New Capabilities for MHD Power Generation Enabled by Nanosecond High-Voltage Pulses and Electron Beam Methods

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Past Experience in Aerospace Applications of MHD

- Electric power generation using MHD
- Use of MHD power to control aerodynamics and propulsion:
  - Surface plasmas for control of the boundary layer and laminar-turbulent transition.
  - Plasma Virtual shapes created by off-body energy addition for drag reduction, steering, shock control, flow turning
  - Plasma-assisted combustion
- Power extraction from one region and its use in another region (MHD bypass)
- Dual-use MHD devices (both power generation and flow control)

Methods of Ionization of Cold Hypersonic Air Flows

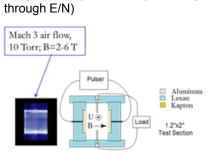
Parameter range:
T=200-1000 K, P=0.01-1 atm, U=1000-4500 m/s
Required electron density:
10^{12} - 10^{14} cm^{-3}

Thermal ionization:

- Works well only at T>2000 K and with alkali seed
- Problems with mixing the seed into the supersonic flow
- Natural ionization for **reentry**

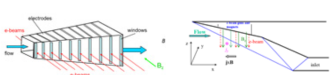
Nonequilibrium field-induced ionization:

- High-voltage ns pulses, *recently ps pulses*
- Issues with arcing instability (caused by coupling between T and ionization through E/N)

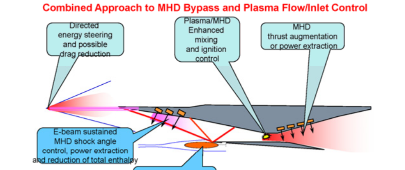


Ionization by electron beams

- The most **efficient** (40-50%) ionization source
- Straightforward and flexible **control**
- **Stability**: short-circuiting through boundary layers and arcing instability can be avoided
- Principal issue: transmission windows (mechanical and thermal strength)



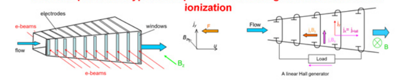
Combined Approach to MHD Bypass and Plasma Flow/Inlet Control



Model: MHD generator on ramp
- 2D marching inviscid CFD code
- On ramp MHD equations
- E-beam ionization and power deposition profiles
- Plasma kinetics
- Vibrational excitation and relaxation

Model: post-combustor MHD generator
- 1D Euler equations plus Faraday/Hall MHD generation and body force
- Hall and ion slip effects included
- Chemically equilibrium flow: ASTRA thermodynamic program
- Saha equilibrium ionization of alkali seed
- Hydrogen fuel; typical scramjet exit conditions
- Expanding or constant-area ducts

An example of Hall type non-equilibrium air MHD generator with e-beam ionization

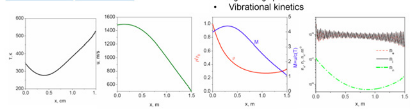


Geometry: L=1.5 m; A_{inl}=0.15x0.15 m^2; A_{out}=0.45x0.45 m^2; Stripe: Δx_{active}=0.5 cm; $\Delta x_{passive}$=2 cm

Input data: B=7 T; p_0=0.0468 Atm; u_0=1484 m/s; T_0=343 K; k_0=0.35; j_{eb}=3 mA/cm^2; ε_{eb}=6 keV

Output: η=45 %; W_{output}=1000 kW; $W_{beam\ input}$=23.5 kW

MHD codes, developed in Princeton University
- 1D and 2D Navier-Stokes and Euler CFD codes
- Faraday or Hall MHD generator/accelerator
- Magnetized non-equilibrium plasma
- Ion slip
- Ionization:
  - ✓ E-beam
  - ✓ Saha equilibrium ionization of alkali metal seed
  - ✓ High-voltage pulses
- Vibrational kinetics

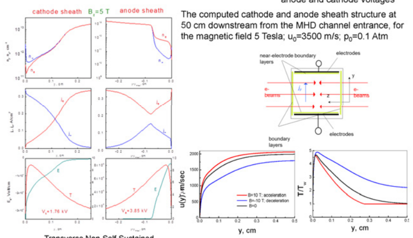


Strong coupling between boundary layers and near electrode sheaths in MHD generator

$$T\uparrow \Rightarrow \rho\downarrow \Rightarrow (\Omega=\omega_c/\nu_m \propto 1/\rho)\uparrow \Rightarrow \mu_{e\perp}\downarrow \Rightarrow V_a\uparrow$$

$V_a \sim V_k$, V_a, V_k are anode and cathode voltages

The computed cathode and anode sheath structure at 50 cm downstream from the MHD channel entrance, for the magnetic field 5 Tesla; u_0=3500 m/s; p_0=0.1 Atm

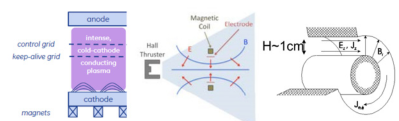


Transverse Non-Self-Sustained Glow Discharge in Magnetic Field

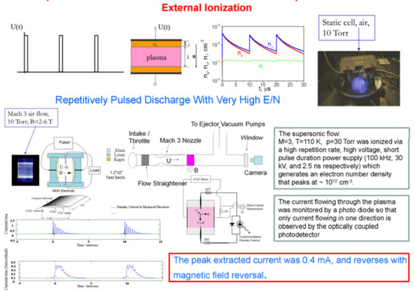
Boundary Layer in MHD generator and accelerator

PPPL Particle-in-cell codes used as a tool of study:
- An electrostatic parallel, implicit, 1D PIC code EDIPIC. Scattering, ionization, and excitation was added into the code, as well as electron-ion and electron-electron collisions.
- 3D LSP and WARP codes include electromagnetic and electrostatic modules, collision modules were implemented into LSP and validated.

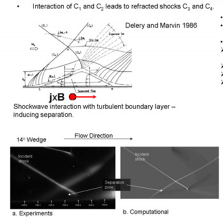
Numerical PIC models were applied for:
- Controlling plasma properties with applied magnetic field
  Electric Propulsion, Plasma Sources for Ion Beams, Magnetron Discharges, High Power Plasma Switch
- Controlling plasma properties in low-collisional plasmas with active boundaries
  Electric Propulsion, Accelerators, Divertors for Magnetic Fusion Devices



First Experimental Demonstration of MHD Effect in Cold Supersonic Air Flow With External Ionization

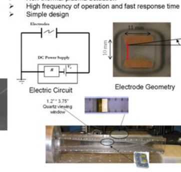


MHD Shock-Wave Boundary Layer Control. "Snowplow Arc": Experiment and Modeling
- Incoming oblique shock (C_1) causes sudden positive pressure gradient on the BL surface.
- This pressure gradient leads to boundary thickening.
- Increase in BL thickness give rise to compression waves and reflected shock (C_2)
- Interaction of C_1 and C_2 leads to refracted shocks C_3 and C_4.



Shockwave interaction with turbulent boundary layer – inducing separation.

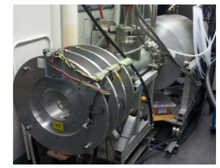
Experiments with 'snowplow arc'
- Mach 2.8 wind tunnel with test section 1.2" x 2.0"
- Essentially a MHD actuator powered using a DC power supply.
- Features:
  - Small localized plasma volume, resulting in low thermal energy input
  - Non-thermal plasma actuation
  - High frequency of operation and fast response time
  - Simple design



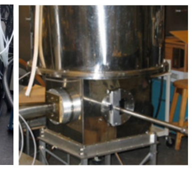
Unique Experimental Facilities

- 60 kV high aperture E-beam gun
- Superconducting magnet B=6 T
- High-voltage picosecond pulse generator

Output voltage – 200 kV
Load – 50 Ohm
Peak current – 4 kA
Rise time – 100 ps
Pulse width – 250 ps
Maximum PRF – 1 kHz



E-beam gun



Magnet

HV pulse generator

New Opportunities for Enhanced Power Generation

- Extension of MHD "topping cycle" power extraction to higher efficiency through higher velocity expansion (to Mach 3 or greater)
  - Low static temperature associated with high Mach number normally reduces the conductivity below operable limits.
  - We propose overcoming the loss of conductivity with high repetition rate, high voltage nanosecond pulses or electron beams that repeatedly ionize the seed material.
  - The low density extends the recombination time, reducing the enthapy/entropy penalty
  - The high Hall parameter at low density allows for "flying electrodes".
- For solving these problems it is necessary to carry out experiments and theoretical modeling
  - Princeton University and PPPL have experimental facilities available, modeling capabilities, and experience with supersonic MHD power extraction that permit us to address this concept.

Relevant Publications

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- A. Starikovskiy, N. Aleksandrov, A. Rakitin. Phil. Trans. R. Soc. A **370**, 740 (2012).

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