Weakly Ionized Plasmas and MHD for Enhanced Performance of Hypersonic Vehicles

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Aerospace Applications of Weakly Ionized Plasmas

- Power generation using MHD
- Use of power to control aerodynamics and propulsion:
    - Surface plasmas for separation and turbulent transition control (virtual shapes)
    - 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)
    - Forces created by magnetic and electric fields acting on charged particles (transferred to neutral gas by collisions)

Aerospace Applications of Weakly Ionized Plasmas

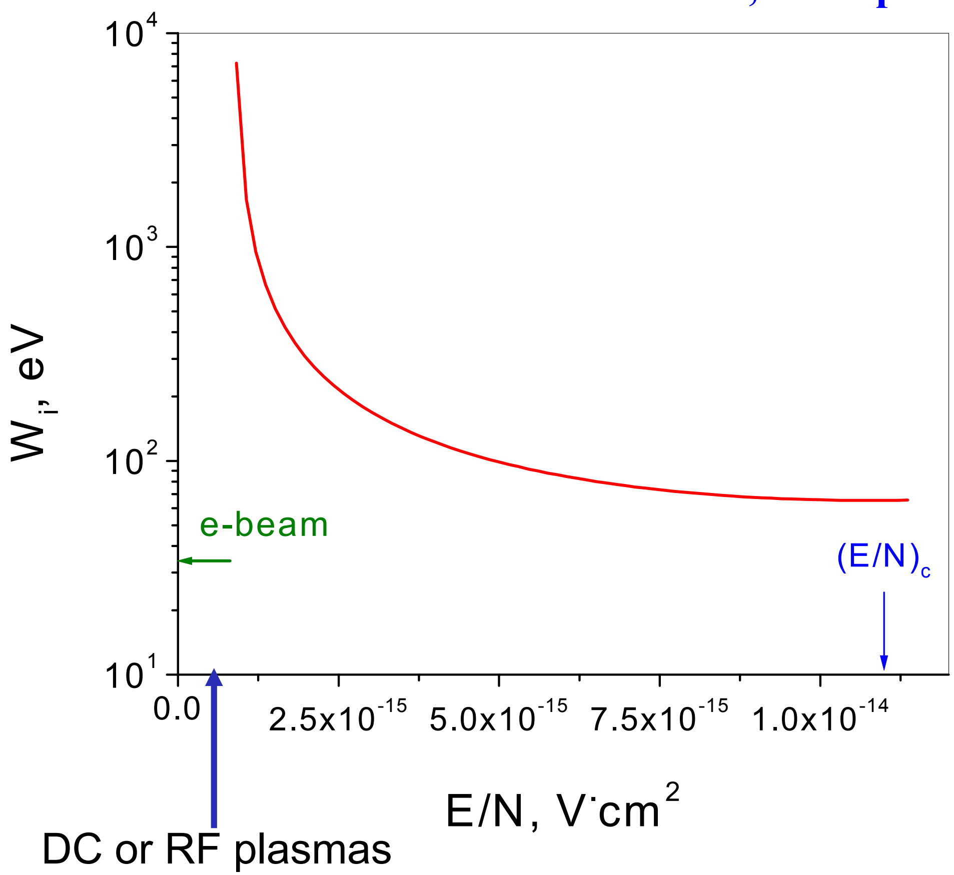
- Ionization level *per se* is not critical if plasmas are used as a means of delivering energy to the flow
- Ionization is critical in MHD power generation and flow control, and in cold-plasma generation of radicals
- At high T (reentry, scramjet combustor) – thermal ionization with alkali seed
- At low T, artificial ionization is needed, and the ionization cost determines design and performance
- Similar to ionization, cold plasma generation of chemically active species for combustion can have considerable energy cost
- Both energy addition and extraction result in flow heating and losses of total pressure and (if in propulsion flowpath) thrust

METHODS AND PROBLEMS OF IONIZATION OF COLD HYPERSONIC AIR

•At M<12, static and stagnation T too low for thermal ionization even with seed

•Need nonequilibrium ionization: its energy cost defines design and performance

ENERGY COST OF IONIZATION IN AIR, in eV per newly produced electron



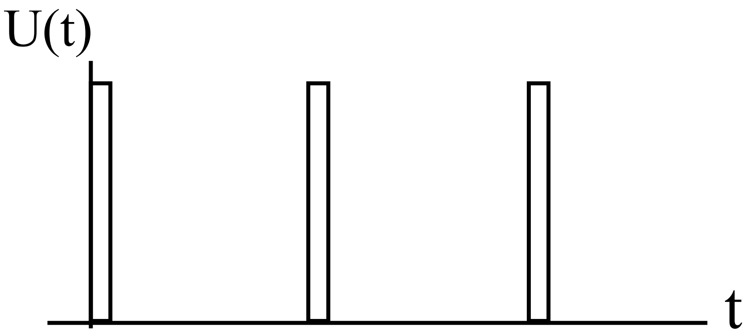
$$W_i = eE\mathrm{v}_{dr} / \nu_i$$

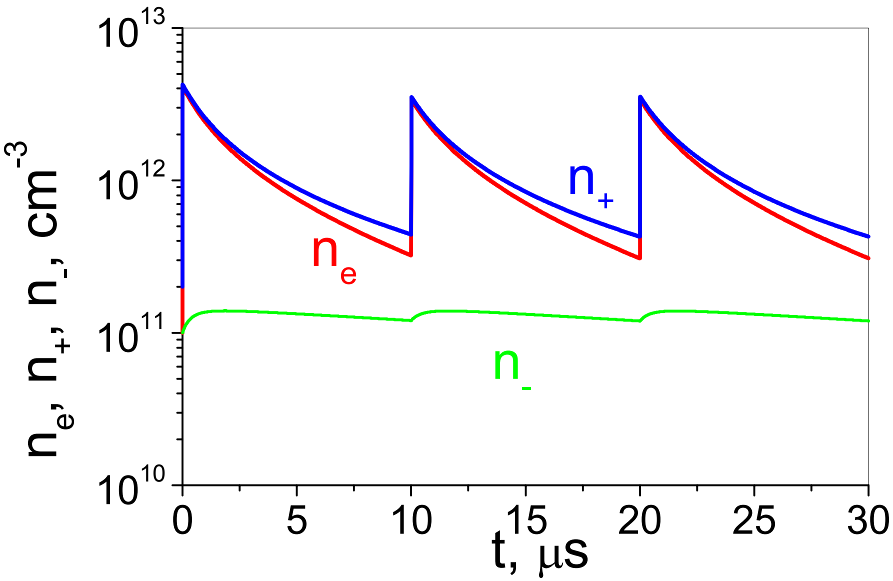
In runaway regime, at $(E/N)_c$, W_i=66 eV - Stoletov's constant

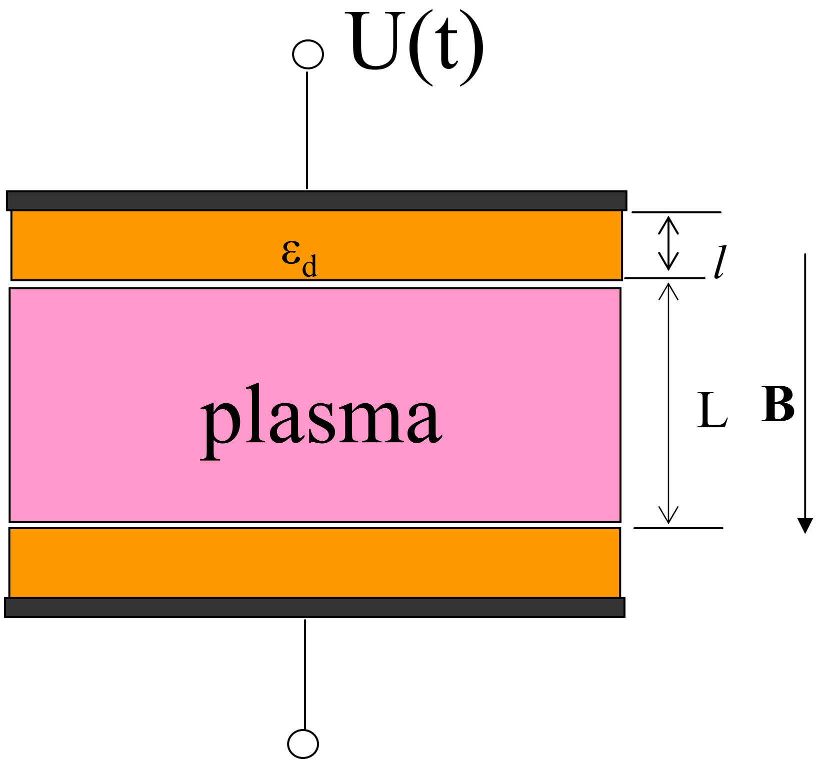
Energy cost of chemically active species (atoms, radicals, and ions):

similar behavior

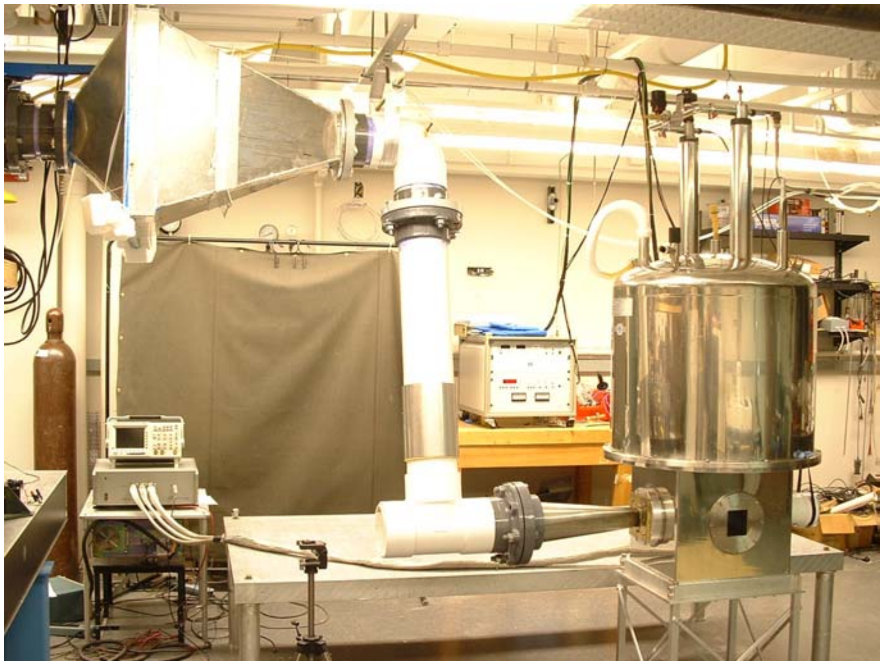
Repetitively Pulsed Discharge



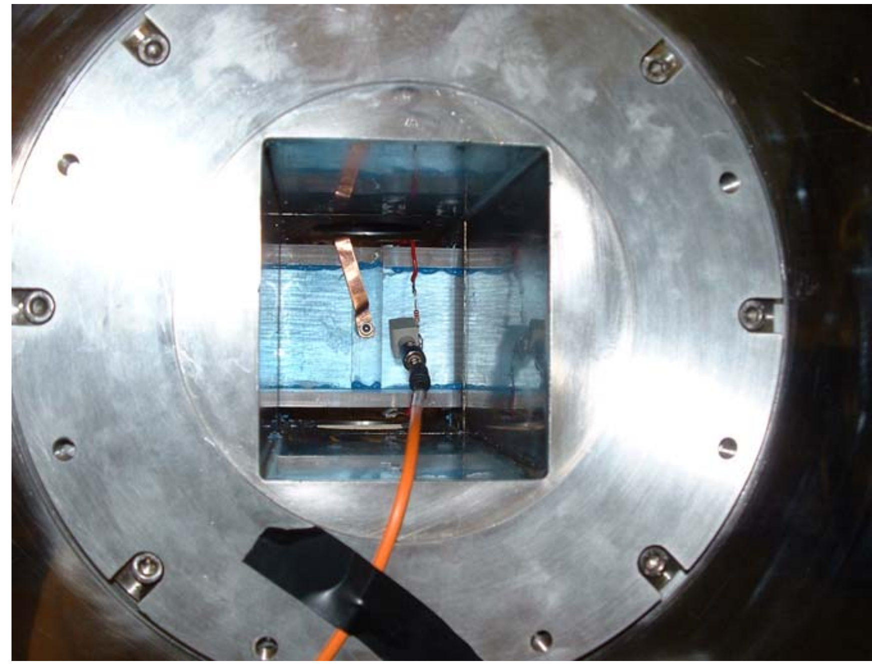




Experimental studies of supersonic MHD effects with ionization by high repetition rate, high-voltage nanosecond pulses

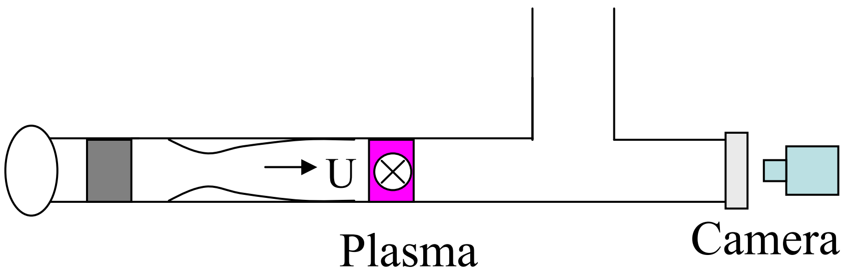


Facility with Mach 3 nozzle, superconducting magnet (6.5 T, 2.5-inch bore), and 30 kV, 100 kHz, 2 ns pulser



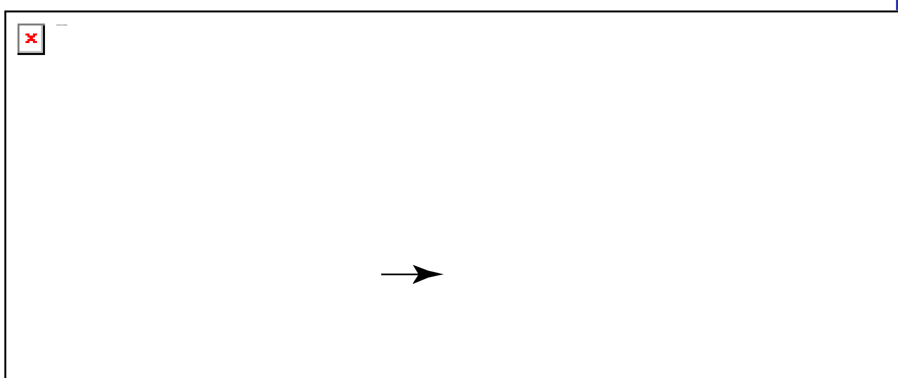
LED circuit attached to the tunnel. The fiber optic cable is orange. The MHD electrodes are on the top and bottom. The pulsed high voltage electrodes are on the front and back walls.

MHD power extraction from an externally ionized, cold, supersonic air flow



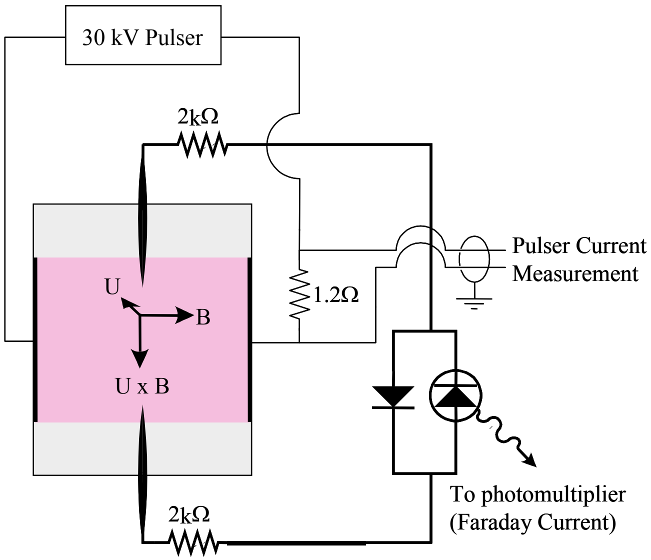
The supersonic flow (Mach 3, 110 K, 30 Torr) is ionized with a high repetition rate, high voltage, short pulse power supply (100 kHz, 30 kV, and 2.5 ns) generating peak electron number density ~ 10^{12} cm^{-3}.

Energy cost per electron (inferred from experiments) is ~100 eV.

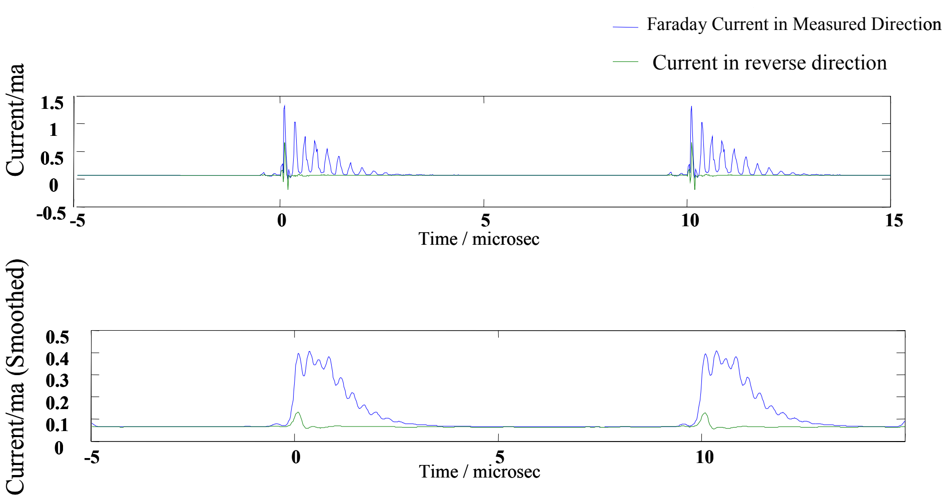


The electric discharge is uniform in the core flow between the electrodes with no arcing through the boundary layer. The wing-shaped MHD power extraction electrodes extend into the flow from the top and bottom walls of the channel.

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

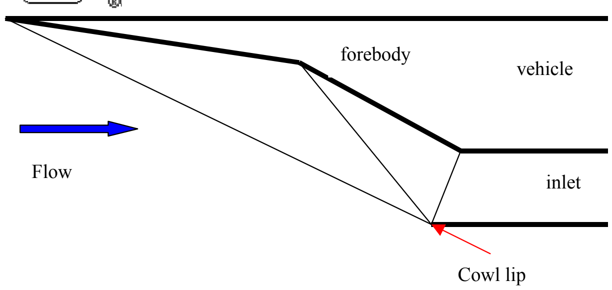


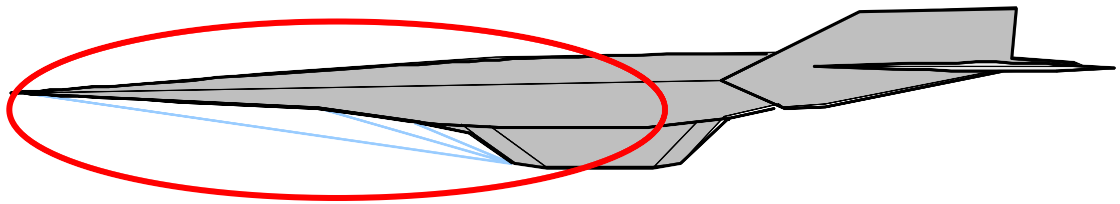
The current flowing through the plasma is monitored by a photo diode so that only current flowing in one direction is observed by the optically coupled photodetector



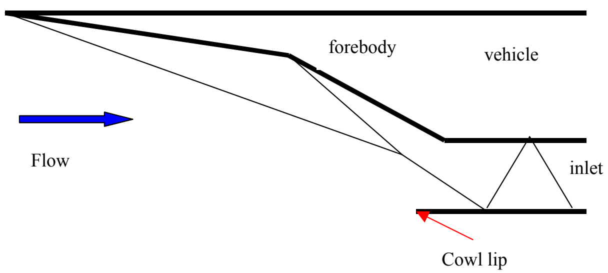
The extracted current reverses with magnetic field reversal

SCRAMJET INLETS AND VEHICLE FOREBODIES ARE DESIGNED FOR A CERTAIN MACH NUMBER, AND PERFORMANCE DETERIORATES IN OTHER REGIMES



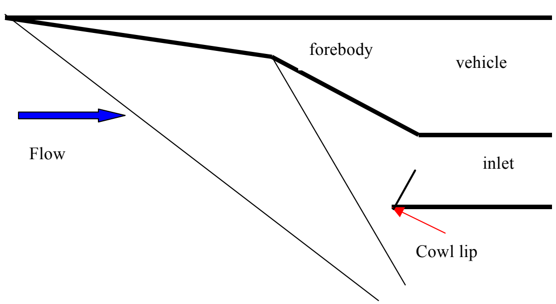


Design Mach number: Shock-on-Lip



Mach number > design Mach number:

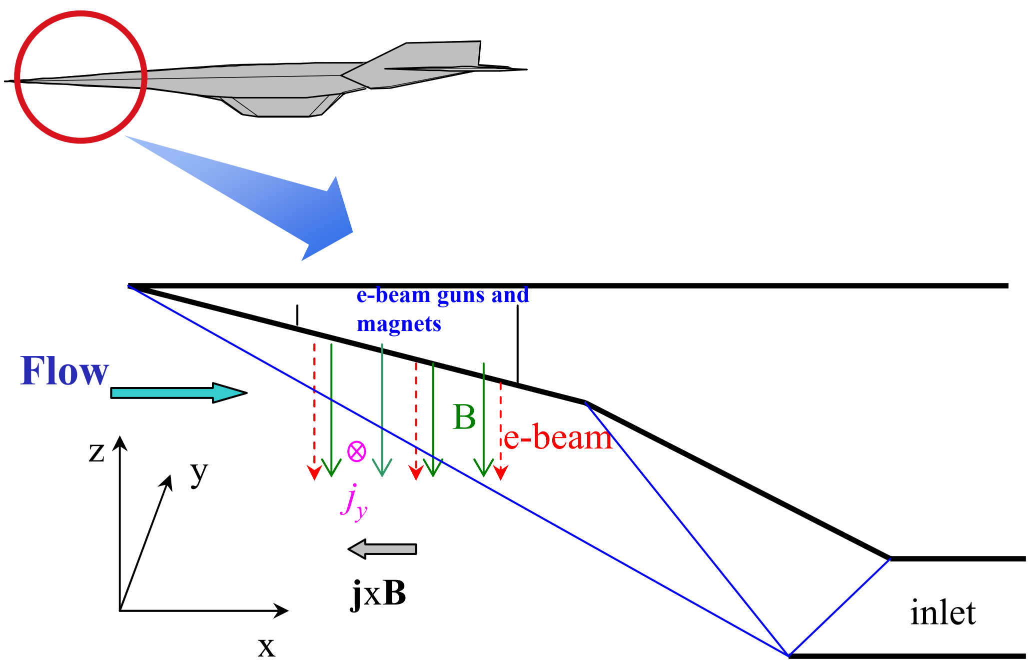
shocks inside the inlet, hot spots, boundary layer separation, engine unstart

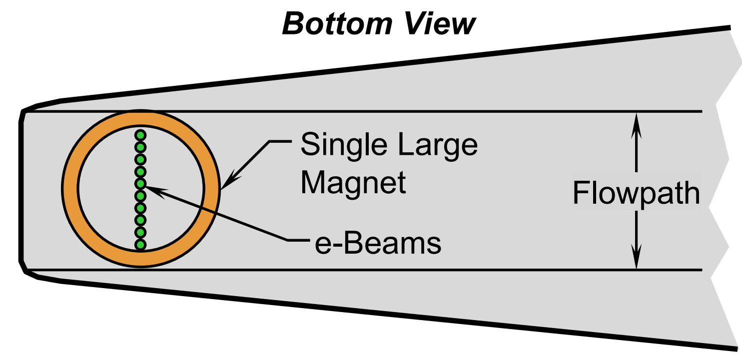


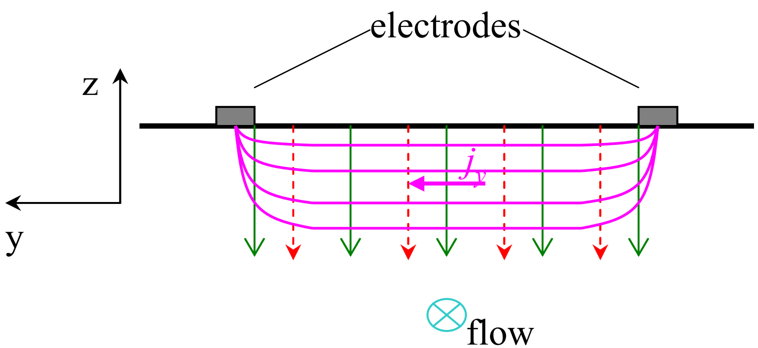
Mach number < design Mach number:

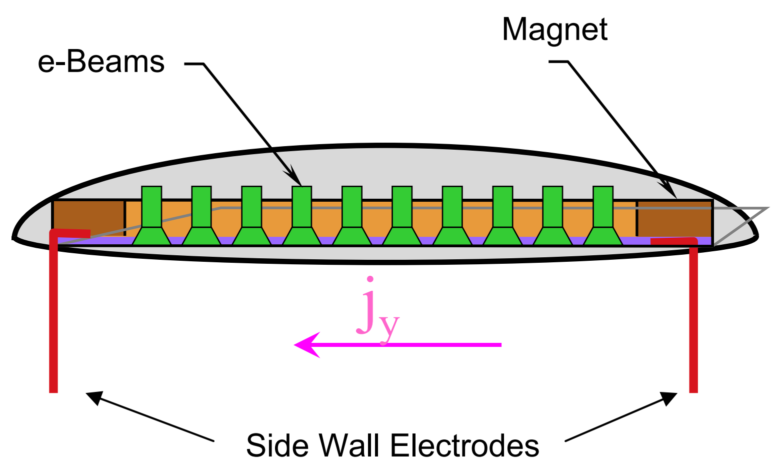
reduced air capture ("spillage"), thus, reduced thrust

Inlet shock control with on-ramp MHD generator



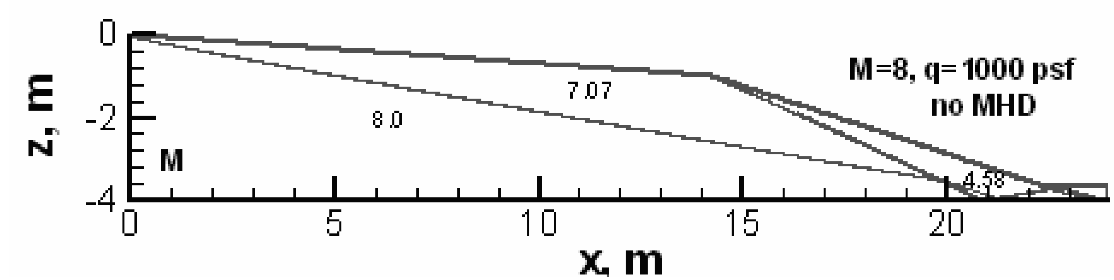


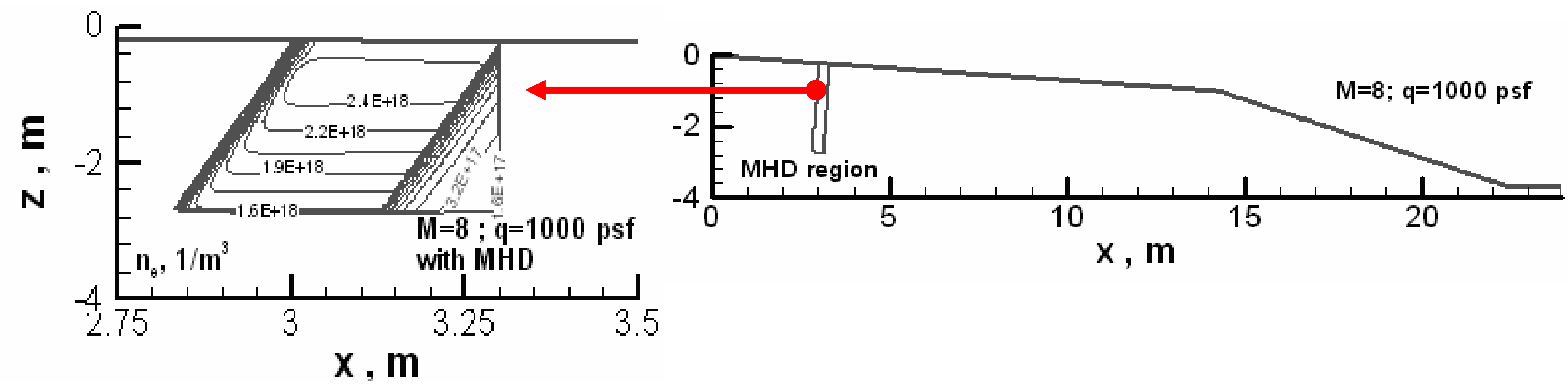


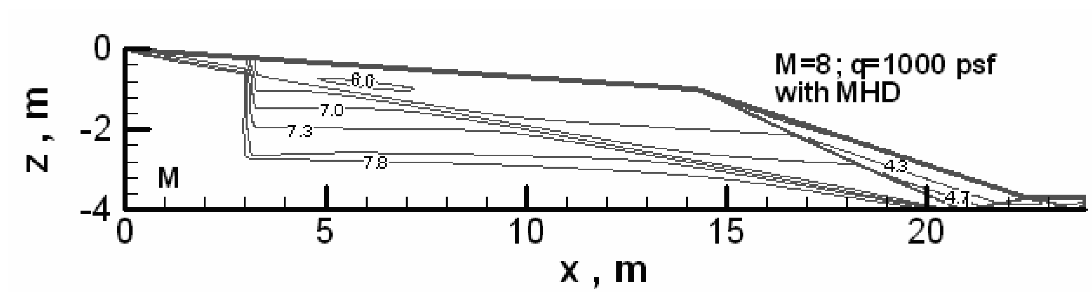


Inlet shock control with on-ramp MHD generator: restoration of shock-on-lip condition at Mach 8 (design – Mach 7, 1000 psf)

B_{max}=1.5-1.7 Tesla,
R_{coil}=2.5 m, L_{MHD}=0.3-0.5 m







Inlet shock control with on-ramp MHD generator: restoration of shock-on-lip condition at Mach 8 (design – Mach 7, 1000 psf)

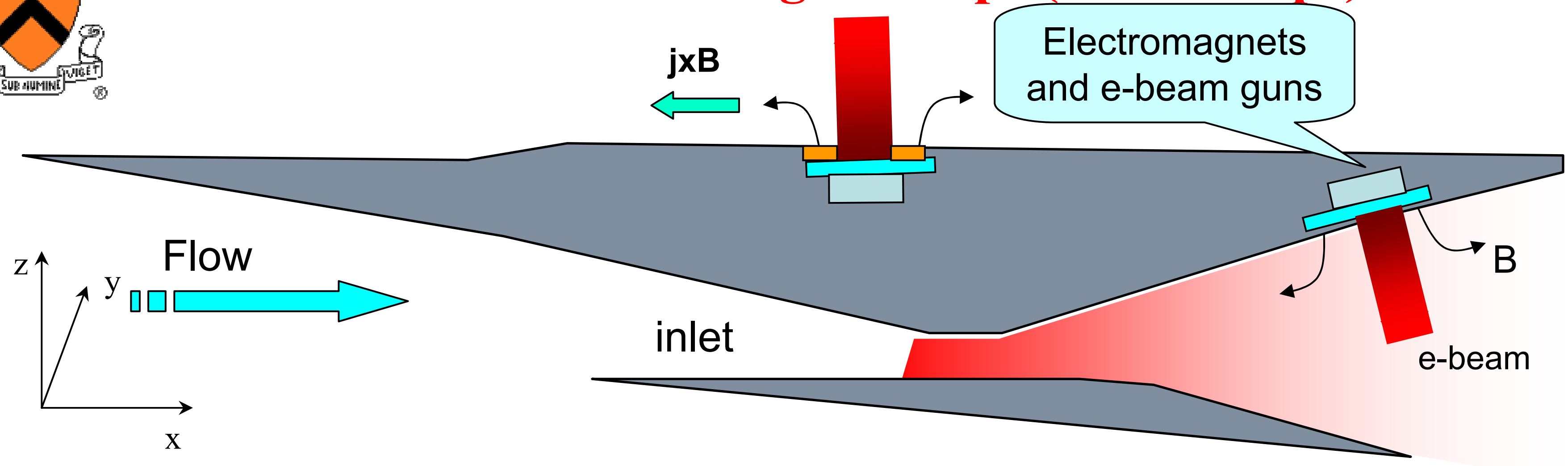
B_{max}=1.5-1.7 Tesla, R_{coil}=2.5 m, L_{MHD}=0.3-0.5 m

Energy balance

Case	Work by jxB force, MW/m	Generated power, MW/m	Joule heating, MW/m	Vibrational excitation, MW/m	E-beam power, MW/m	Interaction parameter	Enthalpy extraction ratio
MHD-1 (k=0.5)	6.935	2.269	3.437	1.228	1.082	0.0183	0.0045
MHD-2 (k=0.8)	5.570	2.333	2.819	0.418	1.616	0.0272	0.00467

Estimated thrust penalty: 5% (primarily due to flow spillage) – small cost to pay for avoiding shock impingement inside cowl, hot spots, flow separation, and engine unstart

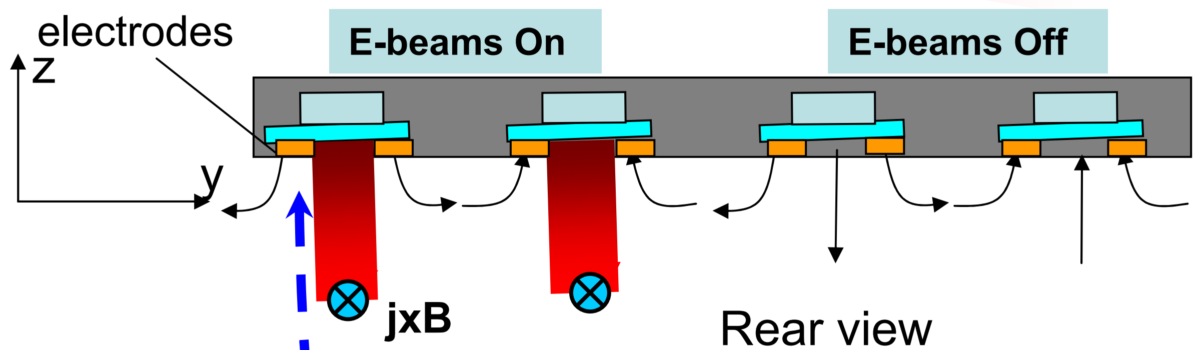
MHD Thrust Vectoring Concept (MHD Flaps)

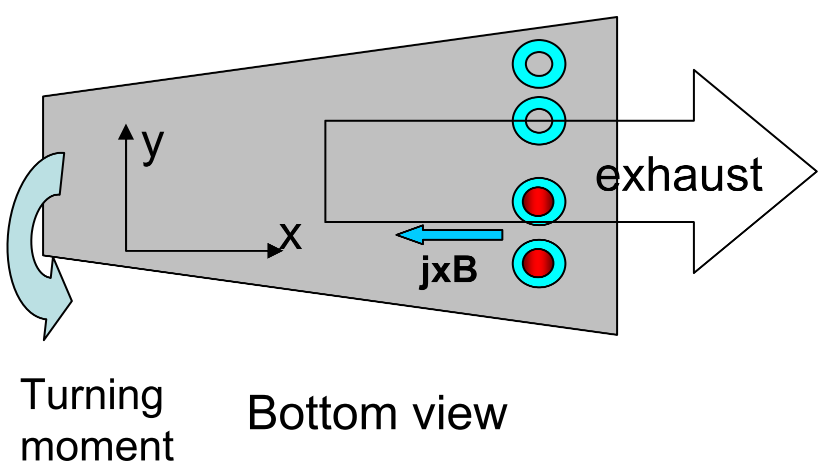


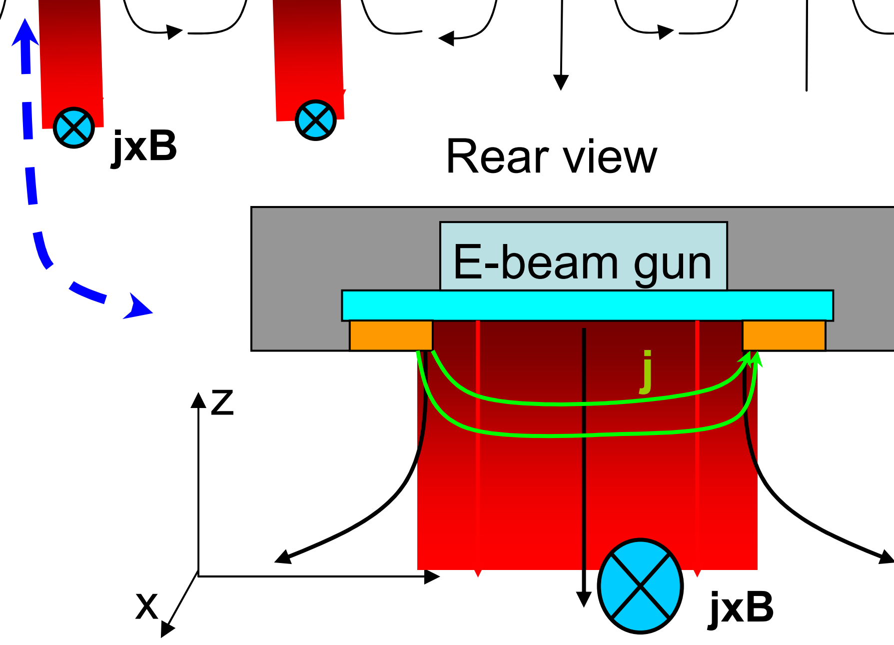
Mach 8, 1000 psf, B=3 T, 15 cm long MHD region:

~1000 N/m force,

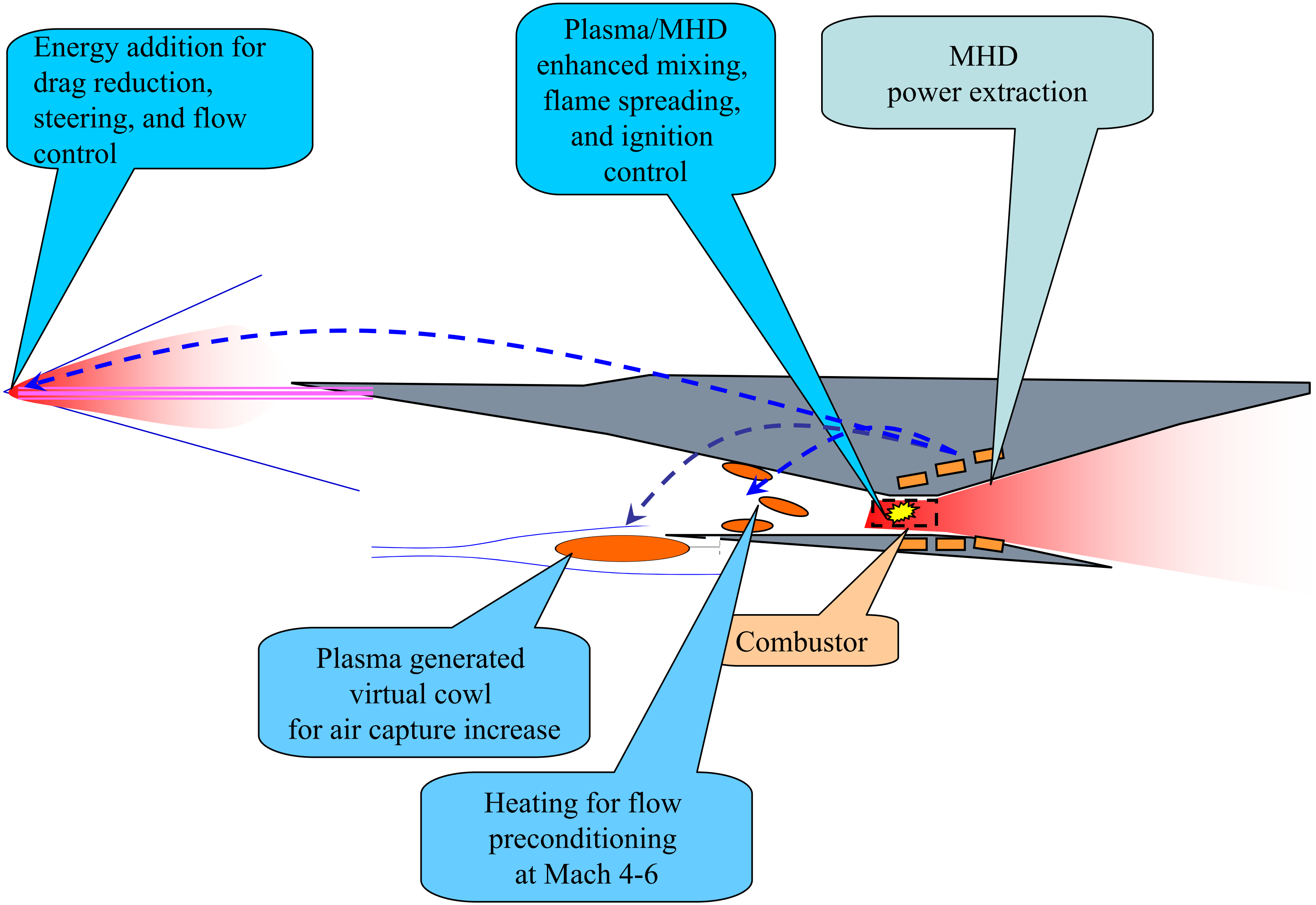
or ~ 1 N per kW of MHD-extracted power







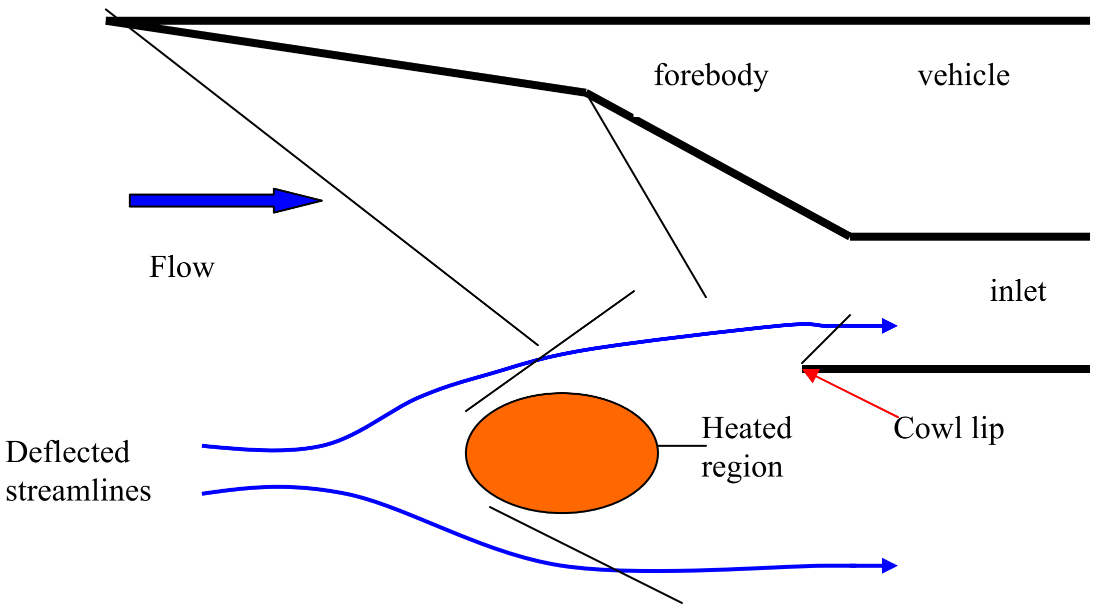
New Energy Bypass Concept



MASS CAPTURE INCREASE BY ENERGY ADDITION OFF THE COWL LIP (VIRTUAL COWL)

First suggested: AIAA 2002-2251 (Maui, 2002)

Detailed analysis: AIAA 2003-0032 (Reno, 2003)



Energy addition by

- **Plasma-controlled external combustion**
- **Combustible pellets**
- **Microwaves plus e-beam/laser guiding**
- **Gas or plasma jets**
- **Power can be generated by MHD in or downstream of combustor**

Advantages:

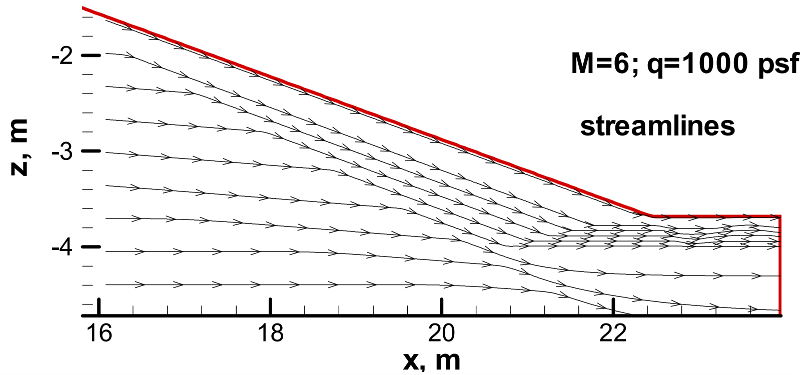
- **<u>Increases</u> mass capture and thrust**
- **<u>Slightly increases</u> total pressure**
- **No B field required**
- **Required power - small fraction (~1%) of enthalpy flux into inlet**
- **Spending power on Virtual Cowl is better than putting it into combustor**

Issues:

- **Substantial absolute power (several MW/m)**
- **Power delivery**

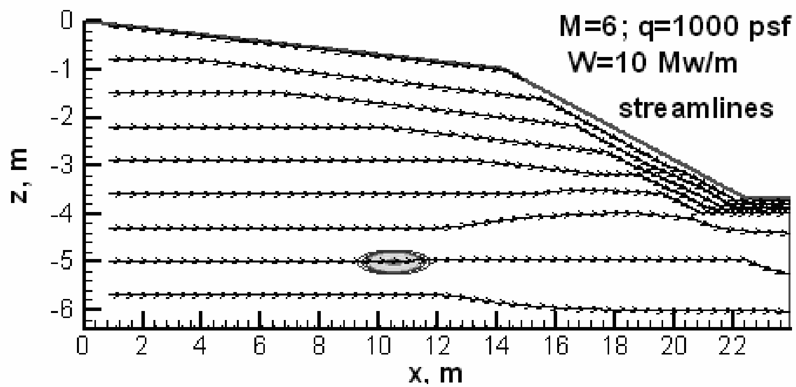
MASS CAPTURE INCREASE BY ENERGY ADDITION OFF THE COWL LIP (VIRTUAL COWL)

Design: Mach 7, Flight: Mach 6, q=1000 psf



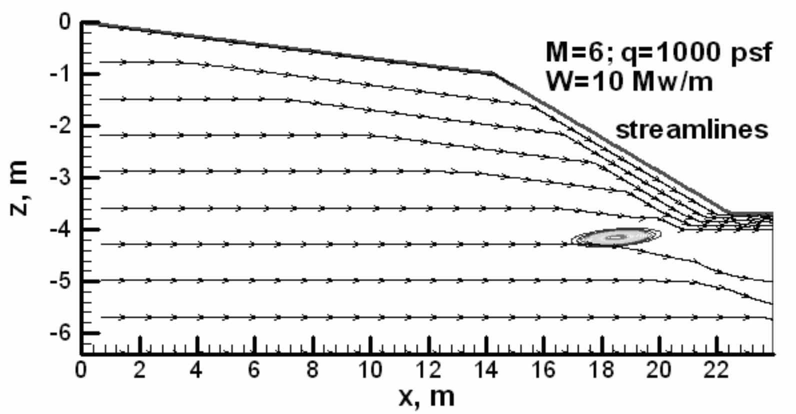
Streamlines at Mach 6, q=1000 psf, with no heat addition:

k_m=0.815



Streamlines at Mach 6, q=1000 psf, with 10 MW/m (2.7% enthalpy flux) heating in optimum location:

k_m=0.95 (+16.6%)



Streamlines at Mach 6, q=1000 psf, with 10 MW/m (2.8% enthalpy flux) heating close to cowl lip:

k_m=0.9 (+9.9%)

Performance of Reverse Energy Bypass:
MHD Generator Downstream of Combustor, Power Used for Virtual Cowl
Inlet designed for Mach 7 SOL; Flight at Mach 6, q=1000 psf (0.5 atm)

Virtual Cowl at optimum location (far from cowl lip, where nose shock intersects continuation of cowl):

- energy beamed by microwave array,
- only ¼ (10 MW/m) of generated power (40 MW/m) is deposited into the flow
- MHD: B=2.5 Tesla, load factor k=0.9, 1% potassium seed
- **Thrust increase: 10%**

Virtual Cowl close to cowl lip:

- DC or RF discharge, 60% (10 MW/m) of generated power (16.87 MW/m) is deposited into the flow
- MHD: B=1.7 Tesla, load factor k=0.9, 1% potassium seed
- **Thrust increase: 6.5%**
    - **Performance would be much better if Virtual Cowl is created by plasma-ignited external combustion, with little electric power generated in the propulsion flowpath**

Engine performance enhancement by controlled energy addition in the inlet:

CAN ISOLATOR DUCT BE ELIMINATED?

- Hypersonic airbreathing vehicles need to operate over a **wide range of Mach numbers**

- Ramjet operation (Mach 4-6): **needs a long isolator stage**, which acts as a supersonic diffuser to slow the inlet flow to subsonic (also to minimize adverse pressure gradients and avoid separation). **No need for an isolator at cruise speed (Mach 7-10)**

- Some level of performance loss can be tolerated during the transient ramjet operation

- Long isolator stage adds **considerable weight** to the engine

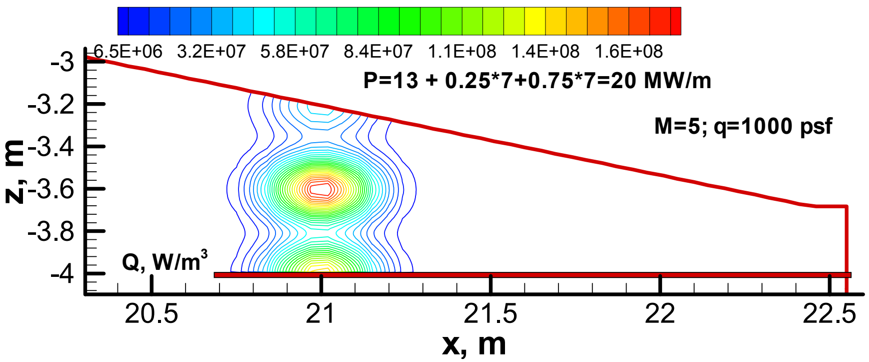
- The interior of the isolator is a **major part of the cooling load**, particularly at high Mach numbers when the isolator is still in the flow path, but is not needed

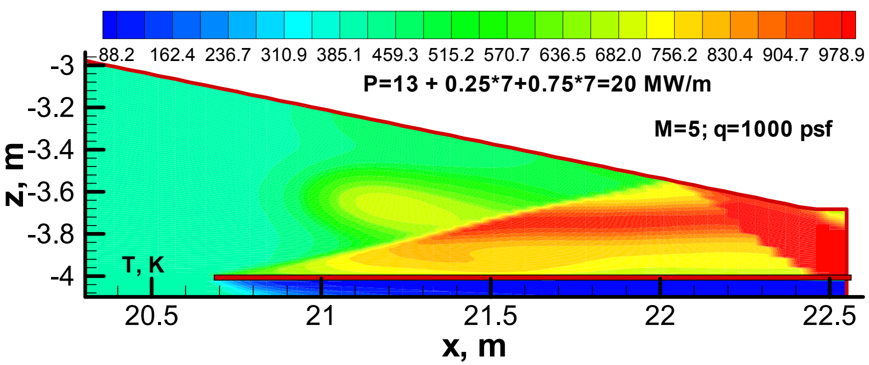
- **Is it possible to minimize or eliminate the isolator stage using active control based on energy addition upstream of the inlet throat?**

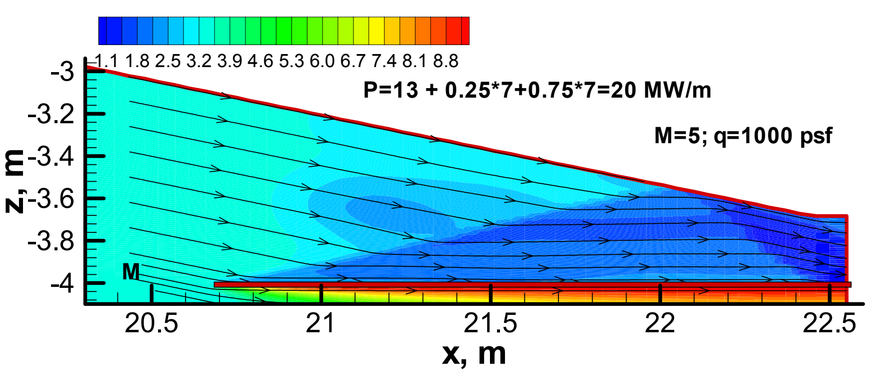
- The energy addition can be accomplished by, e.g., **microwave or DC plasma heating or (preferably) localized plasma-assisted combustion.**

Performance of Reverse Energy Bypass: MHD Generator Downstream of Combustor, Power Used for Heating Upstream of Inlet Throat

Inlet designed for Mach 7; Flight at Mach 5, q=1000 psf (0.5 atm)







- **Total heating rate: 20 MW/m (52% of MHD-generated power):**
- **Average Mach No. at throat = 1.15**
- **Can operate ramjet without isolator**
- MHD: B=3.38 T, k=0.9, 1% seed
- MHD reduces thrust by 11%, and inlet heating reduces thrust by 5%, so the total thrust reduction is 16%
- Plenty of thrust left for acceleration
- Savings come at cruise: ~1/3 lower cooling demand with no isolator duct
- The plasma discharge can create radicals and ignite combustion (ignition would require power anyway)
- Power delivery by plasma-controlled combustion – attractive option

Electron Beam and Microwave Assisted Fuel Spray Ignition For Hypersonic Drag Reduction, Steering, Lift Enhancement, and Ram/Scram Propulsion Enhancement

Challenge: Vehicle control, drag reduction and lift enhancement by off body energy addition is very promising, but requires large energy deposition at a precise location. Also, ram/scram ignition problem.
Approach: A combined fuel / electron beam / microwave system may be able to achieve this. Pressurized liquid fuel jets can propagate far into the flow (Fig. 1). Break-up and vaporization of the large droplets is achieved by charging them with a low-intensity, high-energy electron beams (Fig. 2). The electron beam localizes the region where the energy addition is to take place, and the Coulomb repulsion in the charged droplets overcomes surface tension, resulting in rapid disintegration of the droplets (Fig. 3) and mixing with the air. A microwave beam is then used to ignite the combustion which produces the energy addition (Fig. 4)

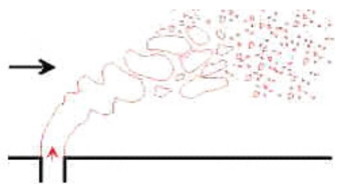


Fig. 1. Liquid jet injection

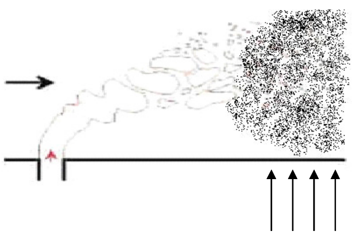


Fig. 2. Liquid jet injection with downstream e-beam-induced vaporization

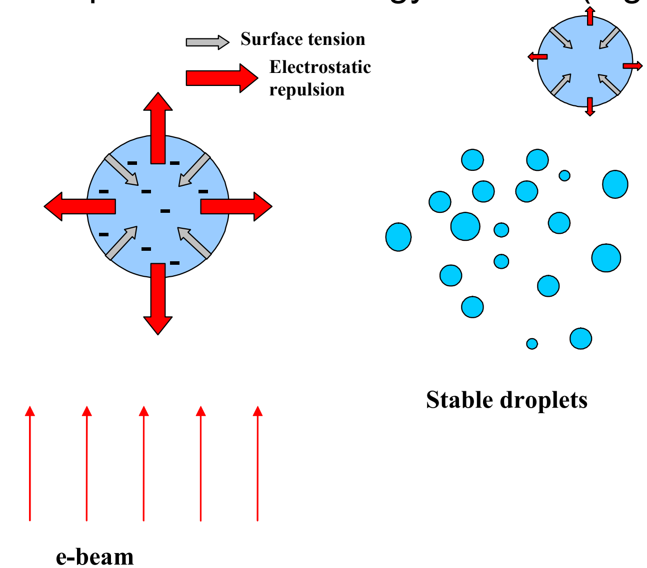


Fig. 3. Schematic of charged droplet break-up due to Coulomb repulsive forces

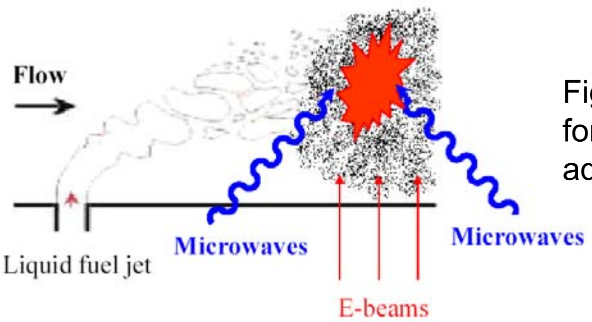


Fig. 4. Microwave ignition for controlled energy addition and ignition

Plasma Steering by Off Body Energy Addition

Mechanism

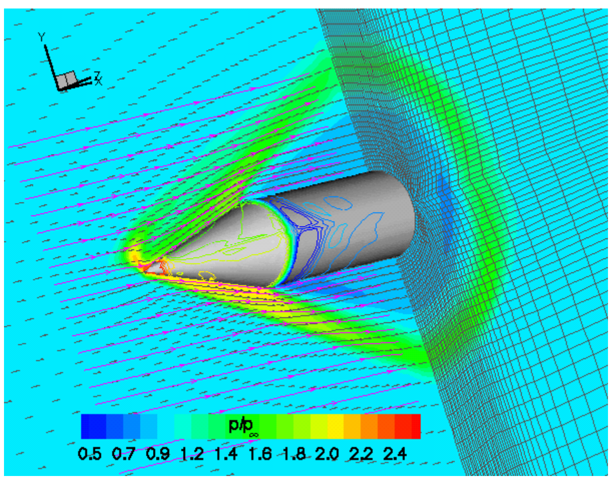
Heating reduces the Mach number and thus reduces the pressure rise behind the shock leading to the control of lift and simultaneous reduction of drag with off axis energy addition

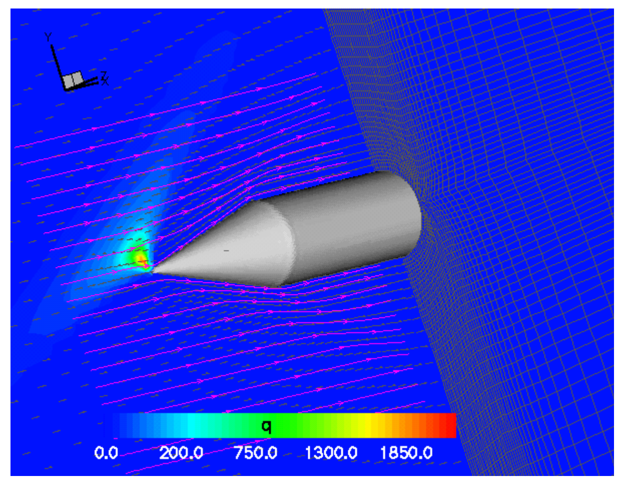
Advantages

- No moving parts
- No boundary layer separation and associated high local heat flux
- High frequency
- High efficiency at high Mach number – no drag penalty for control

Plasma Steering Features

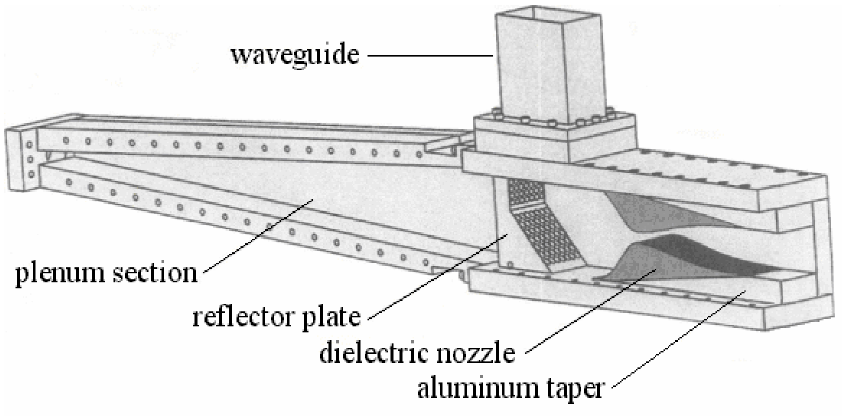
- The ratio of drag power reduction to heating power expended increases with approximately as M^2
- At high Mach number the efficiency of lift by plasma heating (lift force to power added to flow) exceeds the efficiency of lift by angle of attack (lift force to drag power)

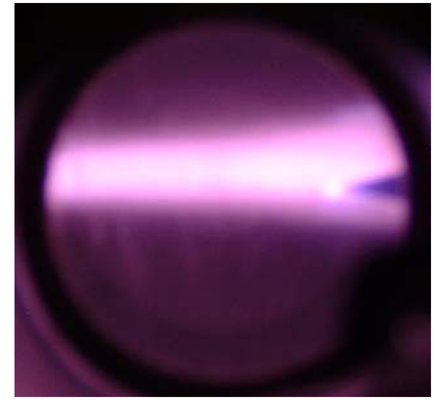




Pressure Distribution (Left) and Power Density (Right) Around the Cone, Using Electron Beam-Controlled, Microwave-Sustained Heat Addition.
(M_∞=3.0, P/P_D=1.0, L_{ext}/D=0.2, θ=60^o, 20 Kev, C_D/C_{Do}=0.37 and C_L/C_D=0.42)

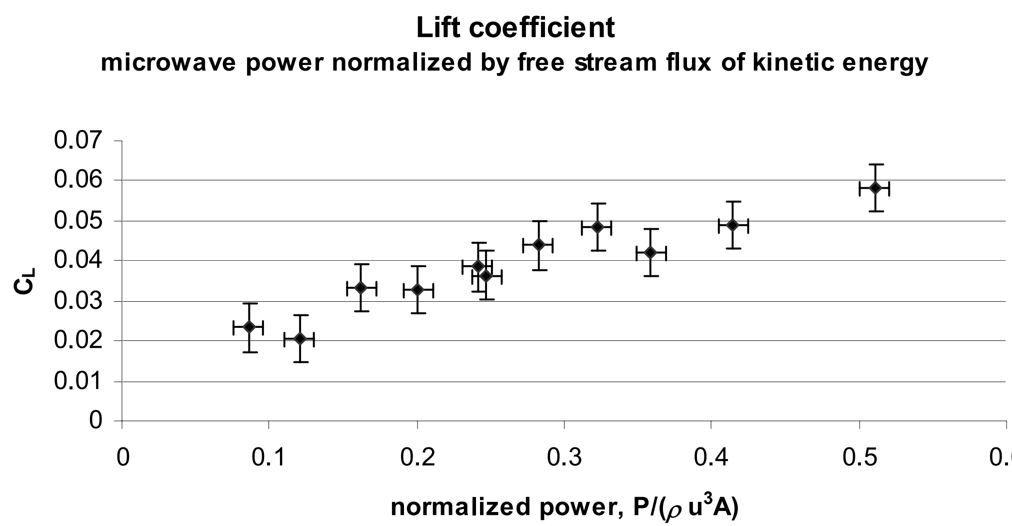
Experiments in Microwave Plasma Wind Tunnel





Operating characteristics:

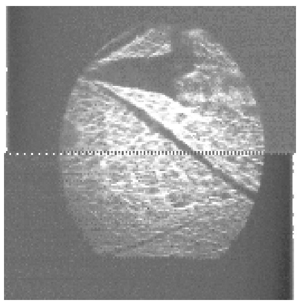
- 20.7 Torr static pressure
- 104 K static temperature
- 615 m/s convective velocity
- 6 kW, 2.45 GHz microwave source



Unsteady Interaction of Shock Wave and Thermal Wake Generated by Laser Spark With an Oblique Shock:

Shock Modulation and Weakening
(Sonic Boom Control, Start of Ramjet Inlet)

Mach 2.4, Energy Deposition: YAG 350 mJ/pulse, 10 Hz, Schlieren/ Shadowgraph: CW Ar laser, Princeton Instruments PSI-4 MHz Framing Rate Camera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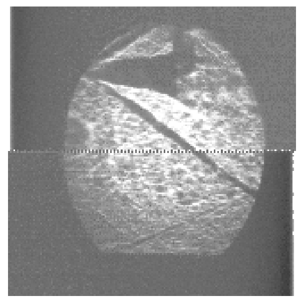
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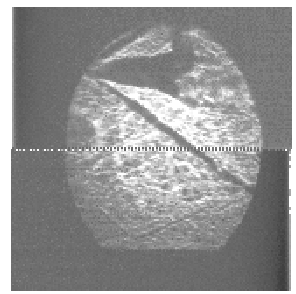
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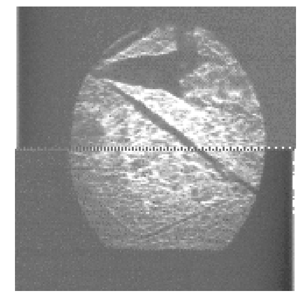
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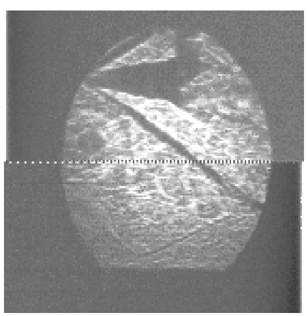
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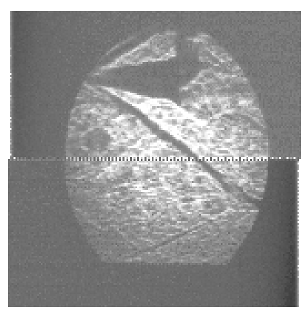
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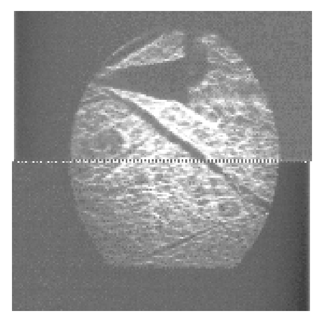
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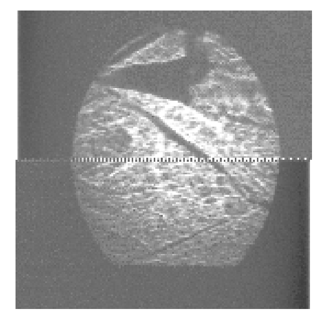
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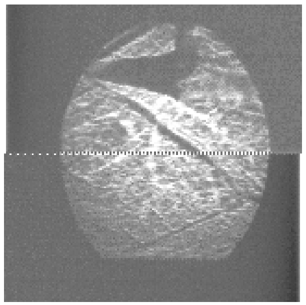
Shadowgraphs of the interaction (4 microsec integration time)



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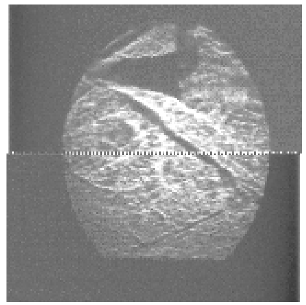

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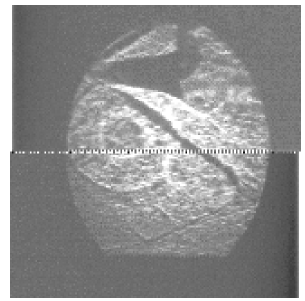

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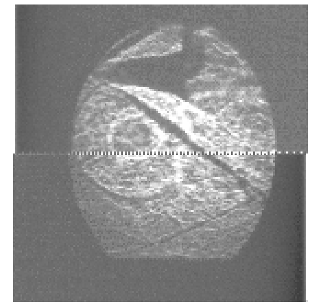

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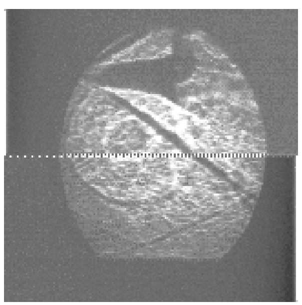

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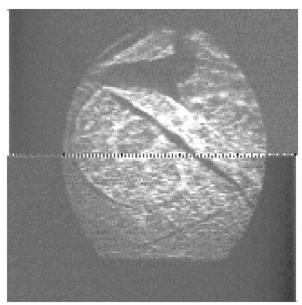

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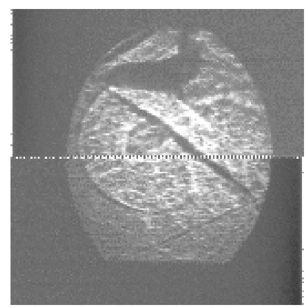

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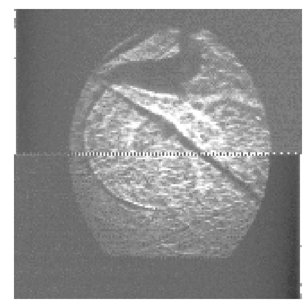

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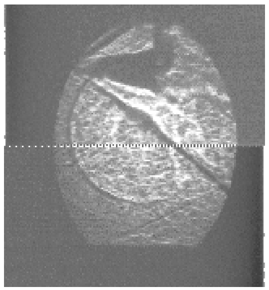
Shadowgraphs of the interaction (4 microsec integration time)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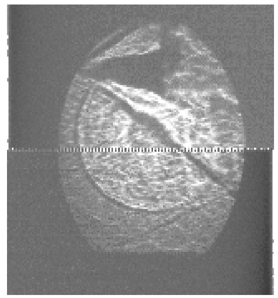
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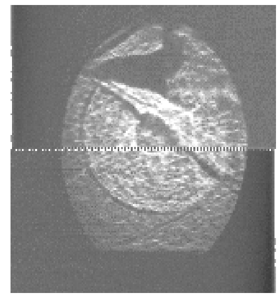
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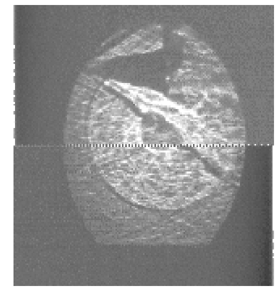
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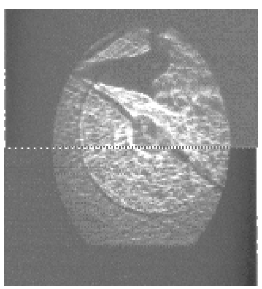
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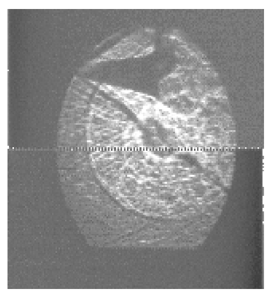
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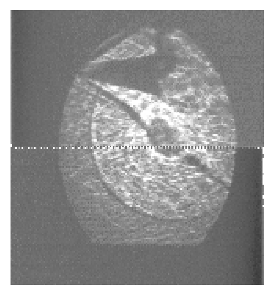
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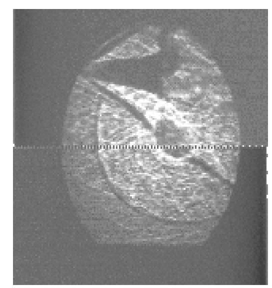
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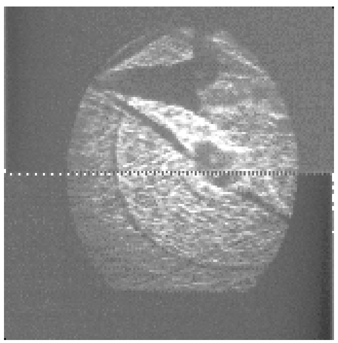
Shadowgraphs of the interaction (4 microsec integration time)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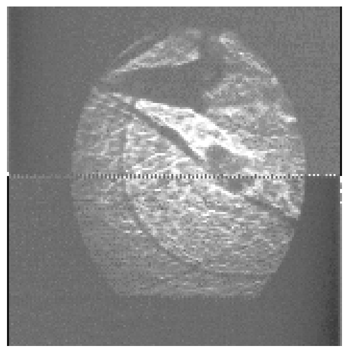
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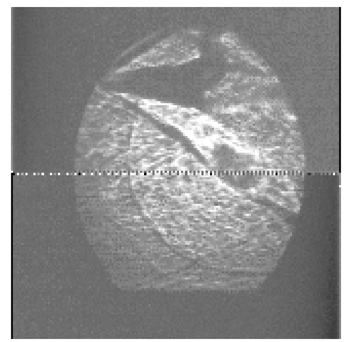
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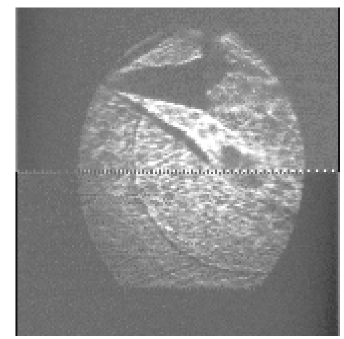
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Plasma-Assisted Combustion:

- Low flame propagation speed reduces thrust in scramjets (narrow-angle cones of combustion)
- Ignition problems

Volumetric cold-plasma ignition: energy cost

- Mole fraction of atoms, radicals, or ions needed for 10 μs ignition: $\alpha=(1\text{-}3)\times 10^{-3}$
- Energy loading per molecule: $\varepsilon=\alpha \times (E/N)^2 \times e^2/(m k_{en} k_{diss})$
- Normally, $\varepsilon\approx 0.1\text{-}0.3$ eV/molecule$\approx$0.33-1 MJ/kg. This is comparable with total flow enthalpy (1.5-2.5 MJ/kg @ M=5-7) and translates into >100 MW per square meter of combustor cross section
- With e-beams or MHz rep rate nanosecond pulses at E/N $\approx$1000 Td, energy cost of a radical is $\approx$30 eV, so that min energy loading is $\varepsilon\approx 0.03\text{-}0.1$ eV/molecule$\approx$0.1-0.3 MJ/kg – still ~10% of flow enthalpy
- This power needs to be generated (e.g., by MHD after combustor) and delivered into the flow – another example of Reverse Energy Bypass
- Both generation and delivery entail losses of energy and stagnation pressure – reduced thrust.

Plasma-Assisted Combustion:
flame propagation speed increase in subcritical microwave field

- **Complementary to plasma ignition (may allow to ignite smaller volume)**
- **Flame holding and reignition**

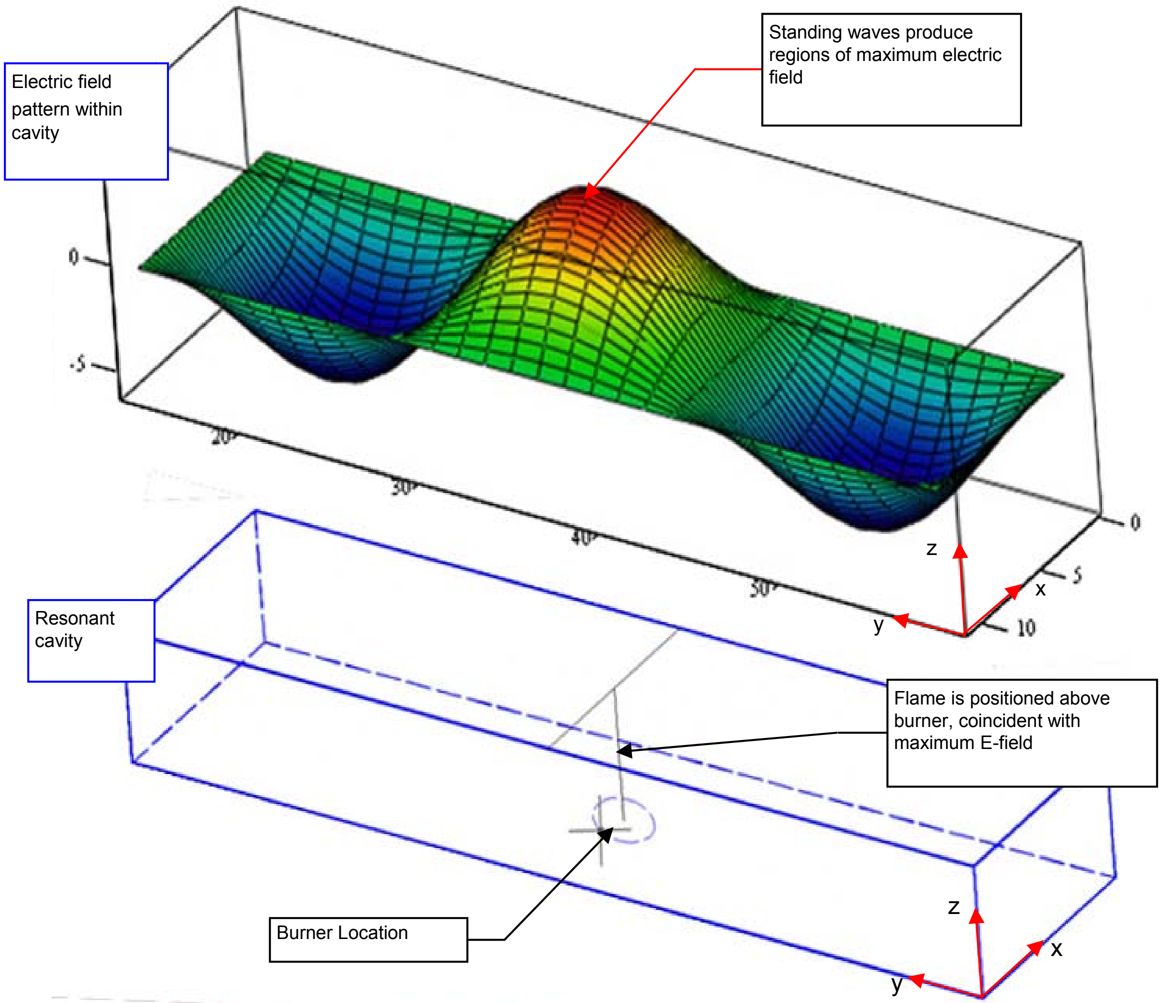
Princeton/RSI work:

- **Sub-critical microwave fields couple selectively into a narrow flame front ~0.2 mm thick reaction zone: T~2000 K, radicals,**

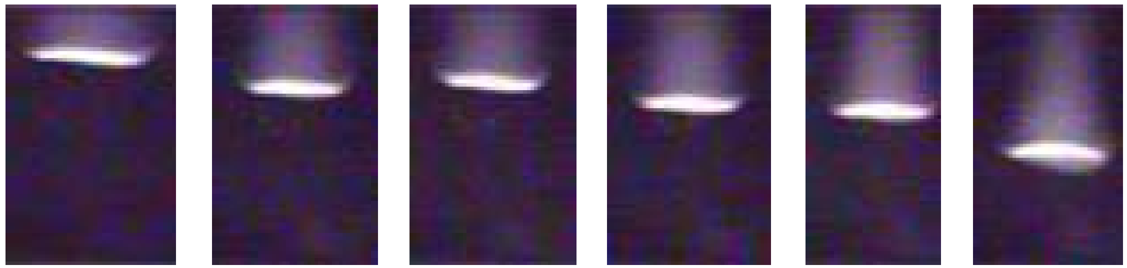
⇒CH+O →CHO^++e, up to 3.5×10^{11} electrons/cm^3, microwave absorption can result in ΔT=20-500 K

- **67% methane/air, propane/air, and ethylene/air (equiv. ratio 0.7) laminar flame speed increase in non-optimized microwave experiments**
- **Absorbed microwave power ~10 W <<combustion power**
- **Stronger effects can occur with proper optimization**
- **Studies with non-premixed flames and turbulent combustion in progress**
- **Need to assess minimum energy cost**
- **Scramjet combustors: use evanescent wave**

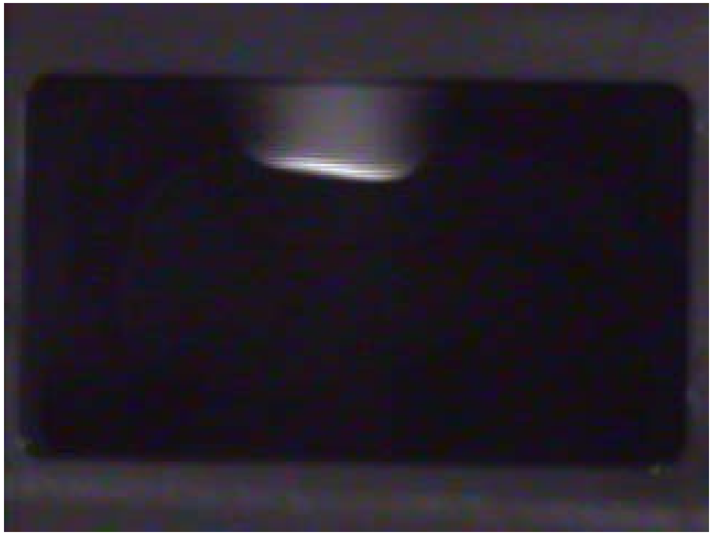
Schematic of microwave cavity for studies of flame propagation speed increase in subcritical microwave field



Flame propagation speed increase in subcritical microwave field

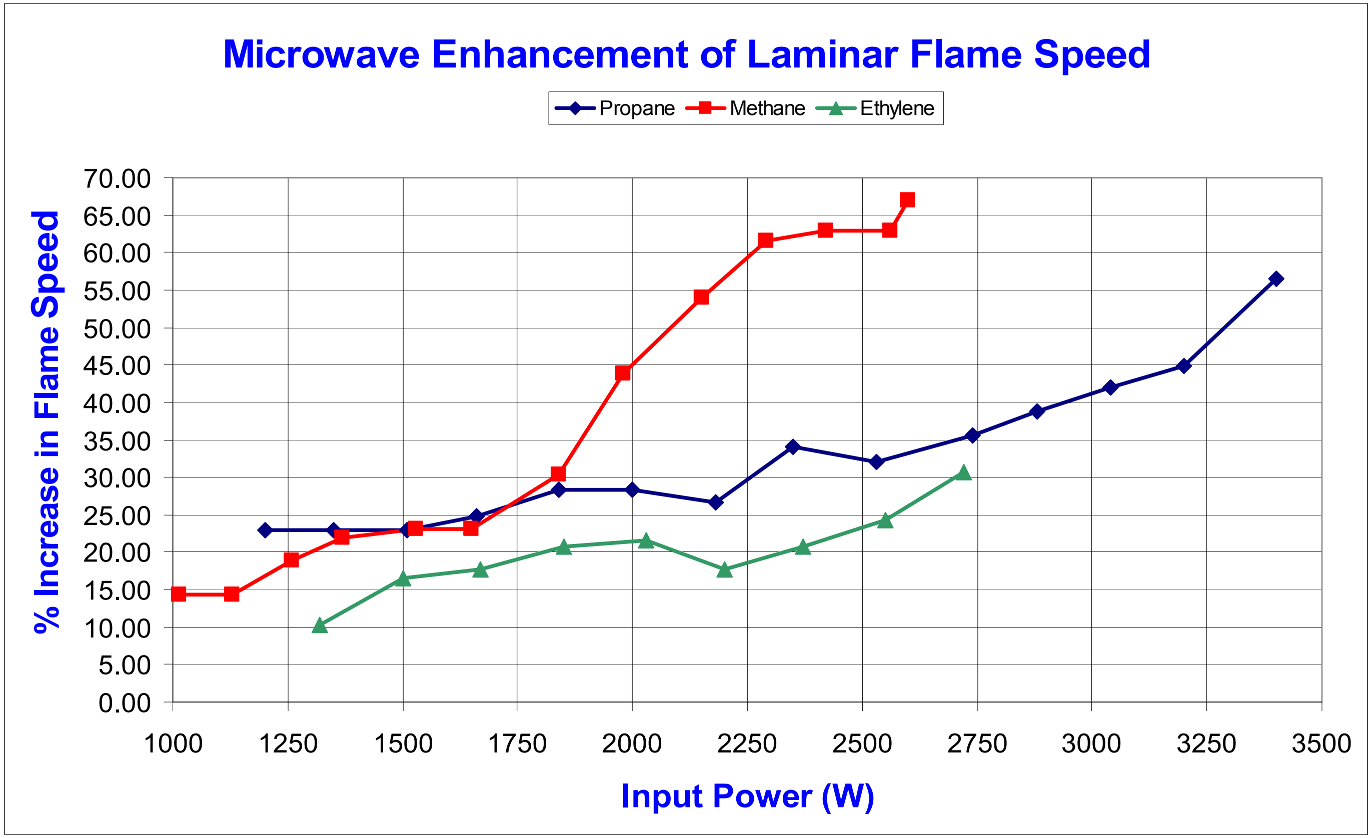


No Power | 1200 W | 1850 W | 2350 W | 2880 W | 3400 W



Methane-air (equiv. ratio =0.7,
microwave power =2420 W)

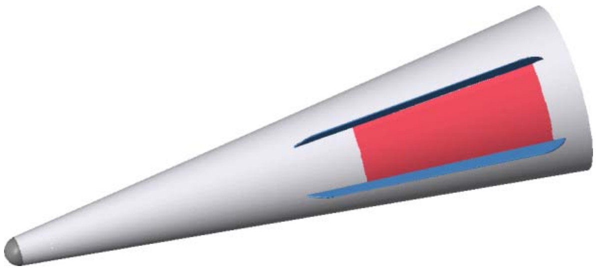
Flame propagation speed increase in subcritical microwave field

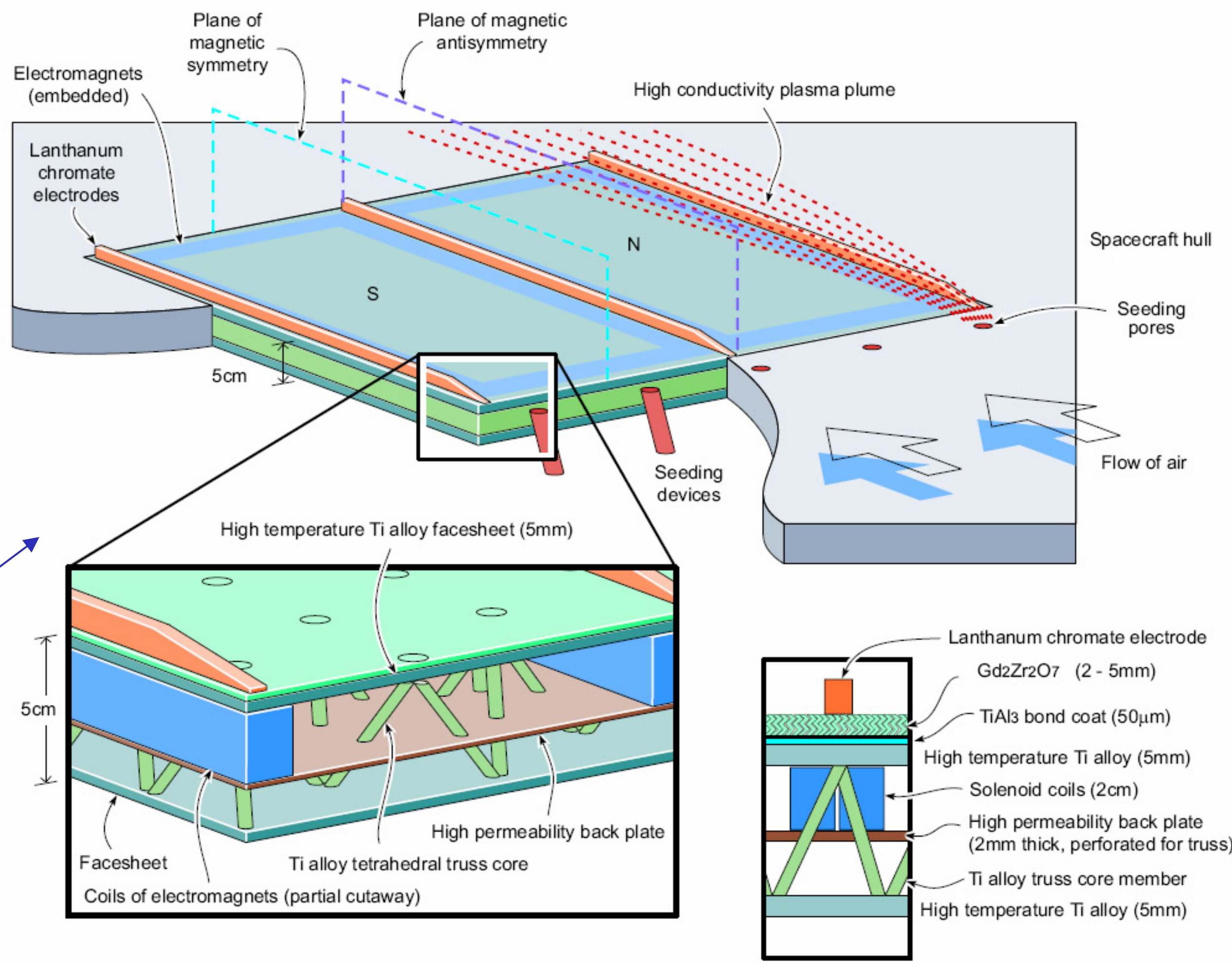


MHD POWER GENERATION AND AERODYNAMIC CONTROL FOR REENTRY VEHICLES

Can large amounts of electric power, at least several hundred kilowatts per square meter of the surface, be extracted from the boundary layer with MHD generators on board reentry vehicles? Can the power be used for aerodynamic control?

Proposed Re-entry Vehicle Configuration, Including MHD Power Extraction Panels





C. Steeves (Princeton),
A. Evans (UCSB),
H.Wadley (UV)

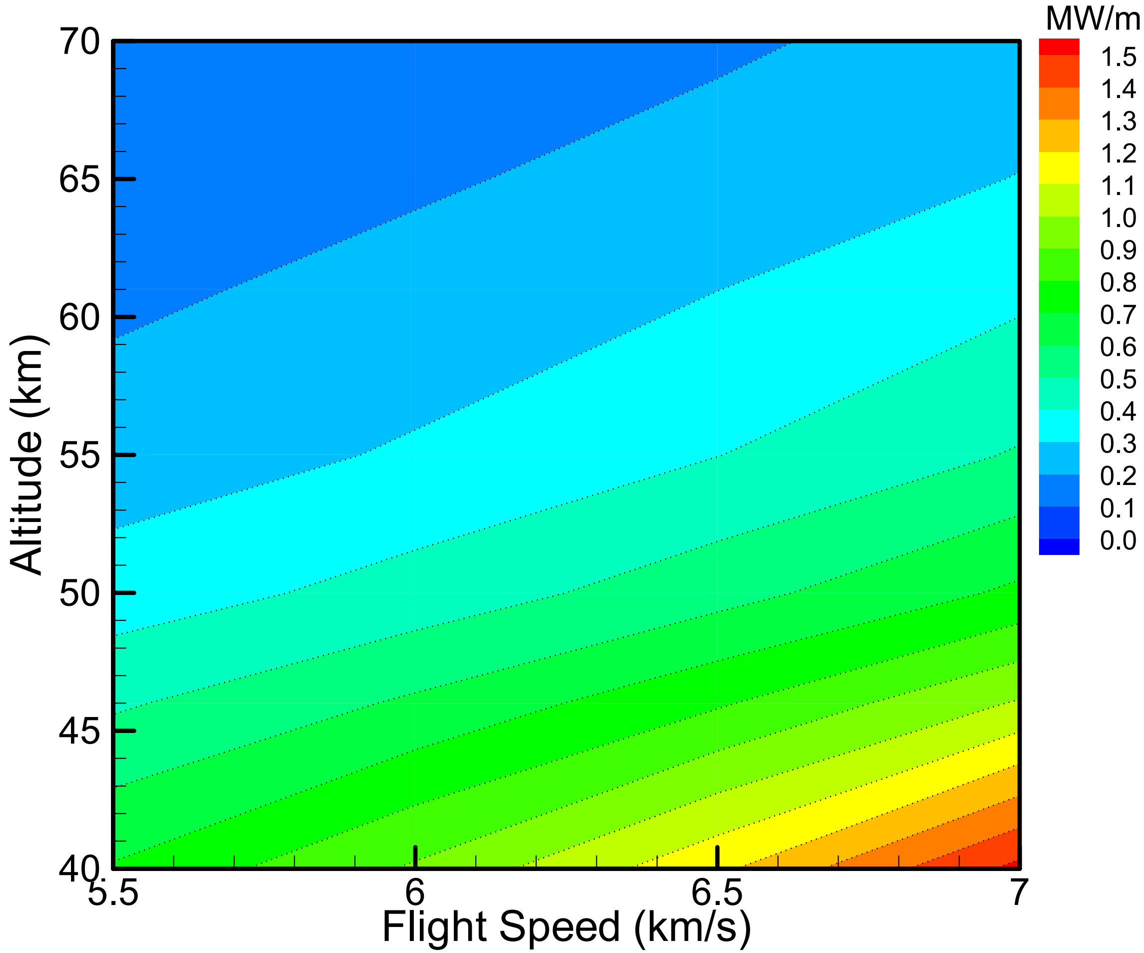
Princeton University

University of Minnesota

Generated power (in MW/m^2) at different altitudes and velocities: 24° wedge, B=0.2 T, constant seed mass flow rate (1% at 46 km)

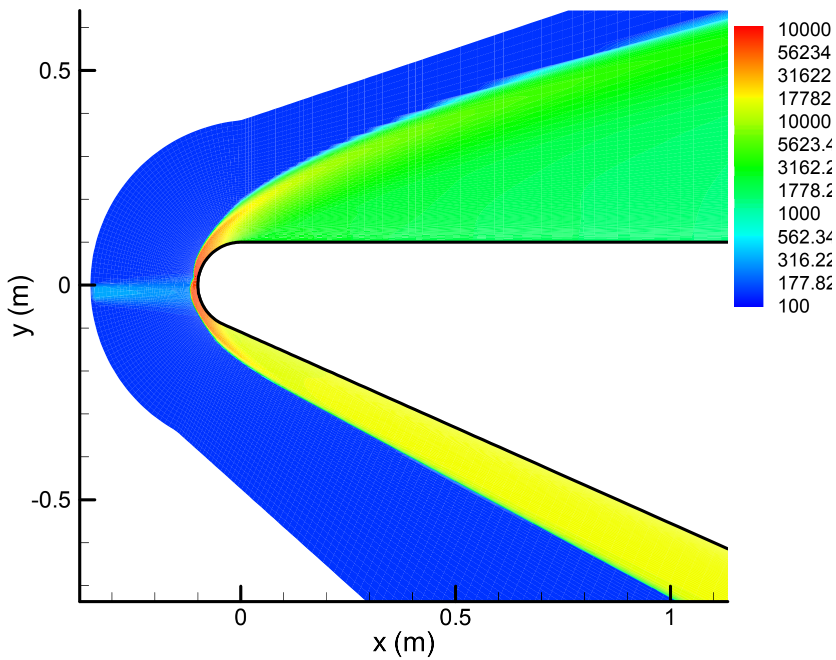
In the preliminary modeling, K seed injection within 3 cm thick layer was assumed.

Seed injection within 15 cm thick layer would dramatically increase the extracted power and the **j**×**B** force on the flow (MHD flap)

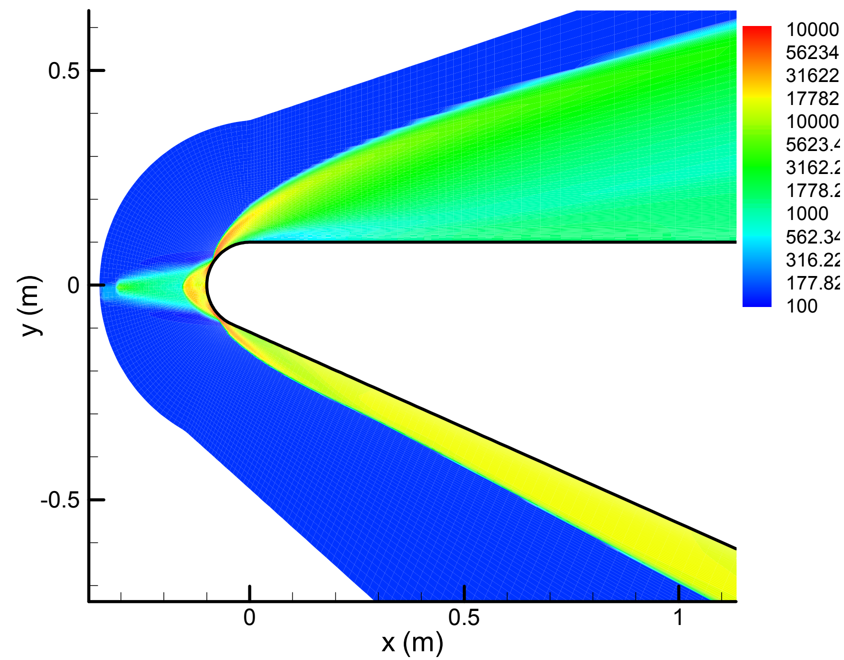


Static pressure contours

46 km, 7 km/s, B_0=0.2 T, 1% K



MHD on, no heat addition



MHD on, heat addition of extracted 800 kW at 2R=20 cm upstream of the nose

Drag power and efficiency

- Non-optimized heat addition results in ~15% reduction in drag and increase in L/D:
  - Power added = **800 kW**
- Total drag power = 220 MW
  - Reduction in drag power = **33.2 MW= 41.5** × **800 kW**
  - Very efficient!
- Result of extreme non-linearity in bow shock
- Much better than using energy for propulsion
- Optimization of shape and location of heat addition, as well as adding more power, will further increase L/D
- Off-axis heating: aerodynamic moments

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