) establishment of a bias incident policy; and,
5) establishment of a 'looping' mentorship program.

OCC Update & our DEI Expert, Prof. Chris Clark, Ed.D. on EBPs [30 min]

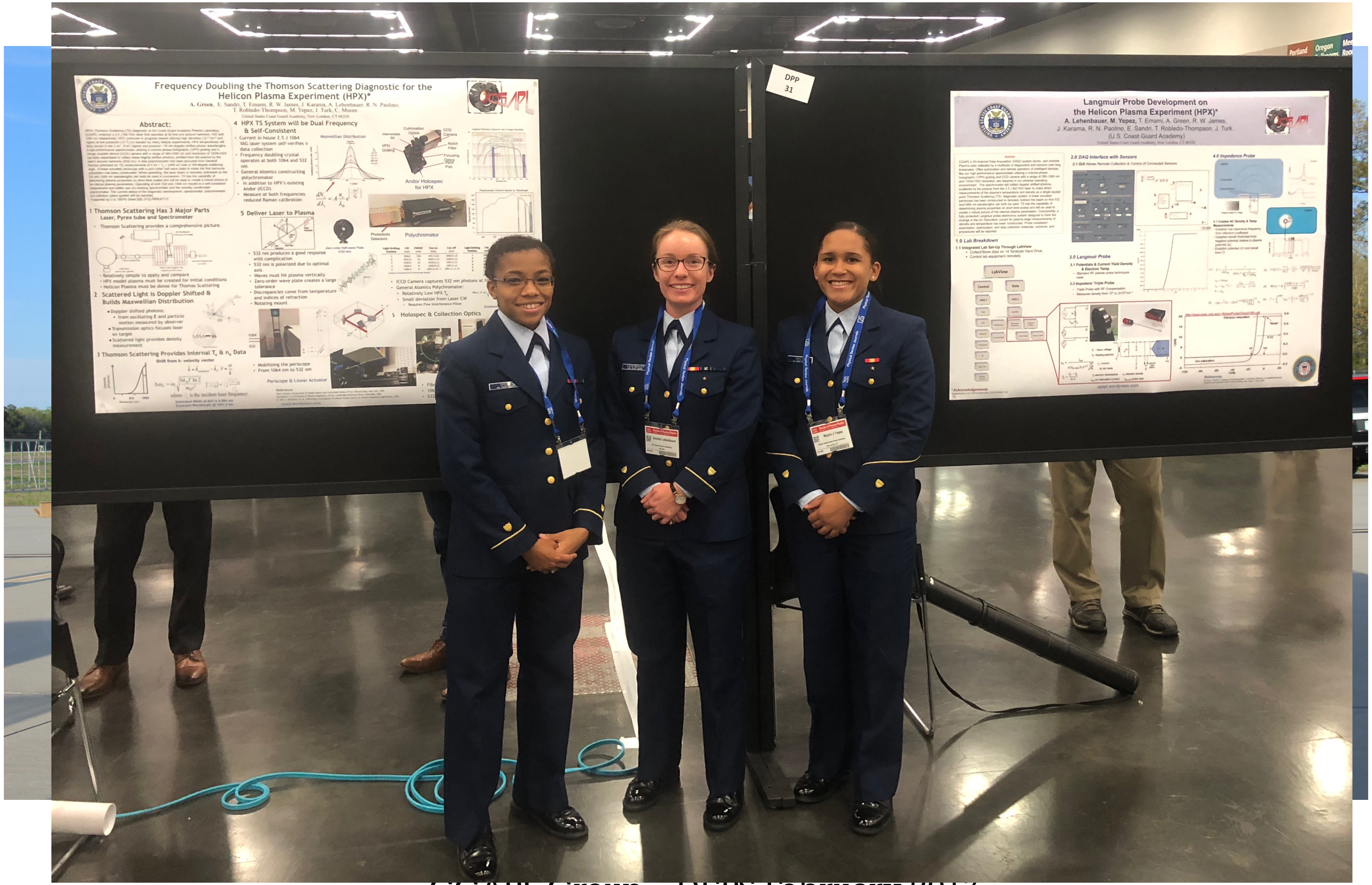


In the space provided, please submit a brief strategy of where and how you might approach implementing one of the above EBPs in your institution. The small group discussions at our Town Hall will be centered on this very premise to facilitate effective actions in our individual and collective work spaces. Participants will also receive a EBP Toolkit to refer to when implementing EBPs. *

Long answer text

05
LEVEL

DIVERSITY AND EQUITY

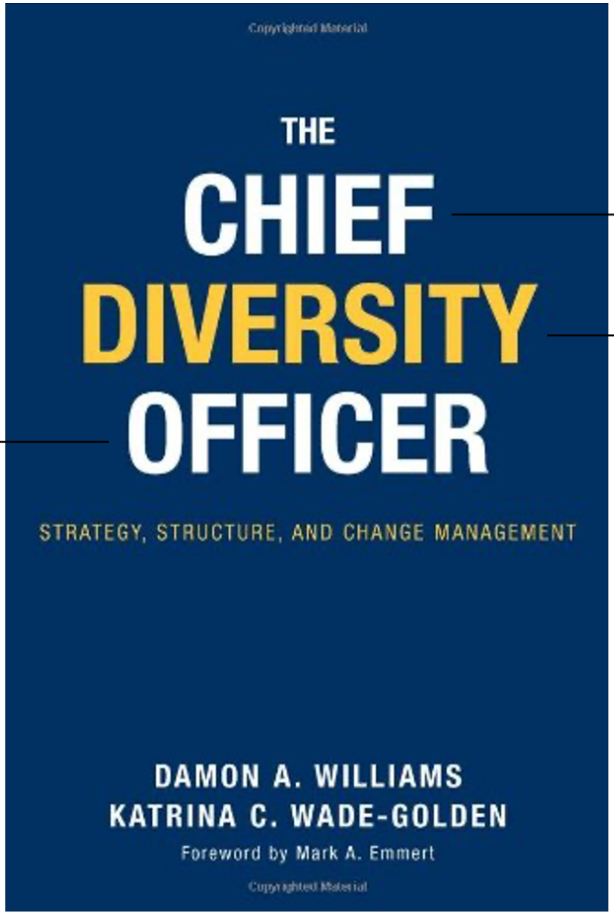


CGAPL Group – DEPS February 2017
CGAPL Group – APS DPP October 2018
CGAPL Group – PPPL March 2014

LEVEL 05

DIVERSITY AND EQUITY

Cultural Competence

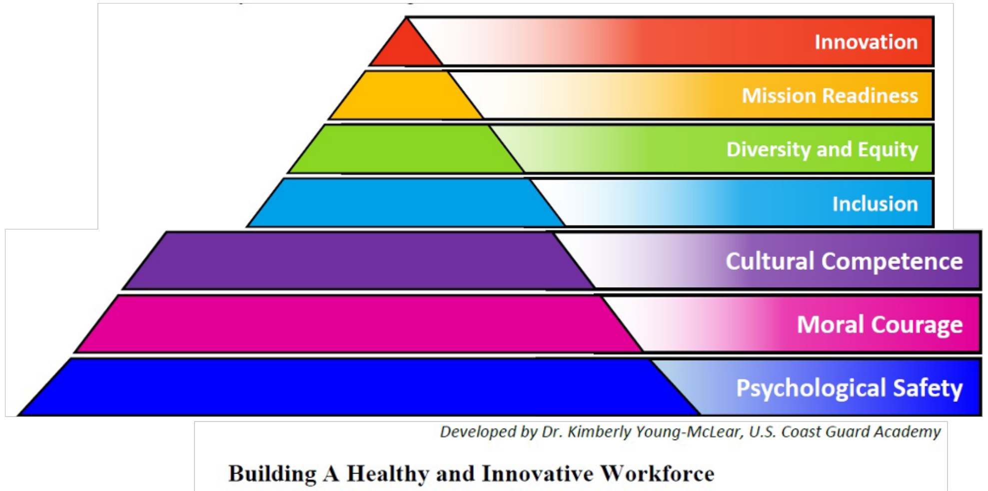


Psychologically Safety

Moral Courage

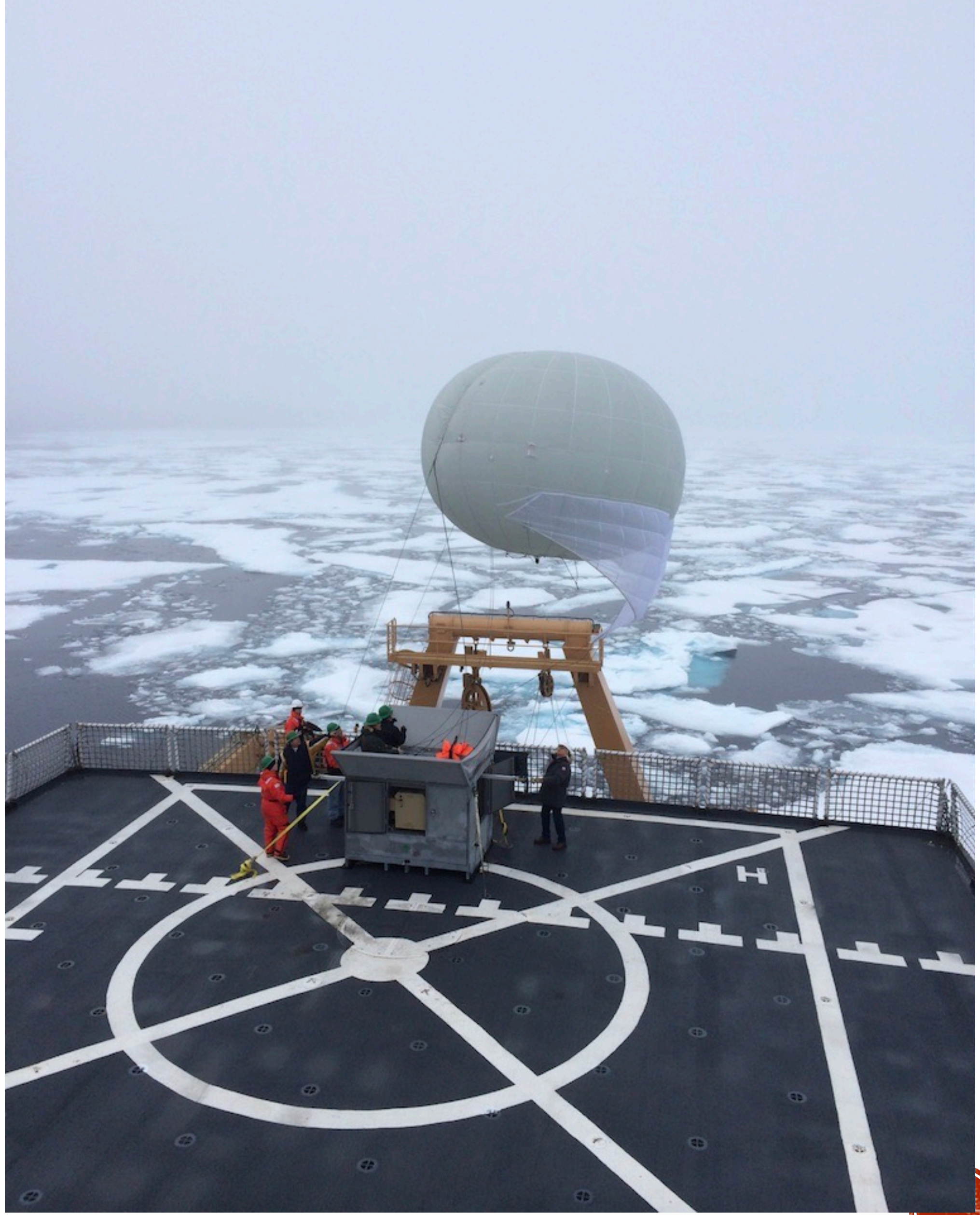
TOTAL FORCE AIRMEN & SPACE WARFIGHTERS

Are Joint Force Social Justice Warriors.



LEVEL 06

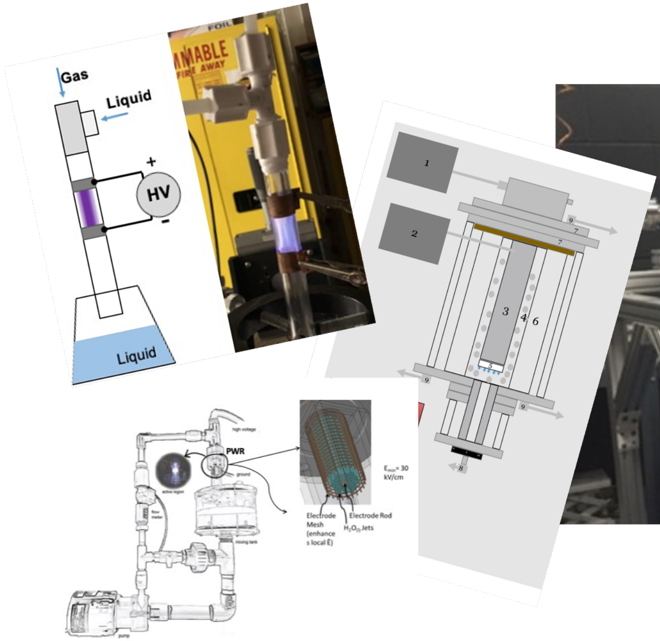
MISSION READINESS

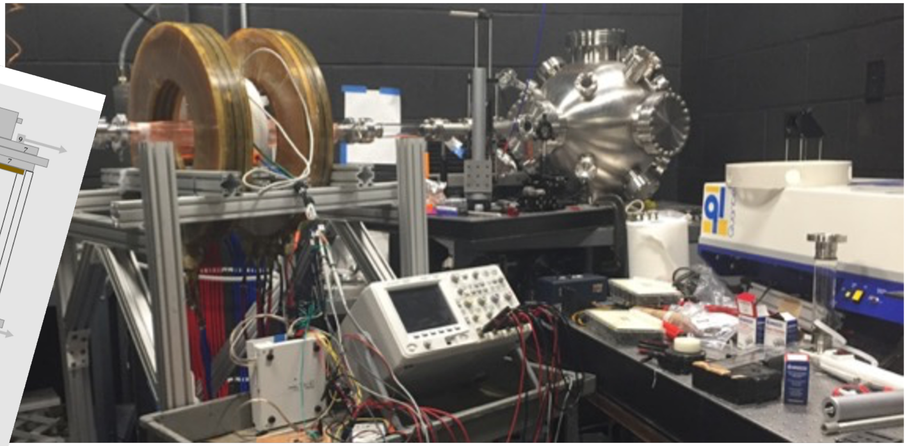


07
LEVEL

INNOVATION

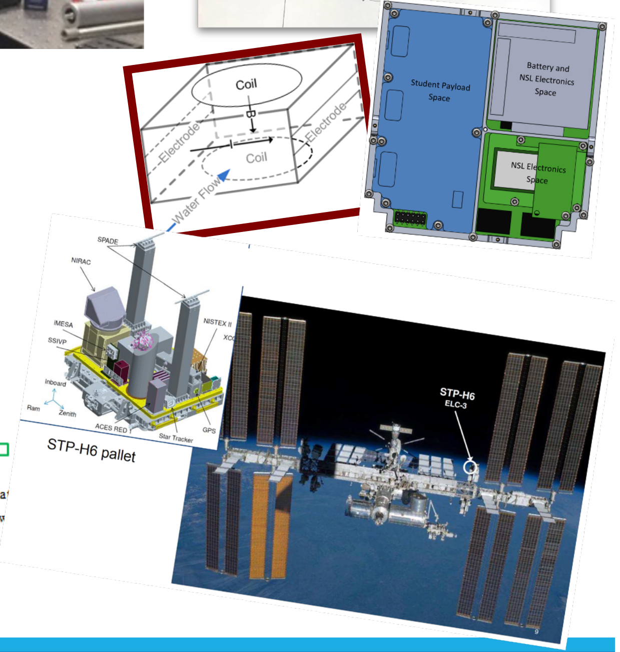
Coast Guard Academy Plasma Lab has Multiple Experiments



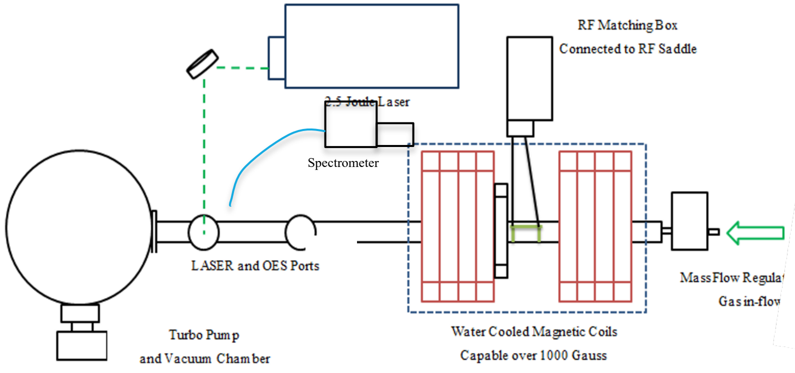


MHD Space

$$\rho \frac{d\vec{u}}{dt} = \frac{m}{V}\vec{u} = \frac{\vec{F}_A}{V}\hat{k} = -(\nabla p) + \vec{j} \times \vec{B}$$



HPX



Plasma Water Treatment

ON TO PLASMA WAVES:
HERE ARE SOME BIG ROCKS

Plasma Prep Tips:

- get proximate with the material
- pre-load before class/lecture (more than just notes)

1) Pre-Load:

- A day or two before class, read the sections for the next class and write out *in your own words* any unfamiliar definitions for symbols/vocabulary/concepts.
- Do all the examples problems in those sections (also before class).
- Rinse, wash, repeat….do this before every class (in all subjects) at he minimum to be ready. This base understanding is needed to get anything out of class. Don't waste your time!! Be disciplined, it will pay off!

2) Work is Class – it's your job: in class you will need to develop your physics "kata" – your profs set the level; it is for you to become proficient at that level! To do this you will need to unabashedly provide ideas and challenge each other's. In this you will learn the physics and become proficient in critical thinking & self-assessment.

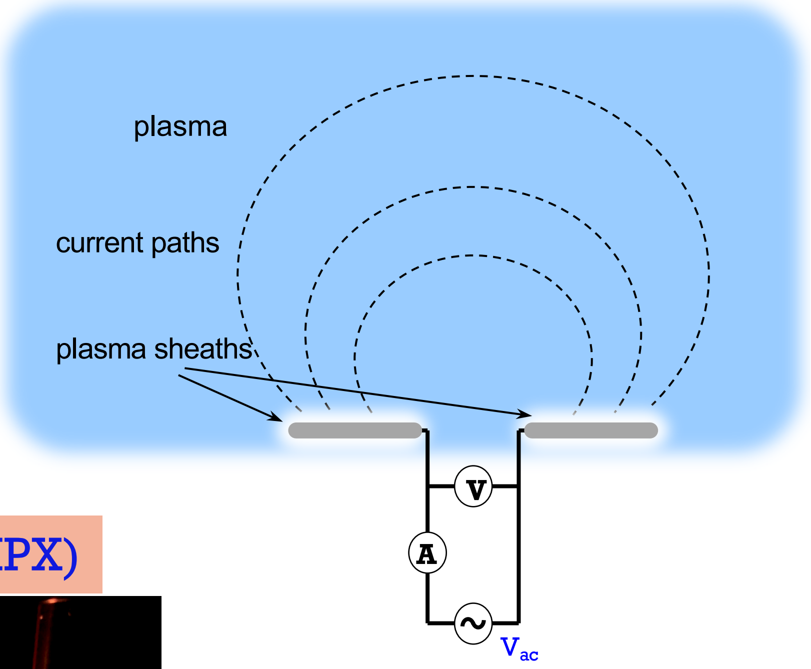
3) Use your HW: these are your guide to tests and assessments. One of the largest stumbling blocks is overconfidence while reviewing concept/solution. Be sure to work problems without the solution in preparation.

ON TO PLASMA WAVES:
HERE ARE SOME BIG ROCKS

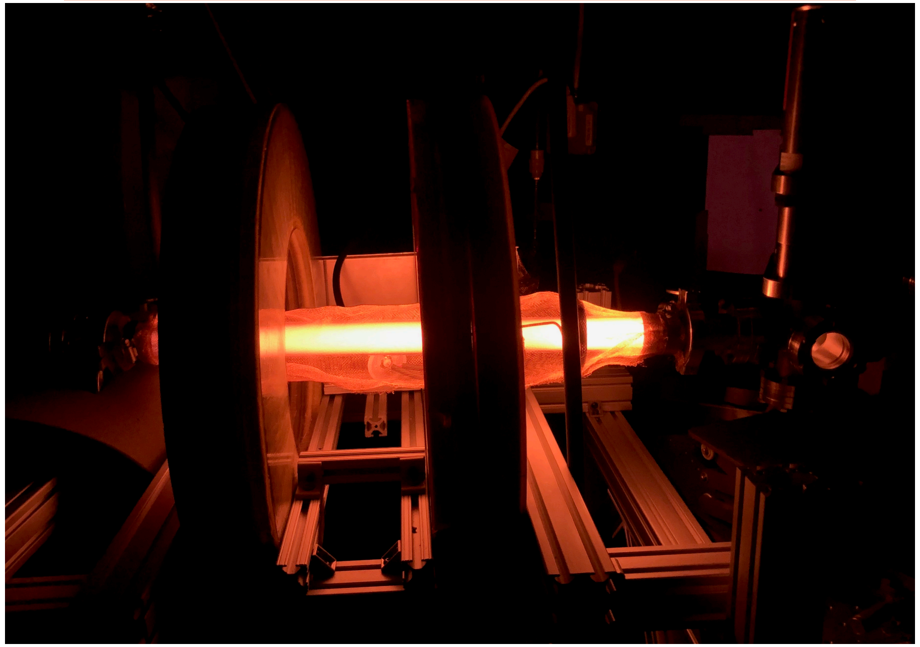
- Plasmas Perpetrating
- Plasma Oscillating
- Electron & Ion Plasma Waves
- Electrostatic Plasma Waves
- Plasma Sound Wave - Whistlers
- Ordinary & Extraordinary
- Alfvén Wave

*FC=Chen, F.F, (2015). Introduction to Plasma Physics and Controlled Fusion (3rd ed.). Springer

CubeSat Impedance Probe



Helicon Plasma Experiment (HPX)



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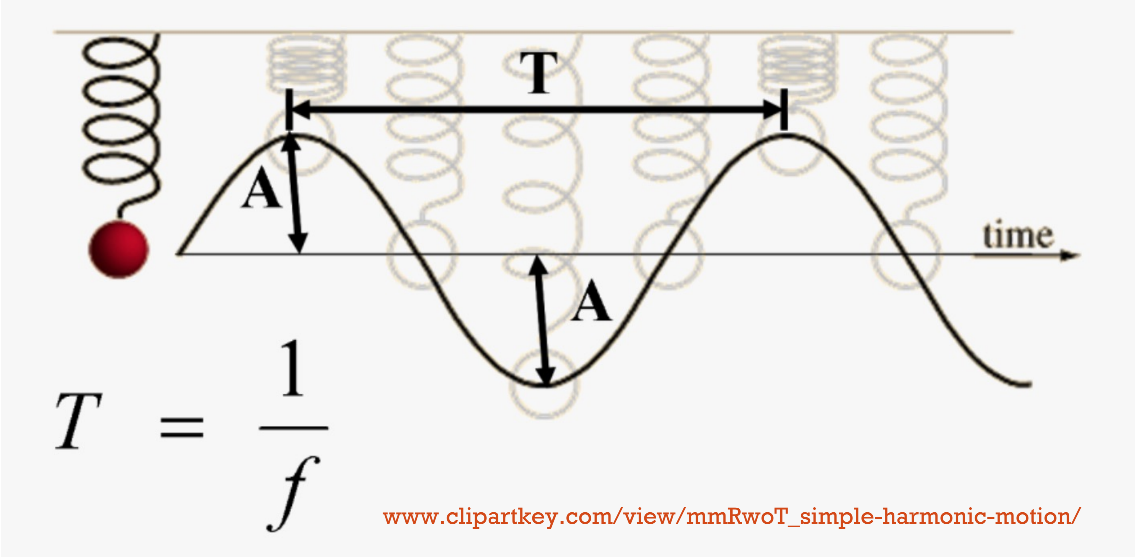
PLASMA LABORATORY

PLASMAS CAN PERPETRATE AS WAVES

Periodic motion of a plasma fluid can be represented as a superposition of sinusoidal oscillations - Thanks Fourier!



In a plasma fluid, the density (n) can be represented as

$$n = \bar{n}\, exp[i(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t)]$$

where:
$\bar{n}$ - amplitude
$\boldsymbol{k}$ - propagation const

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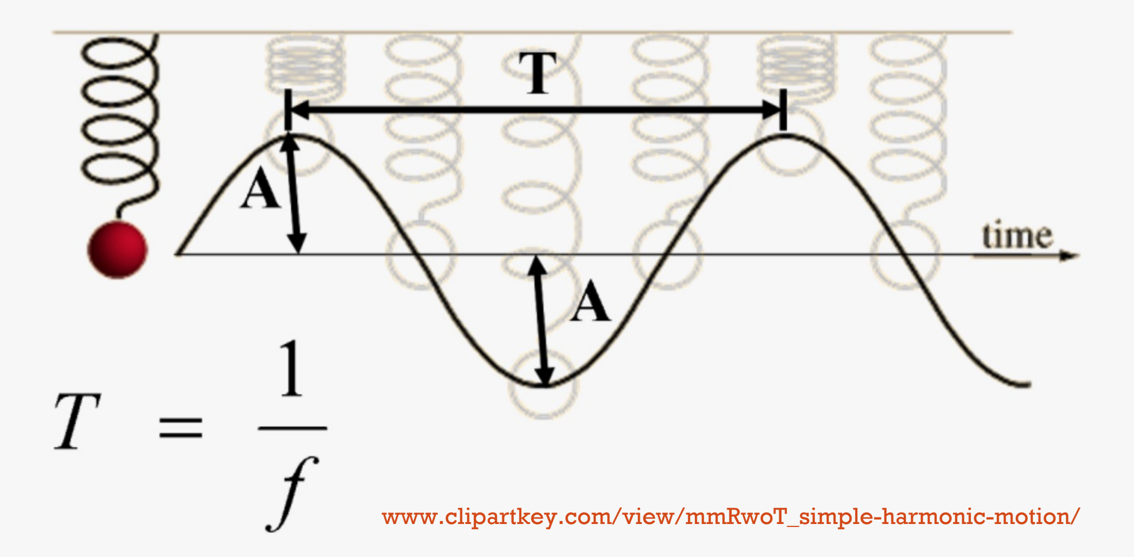

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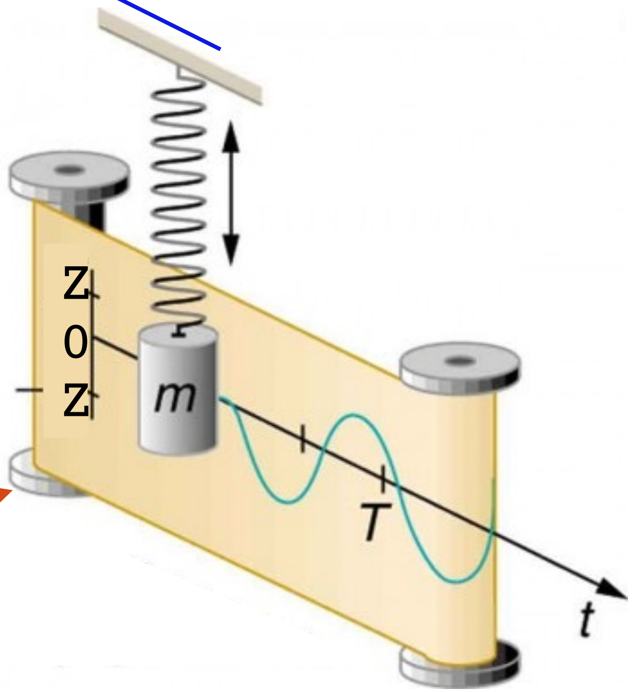

Let's choose the x-direction for wave propagation to get

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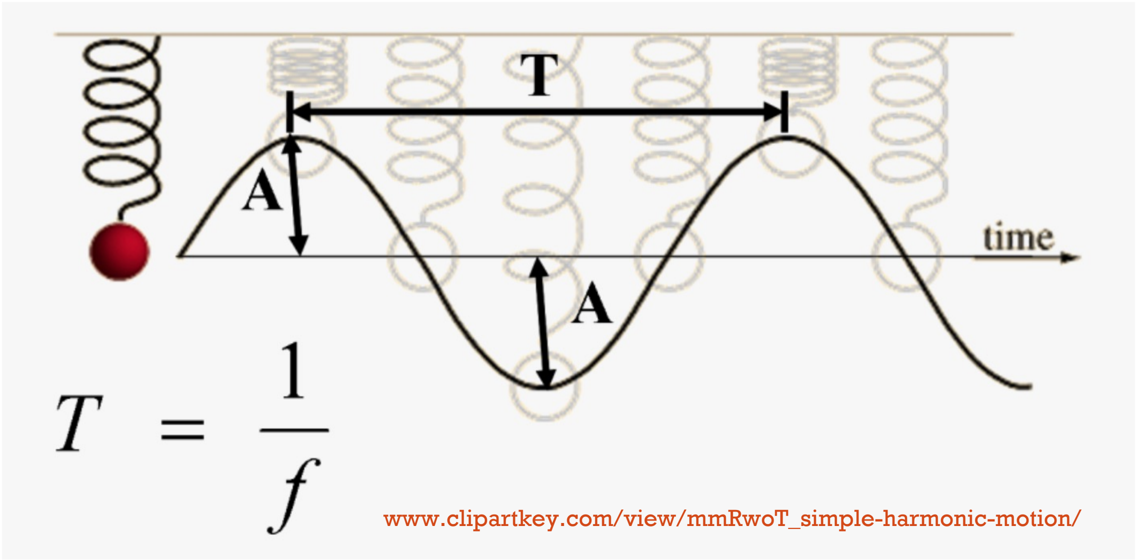

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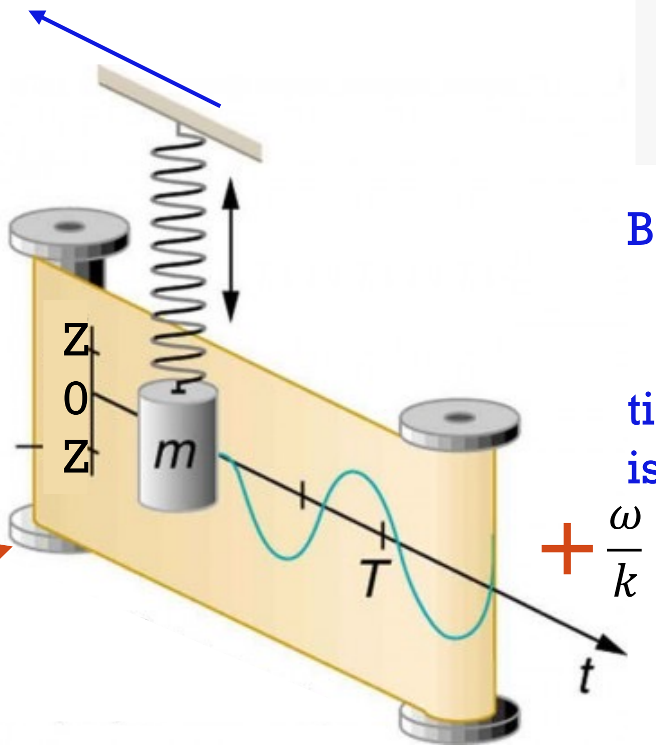

Let's choose the x-direction for wave propagation to get

$$n = \bar{n}\, e^{i(kx-\omega t)}$$

But these are real plasmas, so

$$\text{Re}\ (n) = \bar{n}\, cos(kx - \omega t)$$

time derivative of a point on the wave, $(d/dt)(kx\text{-}\omega t)=0$, is the phase velocity

$$\frac{dx}{dt} = \frac{\omega}{k} \equiv v_\varphi$$

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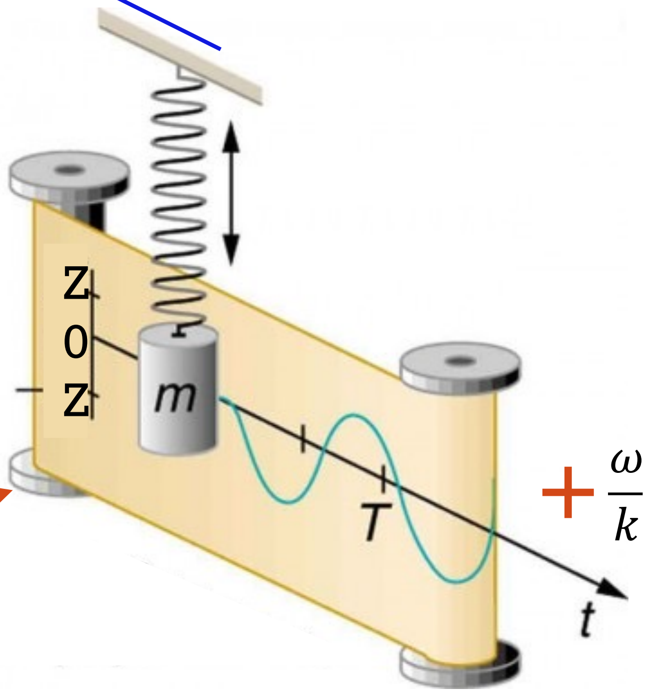

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Chose n to have no phase, but the plasma has an E-field one in the complex vector form

$$\boldsymbol{E} = \overline{\boldsymbol{E}}\, e^{\delta} e^{i(kx - \omega t)} \equiv \overline{\boldsymbol{E}}_c e^{i(kx - \omega t)}$$

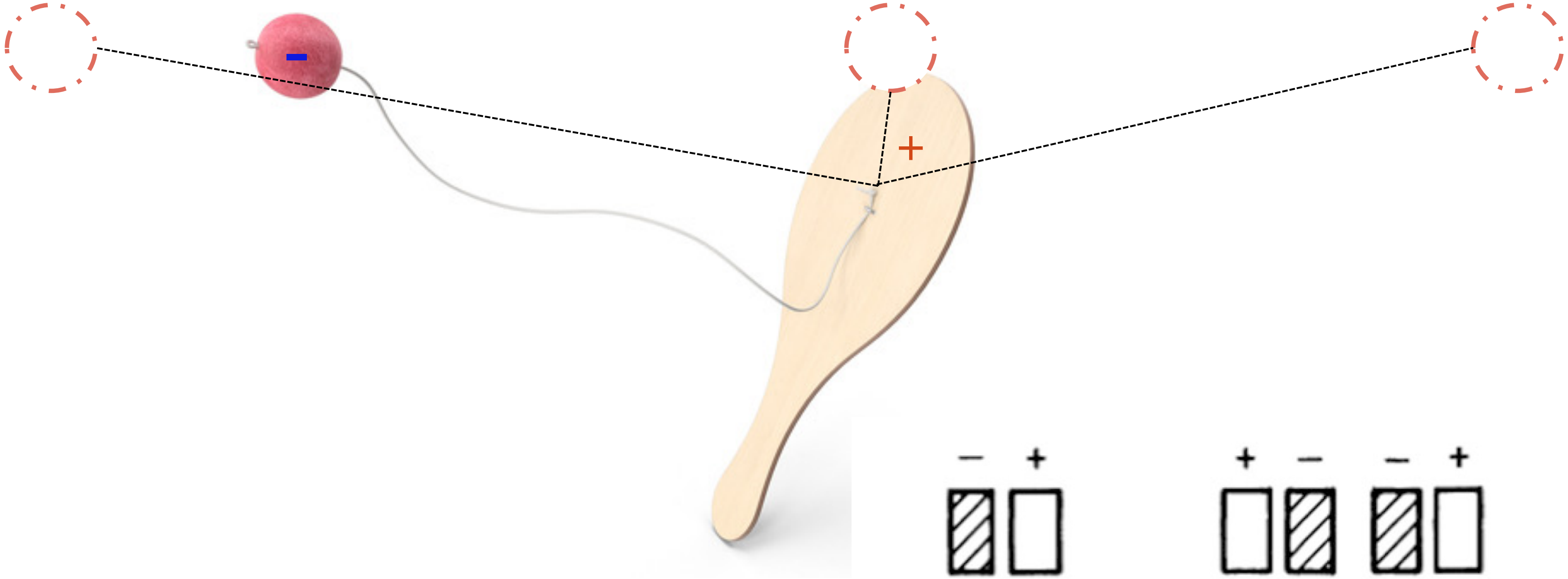
*FC

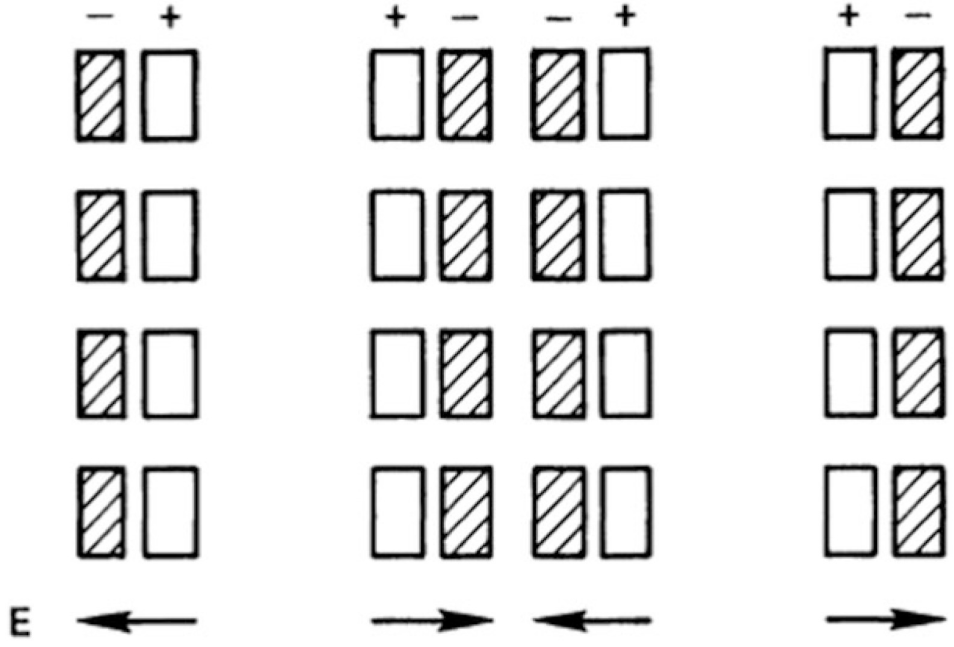
$$\frac{\Delta\omega}{\Delta k} \lim_{\Delta\omega} 0 \to \frac{d\omega}{dk} = v_g$$ cannot exceed c!

COULOMB FORCE DRIVES PLASMA OSCILLATION

Linearize to eliminate the high order terms

Electrons displaced and bound by coulomb force - overshoot and oscillate





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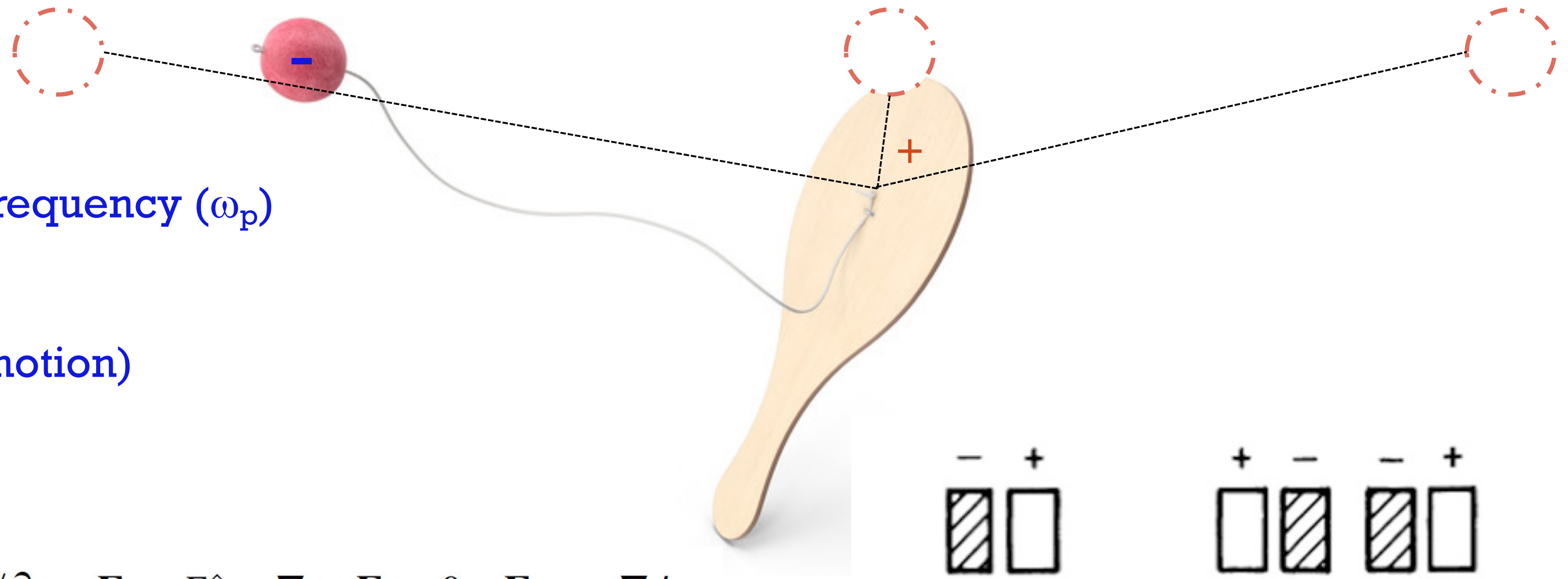
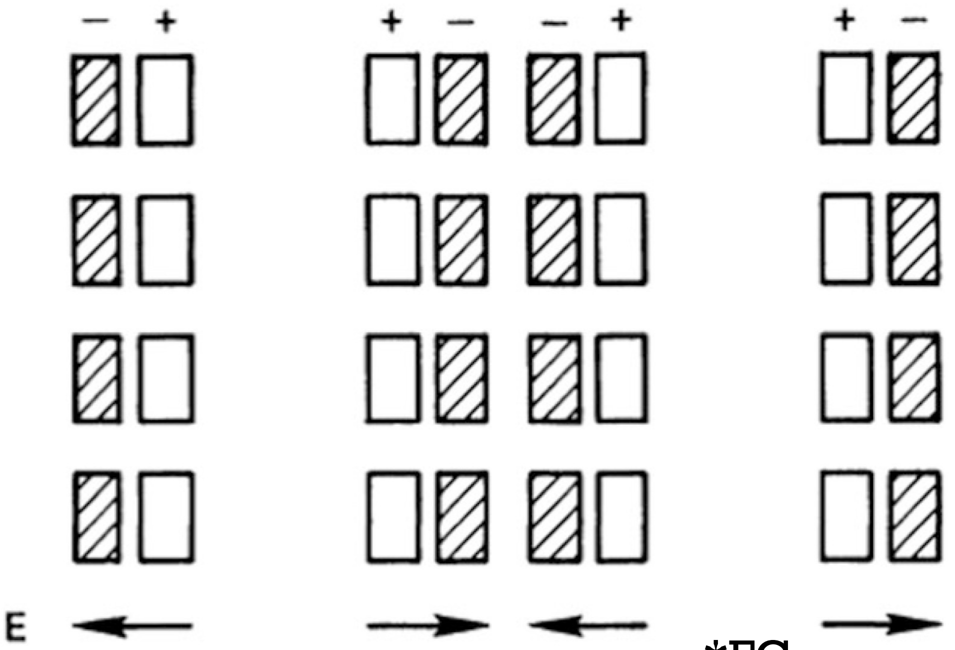


Simple Case Plasma Frequency (ω_p)

1. No B-field
2. KT=0 (no thermal motion)
3. Ions are unmoved
4. Infinite Plasma
5. 1-D, x-direction

$$\nabla = \hat{\mathbf{x}}\,\partial/\partial x \quad \mathbf{E} = E\hat{\mathbf{x}} \quad \nabla \times \mathbf{E} = 0 \quad \mathbf{E} = -\nabla\phi$$



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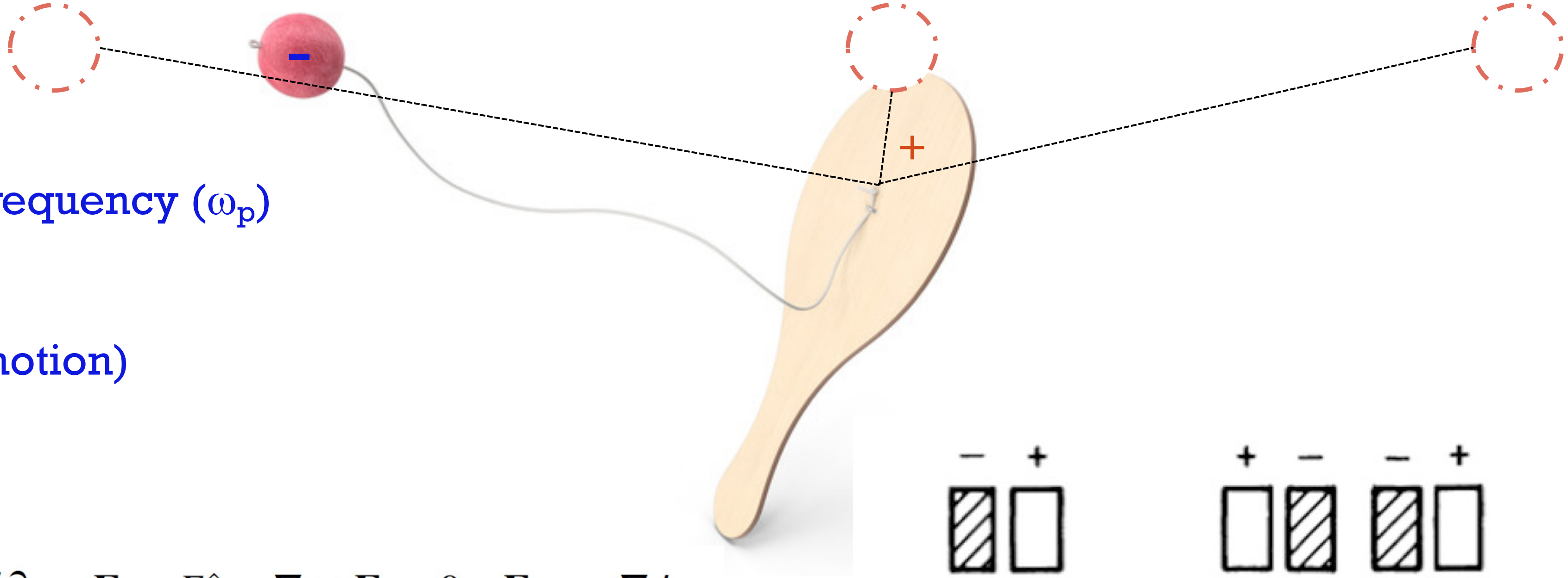

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Equation of Motion:

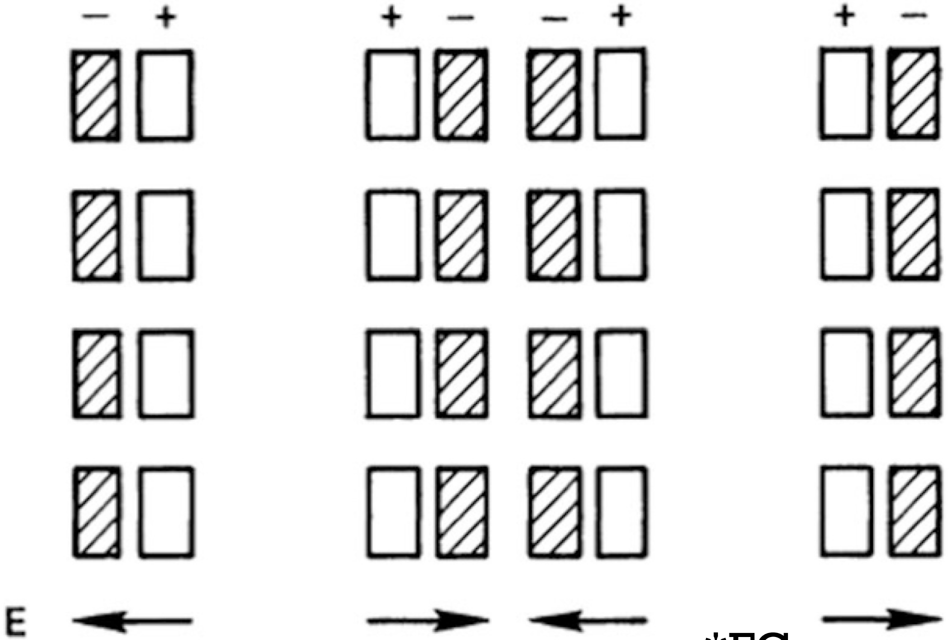
$$mn_e\left[\frac{\partial \mathbf{v}_e}{\partial t} + (\mathbf{v}_e \cdot \nabla)\mathbf{v}_e\right] = -en_e\mathbf{E}$$

Continuity Equation:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{v}_e) = 0$$

High frequency - use Poison's:

$$\varepsilon_0 \nabla \cdot \mathbf{E} = \varepsilon_0 \partial \mathbf{E}/\partial \mathbf{x} = e(n_i - n_e)$$



*FC

LINEARIZE TO ELIMINATE HIGH ORDER TERMS...

Group dependent variables into equilibrium (sub_0) and perturbed (sub_1)

$$n_e = n_0 + n_1 \quad \mathbf{v}_e = \mathbf{v}_0 + \mathbf{v}_1 \quad \mathbf{E} = \mathbf{E}_0 + \mathbf{E}_1$$

Still in our simple case so

$$\nabla n_0 = \mathbf{v}_0 = \mathbf{E}_0 = 0$$

1. no oscillation yet
2. Electrons not displaced yet

$$\frac{\partial n_0}{\partial t} = \frac{\partial \mathbf{v}_0}{\partial t} = \frac{\partial \mathbf{E}_0}{\partial t} = 0$$

Plasma Frequency →

$$\omega_p = \left(\frac{n_0 e^2}{\varepsilon_0 m}\right)^{1/2} \quad \text{rad/ sec}$$

LINEARIZE TO ELIMINATE HIGH ORDER TERMS...

Group dependent variables into equilibrium (sub$_0$) and perturbed (sub$_1$)

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Linearized Equation of Motion:

$$m\left[\frac{\partial \mathbf{v}_1}{\partial t} + (\mathbf{v}_1 \cdot \overset{0}{\nearrow}\nabla)\mathbf{v}_1\right] = -e\mathbf{E}_1$$

Linearized Continuity Equation:

$$\frac{\partial n_1}{\partial t} + \nabla \cdot (n_0 \mathbf{v}_1 + \overset{0}{\nearrow}n_1 \mathbf{v}_1) = 0$$

$$\frac{\partial n_1}{\partial t} + n_0 \nabla \cdot \mathbf{v}_1 + \mathbf{v}_1 \cdot \overset{0}{\nearrow}\nabla n_0 = 0$$

Linearized Poison's:

$$\varepsilon_0 \nabla \cdot \mathbf{E}_1 = -en_1$$

Plasma Frequency →

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Linearized Poison's:

$$\varepsilon_0 \nabla \cdot \mathbf{E}_1 = -en_1$$

Oscillate Sinusoidally so:

$$\mathbf{v}_1 = v_1 e^{i(kx-\omega t)}\hat{\mathbf{x}}$$

$$n_1 = n_1\, e^{i(kx-\omega t)}$$

$$\mathbf{E} = E_1\, e^{i(kx-\omega t)}\hat{\mathbf{x}}$$

Substitute the time derivative and gradient:

$$-im\omega v_1 = -eE_1 \qquad \frac{\partial}{\partial t} = -i\omega$$

$$-i\omega n_1 = -n_0 ikv_1$$

$$ik\varepsilon_0 E_1 = -en_1 \qquad \boldsymbol{\nabla} = ik\hat{\boldsymbol{x}}$$

$$-im\omega v_1 = -e\frac{-e}{ik\varepsilon_0}\frac{-n_0 ikv_1}{-i\omega} = -i\frac{n_0 e^2}{\varepsilon_0\,\omega}v_1$$

Plasma Frequency →

$$\omega_p = \left(\frac{n_0 e^2}{\varepsilon_0 m}\right)^{1/2} \quad \text{rad/sec}$$

WAVES - MOVING PLASMA OSCILLATIONS
FOR BOTH ELECTRONS & IONS

Oscillation Poll!

Fig. 4.3 Synthesis of a wave from an assembly of independent oscillators

*FC

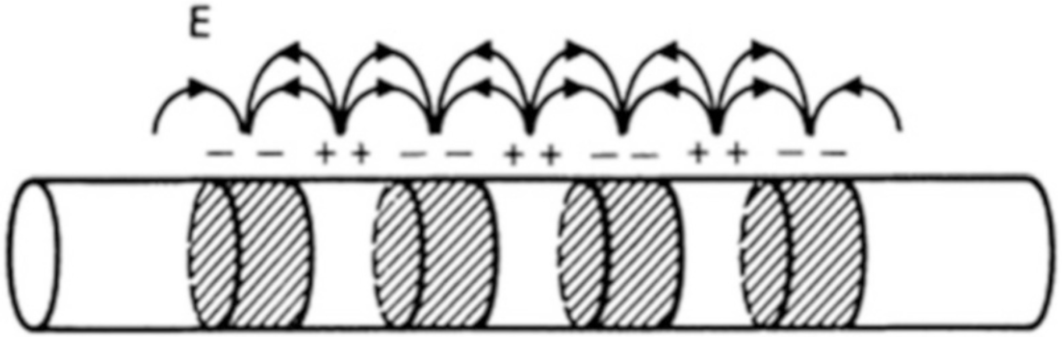

Fig. 4.4 Plasma oscillations propagate in a finite medium because of fringing fields

- Electron Waves
- Ion Waves
  - Plasma Approximation

WAVES - MOVING PLASMA OSCILLATIONS
FOR BOTH ELECTRONS & IONS

- Electron Waves
  - Add $-\nabla p_e$ to Equation of Motion with 3 degrees of freedom

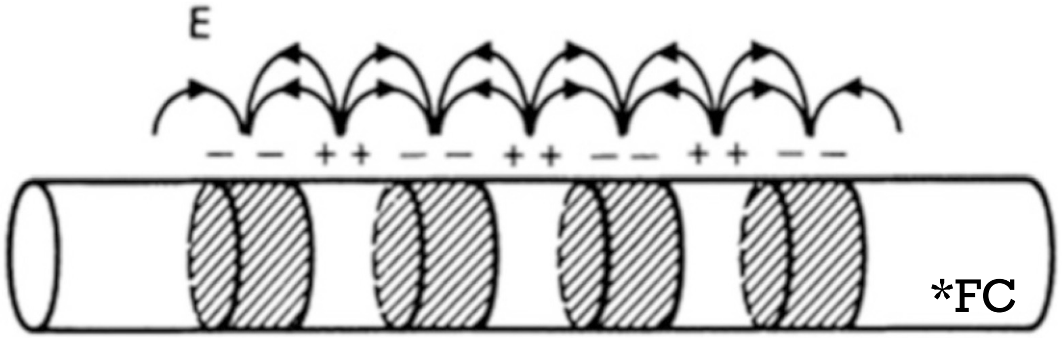

Fig. 4.4 Plasma oscillations propagate in a finite medium because of fringing fields

Dispersion Relation (resulting freq.): $\omega^2 = \omega_p^2 + \frac{3}{2}k^2 v_{th}^2\,; \quad v_{th}^2 \equiv 2KT_e/m$

Group velocity is still less than c: $v_g = \frac{d\omega}{dk} = \frac{3}{2}\frac{k}{\omega}v_{th}^2 = \frac{3}{2}\frac{v_{th}^2}{v_\phi}$

With thermal motion information is connected across regions - now a wave

$$\nabla p_e = 3KT_e \nabla n_e = 3KT_e \nabla(n_0 + n_1) = 3KT_e \frac{\partial n_1}{\partial x}\hat{\mathbf{x}}$$

Linearized Equation of Motion:

$$mn_0 \frac{\partial v_1}{\partial t} = -en_0 E_1 - 3KT_e \frac{\partial n_1}{\partial x}$$

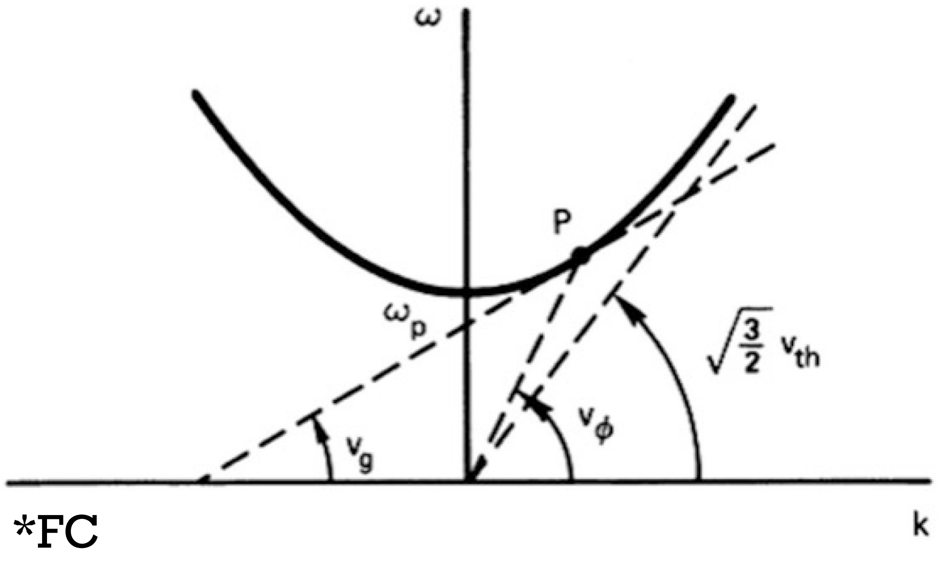

Fig. 4.5 Dispersion relation for electron plasma waves (Bohm–Gross waves)

WAVES - MOVING PLASMA OSCILLATIONS
FOR BOTH ELECTRONS & IONS

- Electron Waves
  - Add $-\nabla p_e$ to Equation of Motion with 3 degrees of freedom

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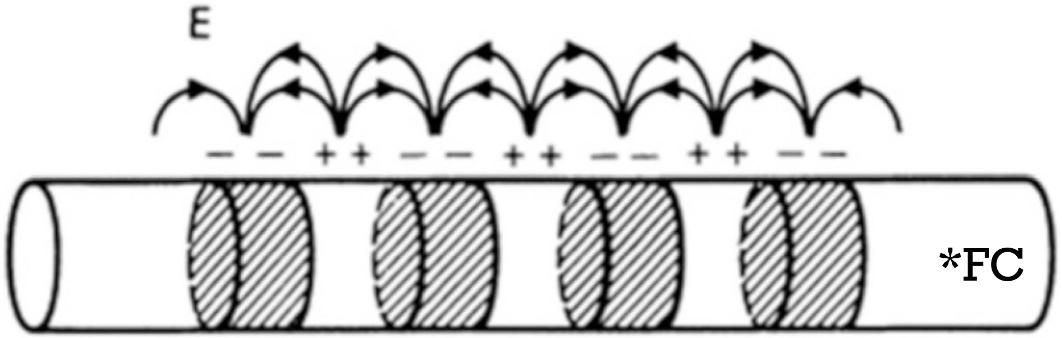

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WAVES - MOVING PLASMA OSCILLATIONS
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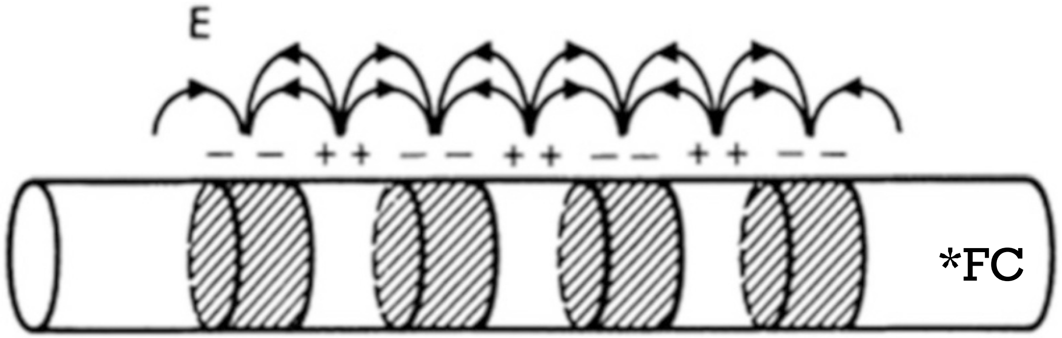

Fig. 4.4 Plasma oscillations propagate in a finite medium because of fringing fields

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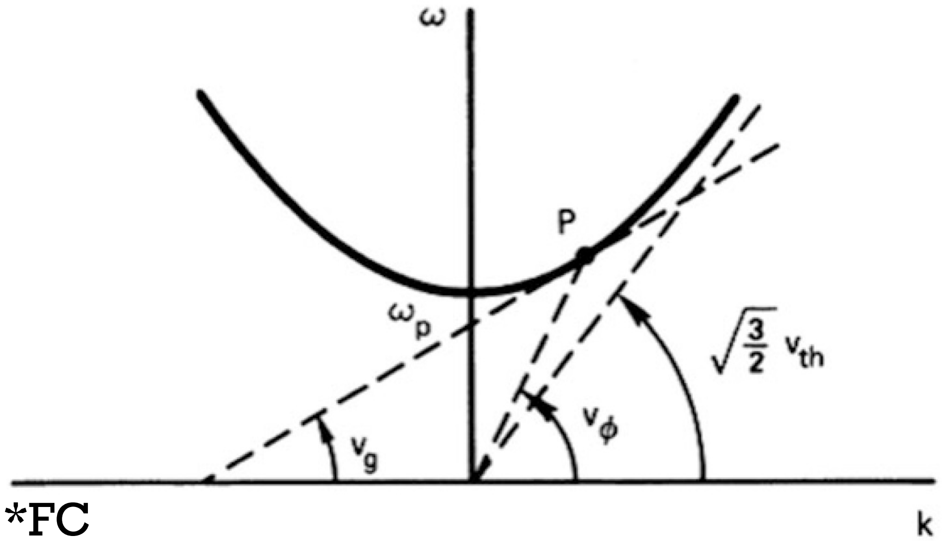


Fig. 4.5 Dispersion relation for electron plasma waves (Bohm–Gross waves)

WAVES - MOVING PLASMA OSCILLATIONS
FOR BOTH ELECTRONS & IONS

- Ion Acoustic Waves
  - E-Field allows for sound to travel
  - Plasma Approximation

Low Frequency Oscillations & $n_i=n_e=n$
So, no Poison's!

Dispersion Relation
for ion acoustic waves:

$$\frac{\omega}{k} = \left(\frac{KT_e + \gamma_i KT_i}{M}\right)^{1/2} \equiv v_s$$

Ion Fluid Equation of Motion:

$$Mn\left[\frac{\partial \mathbf{v}_i}{\partial t} + (\mathbf{v}_i \cdot \nabla)\mathbf{v}_i\right] = en\mathbf{E} - \nabla p = -en\nabla\phi - \gamma_i KT_i \nabla n$$

Acoustic velocity
is given by:

$$v_s = (KT_e/M)^{1/2}$$

Perturbation Density for
both Ions & Electrons:

$$n_1 = n_0 \frac{e\phi_1}{KT_e}$$

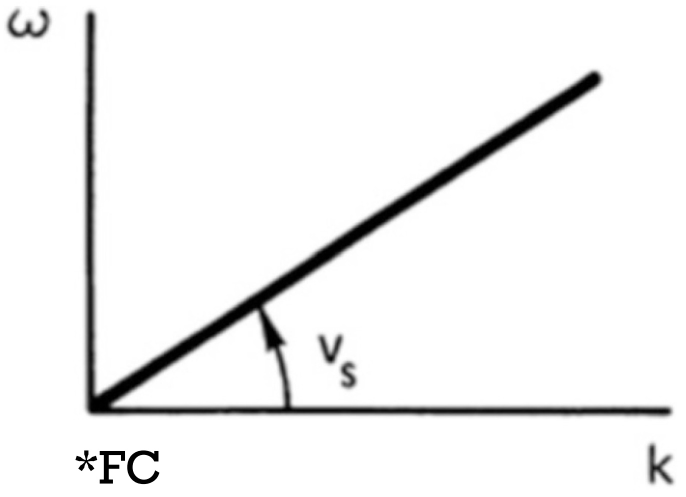


Fig. 4.12 Dispersion relation for ion acoustic waves in the limit of small Debye length

*FC

Linearized Continuity Equation:

$$i\omega n_1 = n_0 ik v_{i1}\,; \quad \omega^2 = k^2\left(\frac{KT_e}{M} + \frac{\gamma_i KT_i}{M}\right); \quad \gamma_i = 3$$

WAVES - MOVING PLASMA OSCILLATIONS
FOR BOTH ELECTRONS & IONS

- Electron Waves
  - Add $-\nabla p_e$ to Equation of Motion with 3 degrees of freedom

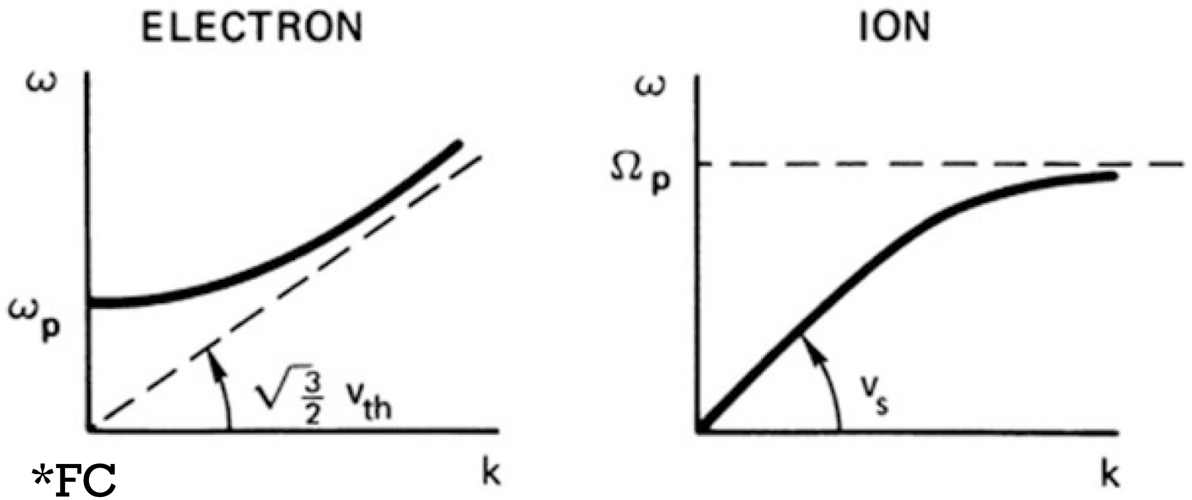
Dispersion Relation (resulting freq.): $\omega^2 = \omega_p^2 + \frac{3}{2}k^2 v_{th}^2$; $v_{th}^2 \equiv 2KT_e/m$

Group velocity is still less than c: $v_g = \frac{d\omega}{dk} = \frac{3}{2}\frac{k}{\omega}v_{th}^2 = \frac{3}{2}\frac{v_{th}^2}{v_\phi}$

- Ion Acoustic Waves
  - E-Field allows for sound to travel
  - Plasma Approximation

Dispersion Relation for ion acoustic waves: $\frac{\omega}{k} = \left(\frac{KT_e + \gamma_i KT_i}{M}\right)^{1/2} \equiv v_s$

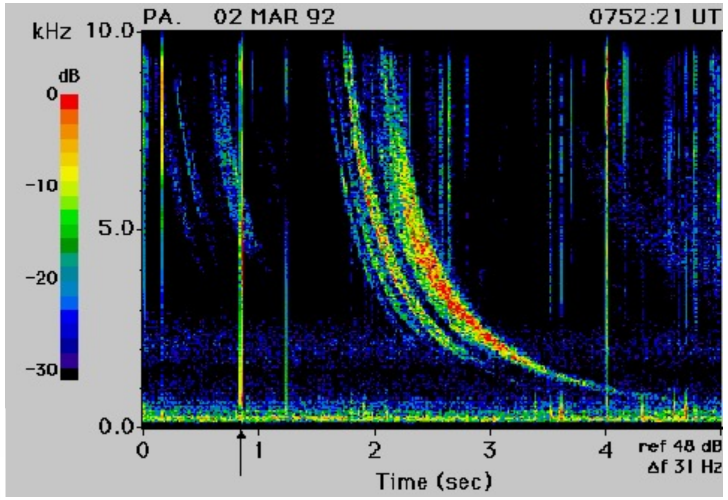
Acoustic velocity is given by: $v_s = (KT_e/M)^{1/2}$



*FC

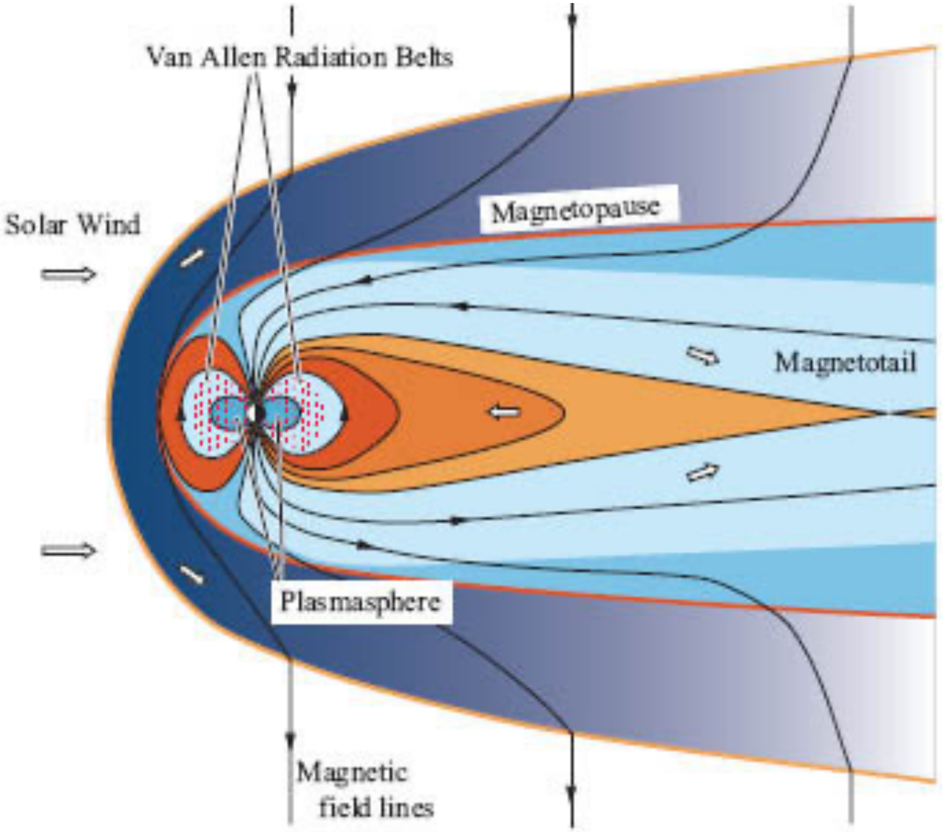
Fig. 4.13 Comparison of the dispersion curves for electron plasma waves and ion acoustic waves

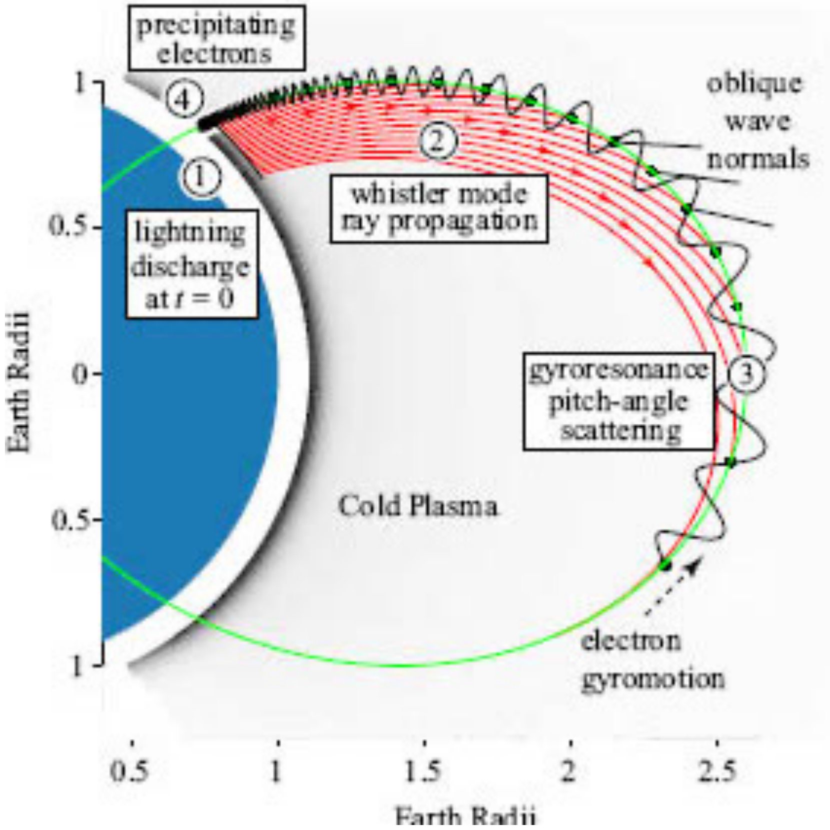
WHISTLERS:
PLASMA OSCILLATIONS IN-ZONE



Example of a whistler recorded at Palmer Station, Antarctica.

https://vlf.stanford.edu/research_topic_inlin/introduction-whistler-waves-magnetosphere/





Whistlers propagate oblique to the Earth's magnetic field lines.

4.20 Summary of Elementary Plasma Waves

Electron waves (electrostatic)

$$\mathbf{B}_0 = 0 \ \text{ or } \mathbf{k} \parallel \mathbf{B}_0: \quad \omega^2 = \omega_p^2 + \tfrac{3}{2}k^2 v_{th}^2 \quad \text{(Plasma oscillations)} \tag{4.143}$$

$$\mathbf{k} \perp \mathbf{B}_0: \quad \omega^2 = \omega_p^2 + \omega_c^2 = \omega_h^2 \quad \text{(Upper hybrid oscillations)} \tag{4.144}$$

Ion waves (electrostatic)

$$\mathbf{B}_0 = 0 \text{ or } \mathbf{k} \parallel \mathbf{B}_0: \quad \omega^2 = k^2 v_s^2 = k^2 \frac{\gamma_e KT_e + \gamma_i KT_i}{M} \quad \text{(Acoustic waves)} \tag{4.145}$$

$$\mathbf{k} \perp \mathbf{B}_0: \quad \omega^2 = \Omega_c^2 + k^2 v_s^2 \quad \text{(Electrostatic ion cyclotron waves)} \tag{4.146}$$

or

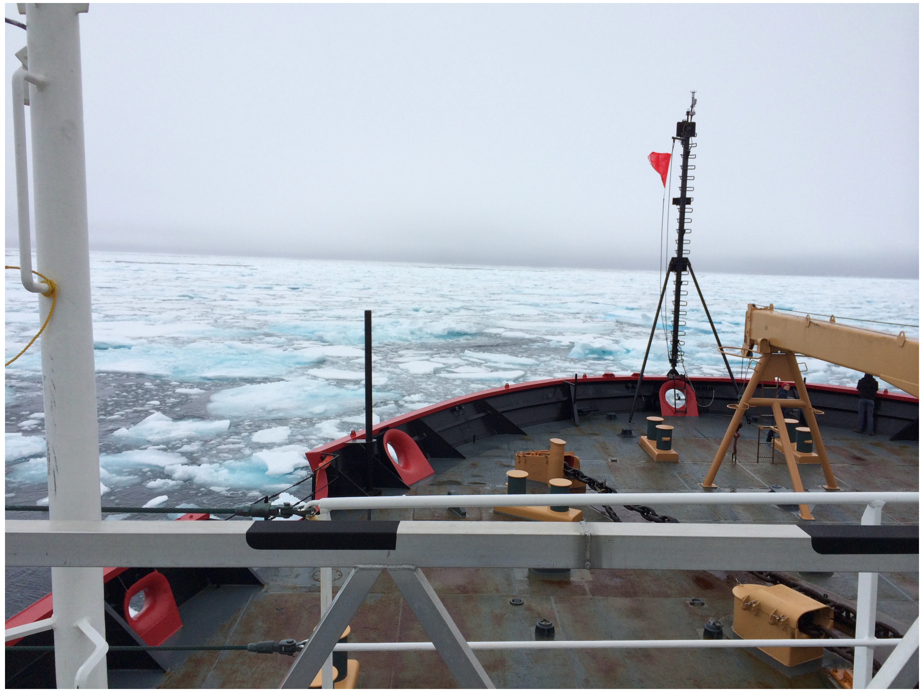
$$\omega^2 = \omega_l^2 = \Omega_c \omega_c \quad \text{(Lower hybrid oscillations)} \tag{4.147}$$

Electron waves (electromagnetic)

$$\mathbf{B}_0 = 0: \quad \omega^2 = \omega_p^2 + k^2 c^2 \quad \text{(Light waves)} \tag{4.148}$$

$$\mathbf{k} \perp \mathbf{B}_0, \ \mathbf{E}_1 \parallel \mathbf{B}_0: \quad \frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2} \quad \text{(O wave)} \tag{4.149}$$

$$\mathbf{k} \perp \mathbf{B}_0, \ \mathbf{E}_1 \perp \mathbf{B}_0: \quad \frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}\frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_h^2} \quad \text{(X wave)} \tag{4.150}$$



TIP OF THE ICEBERG!

$$\mathbf{k} \parallel \mathbf{B}_0: \quad \frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1 - (\omega_c/\omega)} \quad \text{(R wave) (whistler mode)} \tag{4.151}$$

$$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1 + (\omega_c/\omega)} \quad \text{(L wave)} \tag{4.152}$$

Ion waves (electromagnetic)

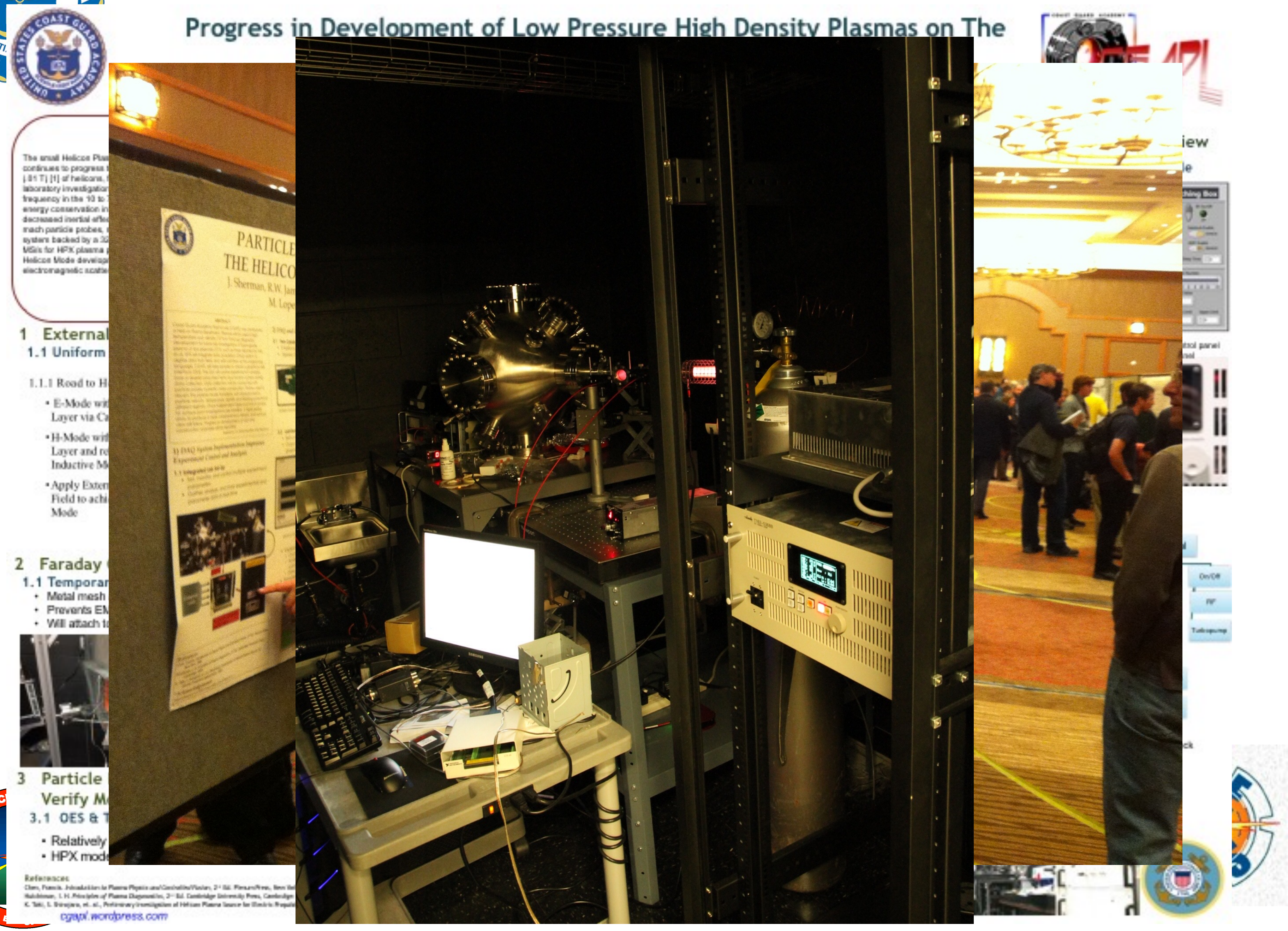
$\mathbf{B}_0 = 0$: None

$$\mathbf{k} \parallel \mathbf{B}_0: \quad \omega^2 = k^2 v_A^2 \quad \text{(Alfvén wave)} \tag{4.153}$$

$$\mathbf{k} \perp \mathbf{B}_0: \quad \frac{\omega^2}{k^2} = c^2 \frac{v_s^2 + v_A^2}{c^2 + v_A^2} \quad \text{(Magnetosonic wave)} \tag{4.154}$$

*FC

BIG THANKS FOR WALKING THE WAVES WITH ME!

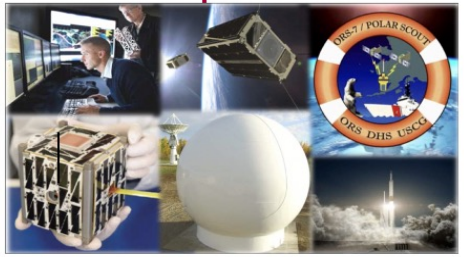


LEVEL 07

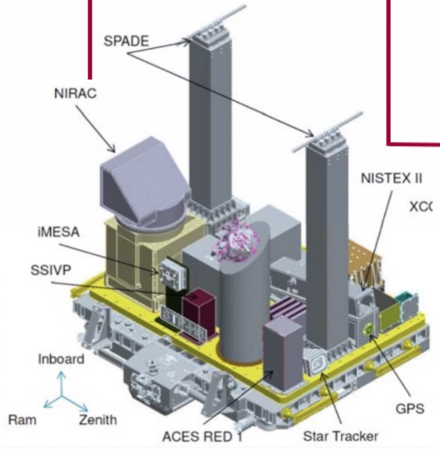
INNOVATION

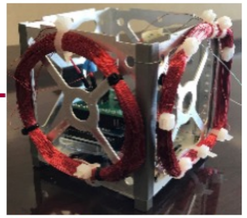
CG Space & Energy Initiatives

Space Initiatives		Space & Energy Crossover		Energy Initiatives
• Operation Polar Scout • RDC/CGA Ground Station & Radome • CubeSat [with Cyber] Ops & Research	• ThinSat Research • Remote Sensing • Geospatial Satellite/AIS Research	• Spacecraft Plasma Propulsion Research • Fusion/Fission • Magnet Torquer CubeSat Attitude Control	• MHD Propulsion [craft/buoys] • Plasma Waste Water Reactor • Corrosion Research	• Energy Production/Alternatives: • Fusion Energy Research • Wind/Wave/Solar Studies • Oil Fingerprinting

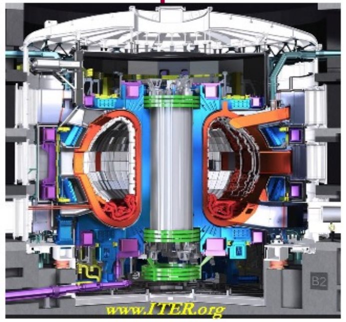


Polar Scout Mission & CGA Radome



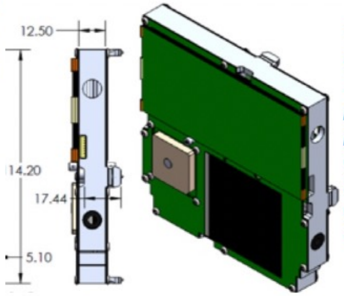

Magnetoquer Attitude Control.

CGA/DOD Corrosion Research

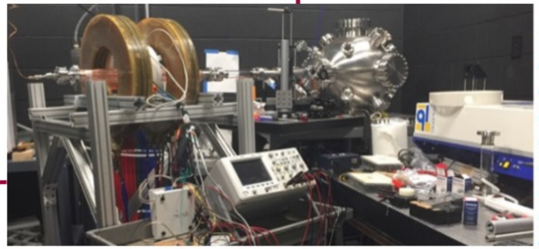


International Tokamak Fusion Experiment, ITER


CGA CubeSat design – dem capstone/ dsp



CGA & NRL collaboration. Impedance probe to monitor plasma density on ThinSat – test for ISS diagnostic, SPADE.


CGA Plasma Laboratory. MHD, Plasma, Directed Energy, Fusion research.

R.W. James, 2018