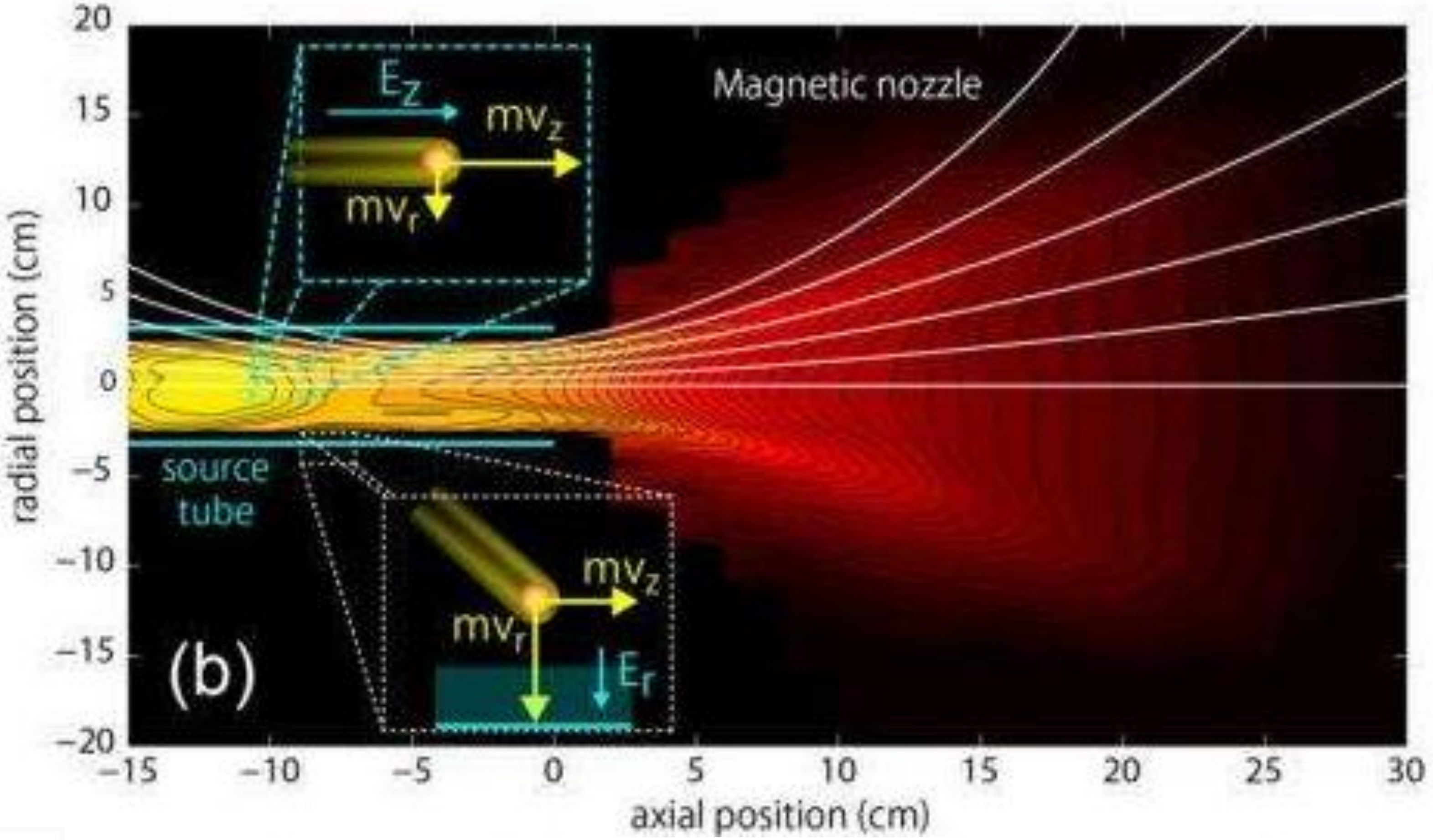
Electron heat conductivity and plasma acceleration in HPT

A. Fruchtman

H.I.T. - Holon Institute of Technology

EXB Workshop
Princeton University, November 1-2, 2018

Helicon Plasma Thruster: Source + Magnetic Nozzle

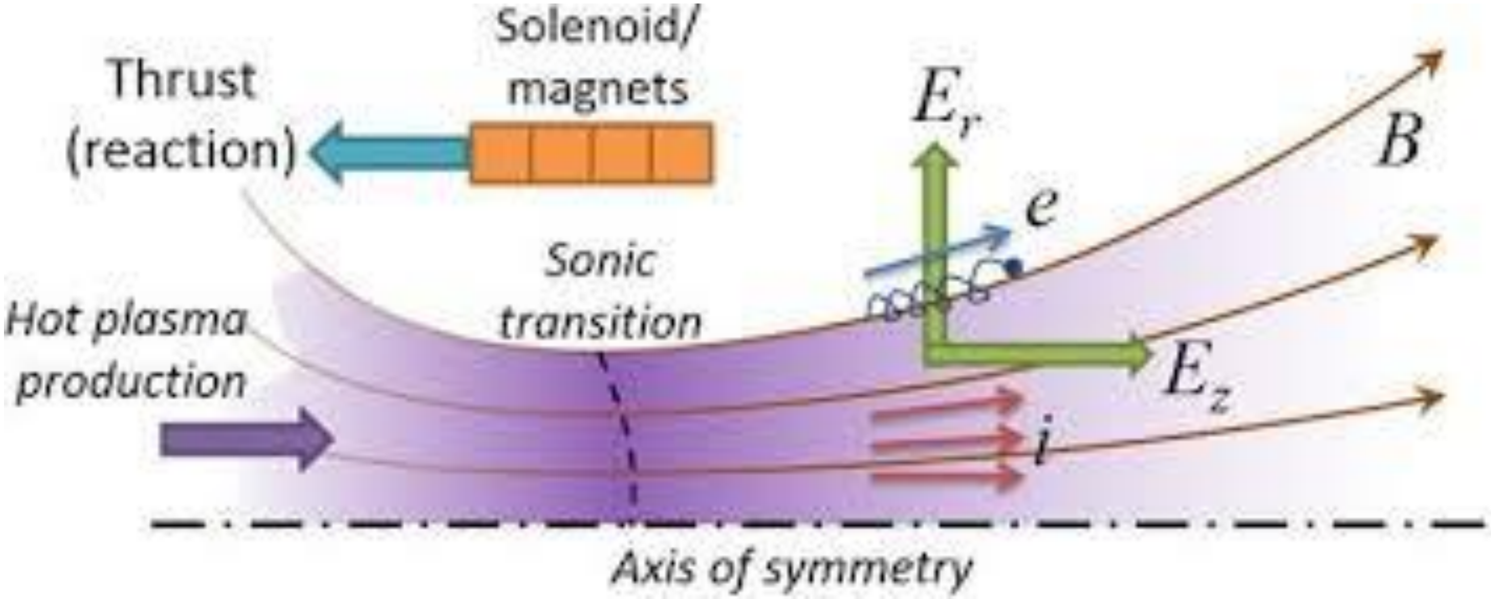


Takahashi and Ando (2015)

The HPT

- The energy source for thrust is only the kinetic energy gained by the electrons.
- Most of this kinetic energy is convected or conducted through the HPT exit, and is then converted to ion directed energy.
- Some suggest additional acceleration, such as: ICRH, rotating electric\magnetic field, DL, or a second stage with Hall or other thruster.

Thrust - HPT



Source: plasma pressure.
On the **backwall**

Magnetic nozzle: magnetic pressure.
On the **coils**

Energy - HPT

- Energy is deposited in the HPT in electrons.
- In order that the propellant participates in the thrust generation, ionization should be large.
- A large part of the energy deposited in the electrons should be converted into ion directed kinetic energy, either in the source or in the magnetic nozzle.

Efficiency

The efficiency is determined by:

1. The fraction of the invested energy that is deposited in the electrons exiting the HPT.
2. The fraction of electron energy that is converted into ion directed energy.

(also the fraction of propellant that carries thrust).

Inefficiency due to

1. Energy not ended in exiting electrons:
   - Wall losses (particles, energy, thrust?).
   - Backwall losses.
   - Energy cost for ionization.

2. Partial conversion only of electron energy exiting the thruster into thrust-generating ion directed kinetic energy.

(also partial ionization only).

Reducing inefficiency

- Wall losses can be reduced by a strong enough magnetic field
- Backwall losses….

Back wall losses

Sheath at the back wall $\longrightarrow$ losses more than 50% expected from inelastic collisions with the wall.

The ions impinge on the wall with energy due to the sheath (and pre-sheath) potential

$$0.5T\left[1+\ln\left(\frac{1}{2\pi}\frac{m}{m_e}\right)\right]$$

The sheath at the backwall

- However, the net force on the backwall is smaller: there is attracting electric force between the negatively-charged wall and the positive plasma.
- The difference between the pushing by the impinging high-energy ions and the pulling by the electric force is much smaller than the force by the high-energy ions, it equals the force by the plasma pressure only.

Energy sheath losses at the backwall

There is a sink of energy in the sheath. Energy loss that does not contribute to thrust.

Sheath losses at the backwall for each ion several times the kinetic energy used for generating thrust

מכון טכנולוגי חולון
Holon Institute of Technology

Reducing backwall losses

1. Magnetic mirror
2. Neutrals shielding
3. Lower electron temperature

Energy cost of ionization

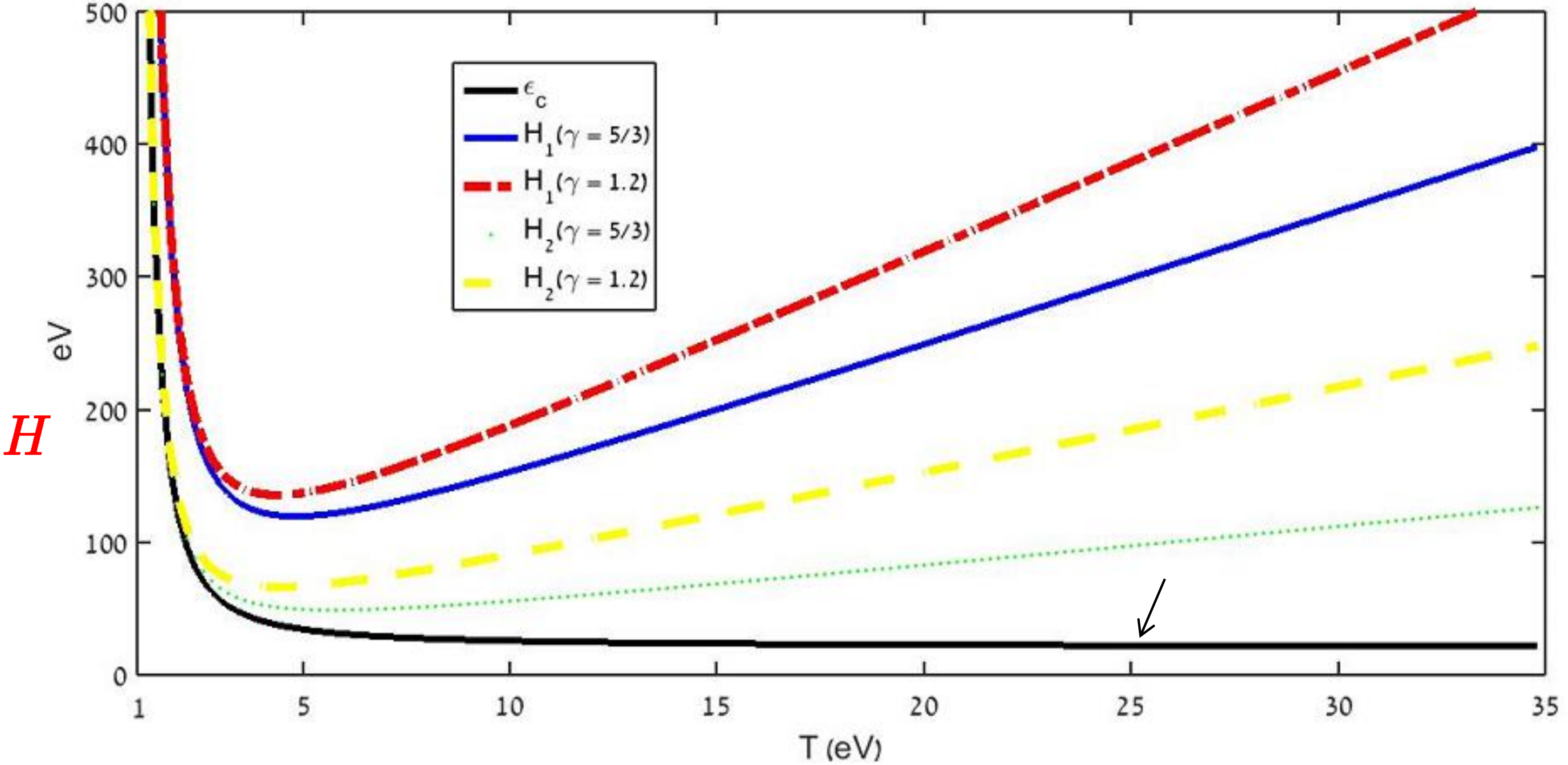
Argon:

$$\varepsilon_c(T) = 13.47\,\mathrm{eV} + 7.085\,\mathrm{eV}\,\exp\left(\frac{5.408\,\mathrm{eV}}{T}\right)$$

A decreasing function of T

(Gudmundsson, 2010)

Energy cost of ionization – argon (black line)



Energy cost of ionization

- For a low electron temperature, this energy is much more than the ionization energy. In Helicon, for $T_e \approx 3-5\,\mathbf{eV}$, the energy cost per ion-electron pair is about 100 – 200 eV.

When ionization is increased, electron temperature may rise and the cost may reduce.

מכון טכנולוגי חולון
Holon Institute of Technology

Energy per ion-electron pair exiting the helicon source at the sonic plane

$$\varepsilon_{Te} = \varepsilon_c + 2.5T + 0.5T + q$$

ε_c	**energy cost of ionization (cannot be used for thrust!)**
$2.5T$	**enthalpy of an electron**
$0.5T$	**ion kinetic energy at the sonic plane**
q	**heat conducted per electron**

Can the conducted heat be used for thrust?

- In some analyses (Merino and Ahedo, ANU, Fruchtman), a high heat conductivity is expressed in a low index of polytropic equation of state.
- The conducted heat is converted to ion directed kinetic energy through the formation of electric potential drop.

Can the conducted heat be used for thrust?

- Little and Choueiri (PRL, 2016) use Spitzer-Harm model for the heat conduction:

$$-k\frac{\partial T_e}{\partial z}A$$

A **is the area cross section**

- They solve the fluid equations and conclude that when k is large, the coupling of electrons and ions is weak.

Can the conducted heat be used for thrust?

- Little and Choueiri (PRL, 2016) thus claim that if heat conduction is large, the efficiency is very low.
- The energy remains in the electrons, electron cooling does not redce the conducted heat. This is because the area increases.

Little and Choueiri (2016)

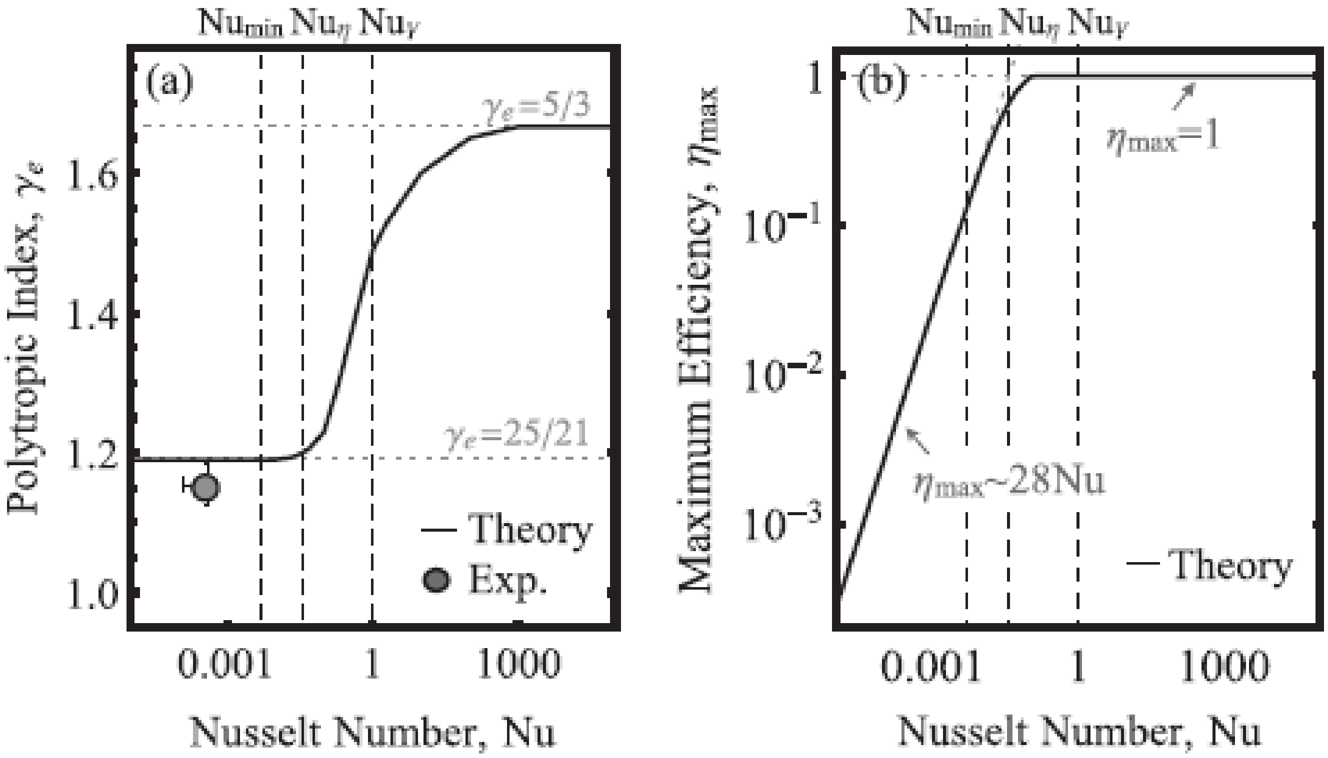


FIG. 4. Theoretical scaling of (a) γ_e vs Nu and (b) $\eta_{\max}$ vs Nu. The experimental data point in (a) represents the average value of γ_e obtained from Fig. 3(e) with Nu calculated using SH thermal conductivity. Power conservation sets the lower bound $\mathrm{Nu}_{\min}$.

MA versus LC

- MA (2015) - Detailed 2D electron and ion dynamics. Axial current is zero only globally. EOS closes the system of equations without an energy equation. **Ions may gain all electron energy**.
- LC (2016) – Quasi-1D formulation. Axial current is zero. Energy equation eith Spitzer-Harm term**. If heat conduction is large, ions do not gain energy**.

Question

What is expected in the case of a high electron heat conductivity, characterized by an effective index $\gamma = 1.2$?

Are ions accelerated or does the energy stay with the electrons?

What is the electric potential that is developed?

Is one of the models incorrect?

What does a kinetic model tell us?

This is a question for discussion.

מכון טכנולוגי חולון
Holon Institute of Technology