Mechanical and Thermal Modeling of a High Pulse Rate Pulsed Inductive Thruster

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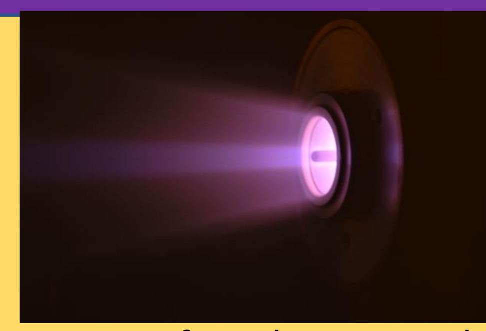
What is Electric Propulsion?

- Electric Propulsion (EP) is **the use of electrical energy to accelerate a propellant**, often in the form of plasma
- **Three main types of EP:** Each uses a different mechanism to generate thrust
  - Electrostatic
  - Electromagnetic
  - Electrothermal



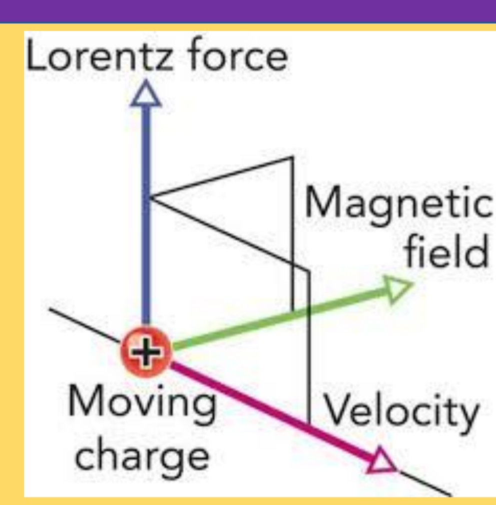
Test Image of an Electron Cyclotron Thruster (ECR), SPACE Lab

Artist's depiction of the Dawn spacecraft, a high-profile mission to Ceres and Vesta using electrostatic EP. [NASA/JPL, 2009]

- **Pros/Cons of EP:**
  - **Pros:**
    - High exhaust velocity -> high efficiency -> lower propellant mass needed for mission success
    - Compact form factor
  - **Cons:**
    - Engineering challenges when scaling for higher power
    - Potentially expensive propellant (e.g., xenon, krypton)
- **Current uses of EP:**
  - Keeping satellites in stable orbits over long periods of time
  - Long distance robotic exploration missions

Inductive Pulsed Plasma Thruster

- **Description:**
  - Form of electromagnetic propulsion using pulses through an inductor coil to ionize and accelerate a gaseous propellant using the Lorentz force
- **Advantages of IPPT:**
  - Electrodeless design means that conductor does not come into direct contact with plasma
  - Allows for use of more volatile propellants: water, nitrogen dioxide, ammonia
  - Propellant flexibility allows In-Situ Resource Utilization and cost benefits vs noble gas propellants



Lorentz force diagram. [University of Kentucky, 2013]

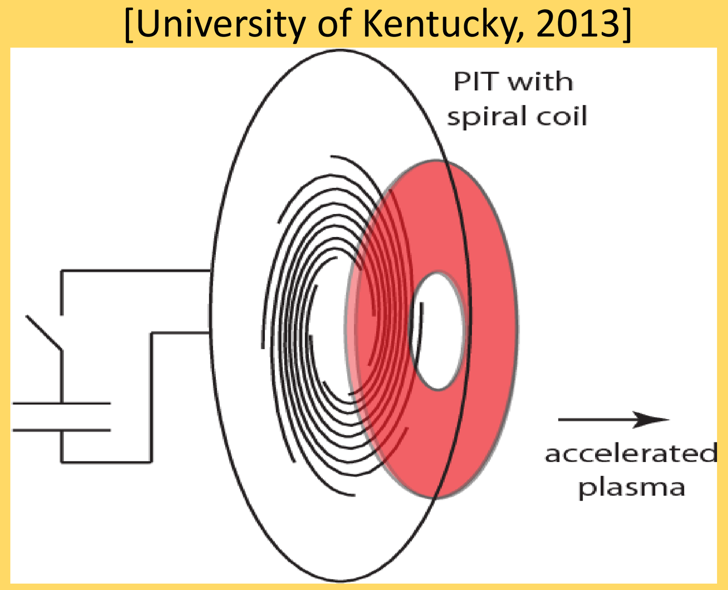
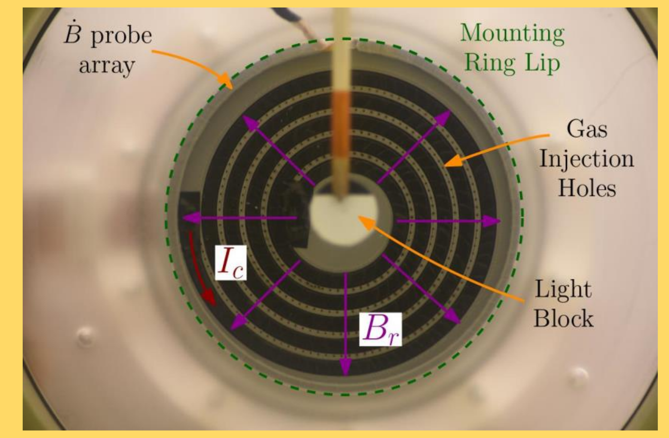


Diagram of IPPT. [Tri Alpha Energy, 2013]

Research Problem and Objectives

- **Research Problem: How can mechanical and thermal modeling tools be applied to the early design process of a flight-ready thruster?**

Vacuum chamber shot of HiPeR-PIT testbed, SPACE Lab



Labeled coil face of HiPeR-PIT testbed, SPACE Lab

- **Model Design Objectives:**
  - **Design thruster thermal management to maintain <200 W heat to the spacecraft for 5 kW thruster**
  - **Design thruster structure to mass budget of <3kg/kW**

Thermal Modeling

- **Where does heat come from?**
  - Electrical resistance
  - Plasma heating
    - Radiation
    - Ion and electron collision
- **How to deal with heat in space**
  - Conduction away from sensitive electronics and instruments
  - Radiation away from the spacecraft
  - Radiative power scales as ~T^4 according to the Stefan-Boltzmann law

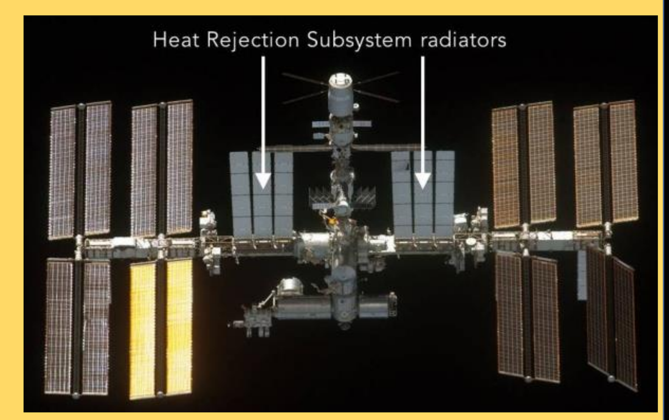
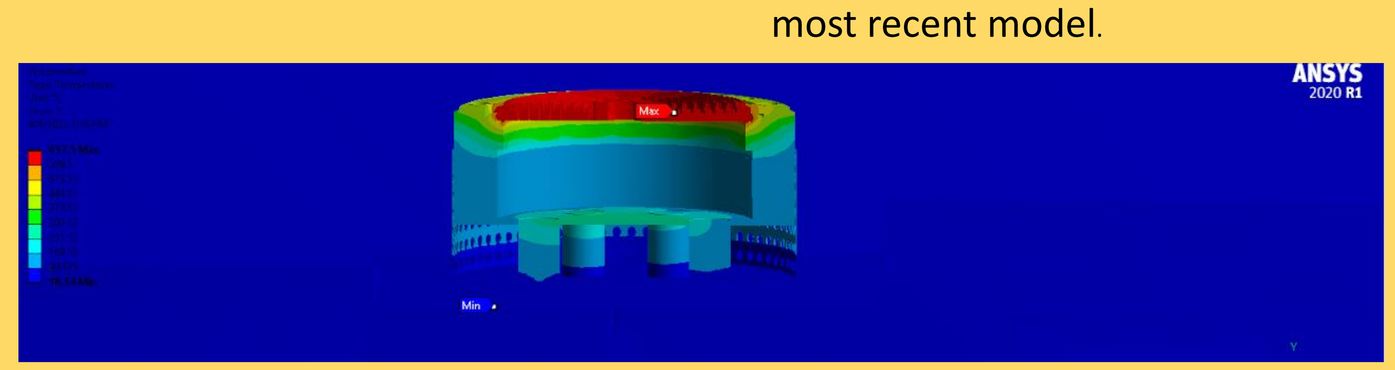


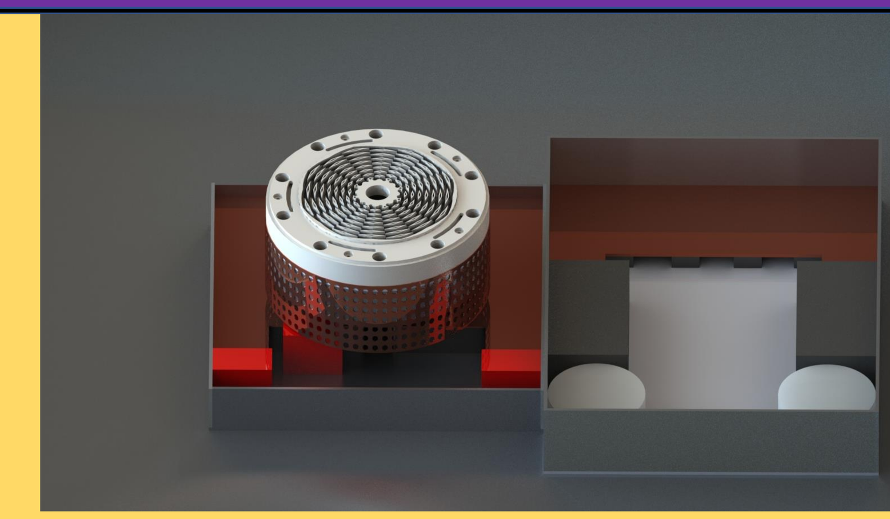
Diagram of radiators on the ISS. [Let's Talk Science, 2019]

- **Computer Modeling**
  - ANSYS Mechanical steady-state thermal simulation used to set material, radiative, and conductive conditions to determine heat flow
  - Shared topology used to model the connections between components

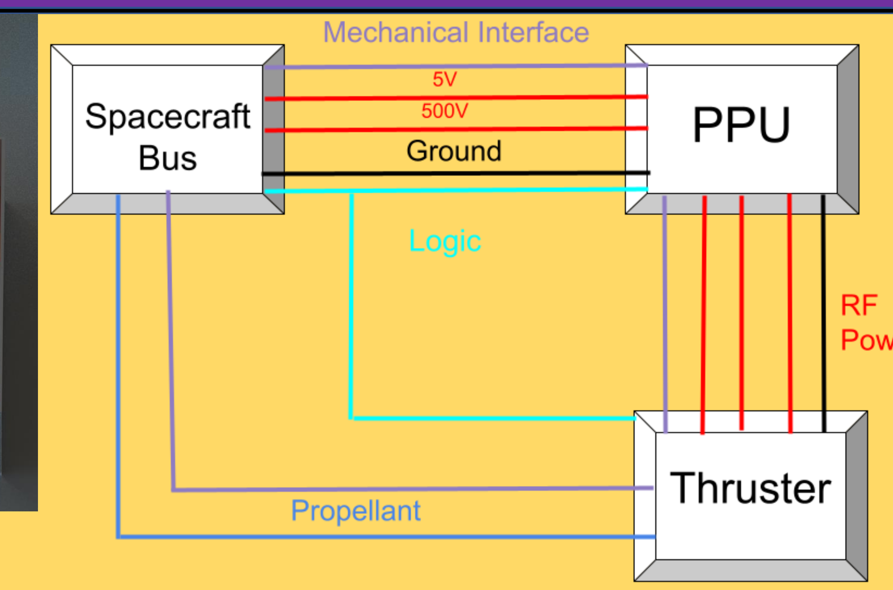
Cutaway of thermal simulation with most recent model.



Mechanical Modeling



3D rendered cutaway of HiPeR-PIT assembly created for thermal modeling.



Overview diagram of interfaces between a spacecraft bus designed by Avalanche Energy and the HiPeR-PIT

- Solidworks applied to create mechanical model starting with higher-level assemblies
- Refined over time to include detailed components and connections
- Basic diagrams of system interconnects necessary for determination of specific connections and contact points
- NASA NEPP handbook was key for determining options for electrical connections, wires, cables, and tubing that were applicable for vacuum environments

Results/Applications

- **Thermal Modeling Conclusions:**
  - Best results for radiative power came from keeping the coil face as hot as possible
  - Low conductivity ceramics in coil mounting and thruster connections was key in minimizing heat conduction to the spacecraft
  - Vacuum gaps where possible also demonstrated positive results (<40W to spacecraft in ideal model)
  - **Future Work:** Insulating electrical connections in the coil and faraday cage is most promising area of future radiative gains

2000W Input Heat Flow

↓

300W to Spacecraft

- **Mechanical Modeling Conclusions:**
  - Solidworks assemblies can effectively model the connections and interactions between components
  - **Future Work:** Study feasibility of high voltage (500V+) connections in vacuum and reduce mass of component casings to stay within 15kg mass budget.