Plasma Thrusters and Double Layers

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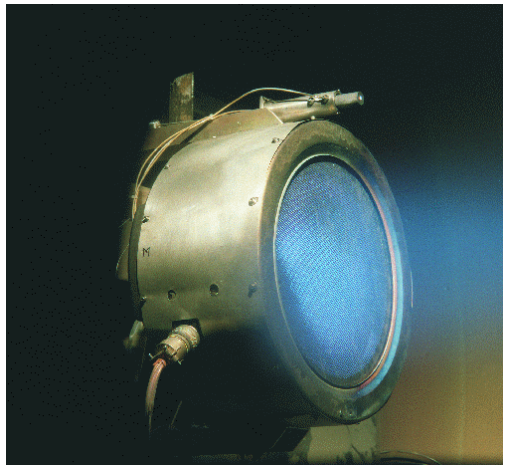
Electric Propulsion – Propellant Saving

(The rocket equation:)

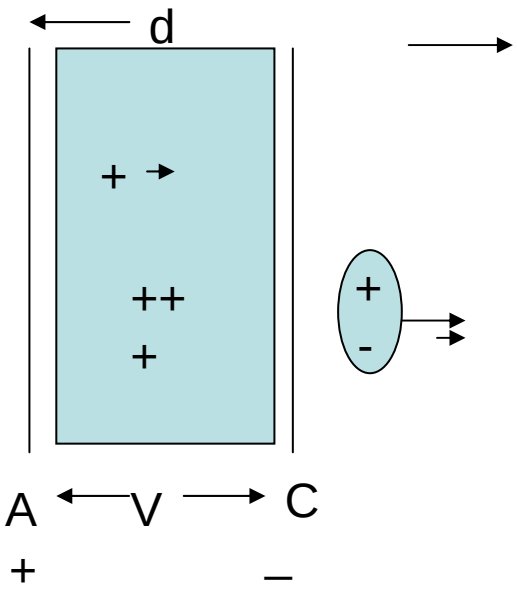
High exhaust velocity results in a large propellant saving.

Deep Space1 – meeting a comet

- Ion thruster was used as the primary propulsion system for NASA's Deep Space 1 (1998-2001)



The Ion Thruster
Electric Field Pressure and Space Charge Limit



Child-Langmuir law

The electric force per unit area (the thrust density) is the difference in the electric field pressure

Gauss law: $\varepsilon_0 \vec{\nabla} \cdot \vec{E} = en$

$$\frac{T}{A} = \int_0^d dx e n E = \int_0^d dx \varepsilon_0 \vec{\nabla} \cdot \vec{E} E = \frac{\varepsilon_0 E^2}{2}_{cathode} - \frac{\varepsilon_0 E^2}{2}_{anode} = \frac{\varepsilon_0 E^2}{2} - 0 = \frac{\varepsilon_0 E^2}{2}$$

$$\frac{\varepsilon_0 E^2}{2} \approx \frac{\varepsilon_0 V^2}{2d^2} = \frac{8.85 \times 10^{-12} \times 100^2}{2 \times 0.01^2} = 0.0005 \ \frac{\mathrm{N}}{\mathrm{m}^2} \quad (V = 100V, d = 0.01\mathrm{m})$$

In order to increase the thrust for given V and u_e, d should be reduced

Shrinking the acceleration gap for increased thrust

If we extract the maximal particle flux from a plasma:

nv_B

and deliver energy

eV

the available thrust is

$$nv_B\left(\frac{eV}{M}\right)^{1/2} = nT_e\left(\frac{eV}{T_e}\right)^{1/2} = 0.3\ \text{N}\left(\frac{eV}{T_e}\right)^{1/2} \quad (n = 10^{18}\ \text{m}^{-3} \quad T_e = 2\ \text{eV})$$

The required acceleration gap is

$$d = \lambda_D\left(\frac{eV}{T_e}\right)^{3/4}$$

A double layer inside the plasma provides a natural acceleration gap

Double layer in Plasma

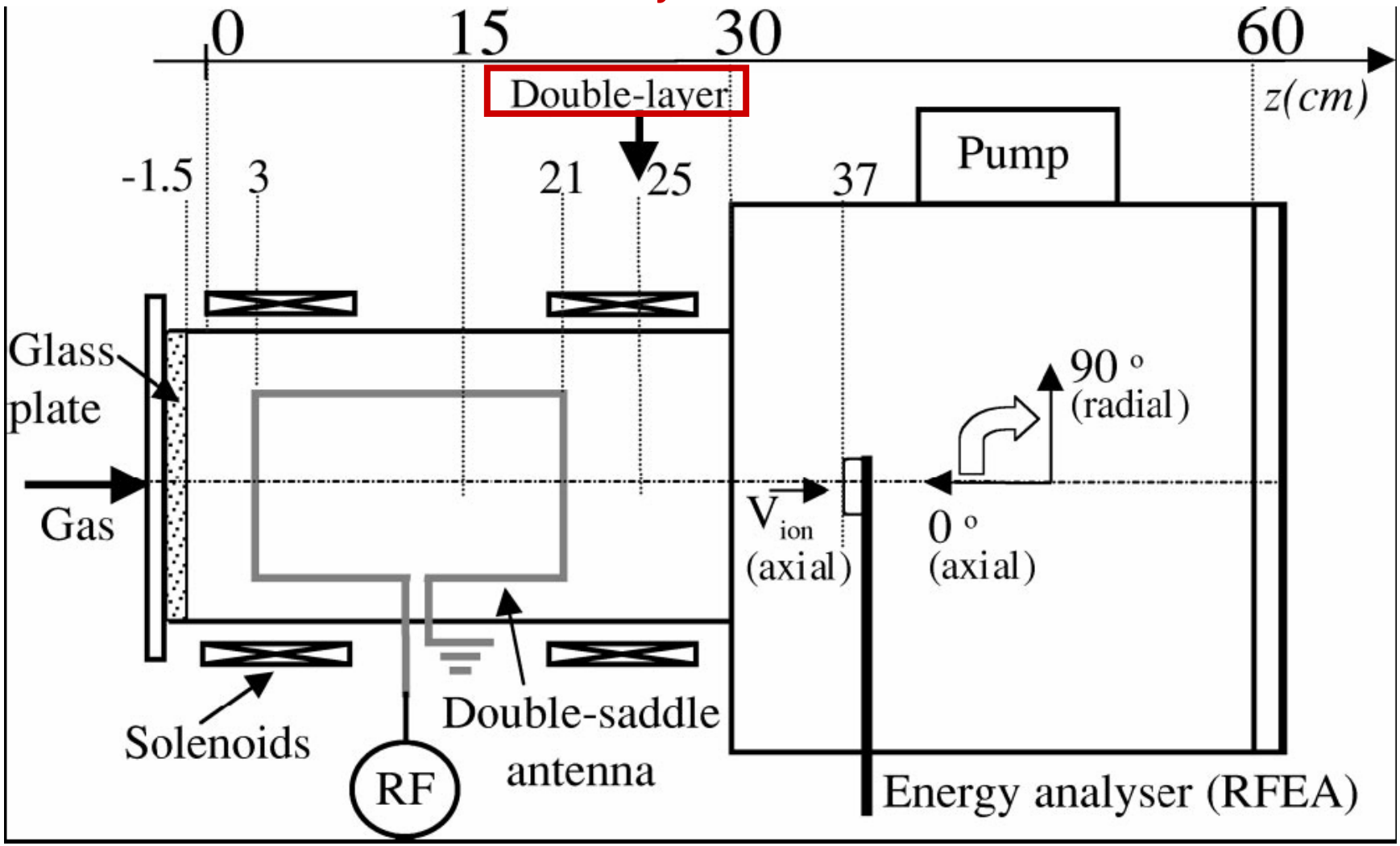
- Increased thrust!

  Characteristic scale Debye length

$$d \approx \lambda_D \approx 10\,\mu\mathrm{m}$$

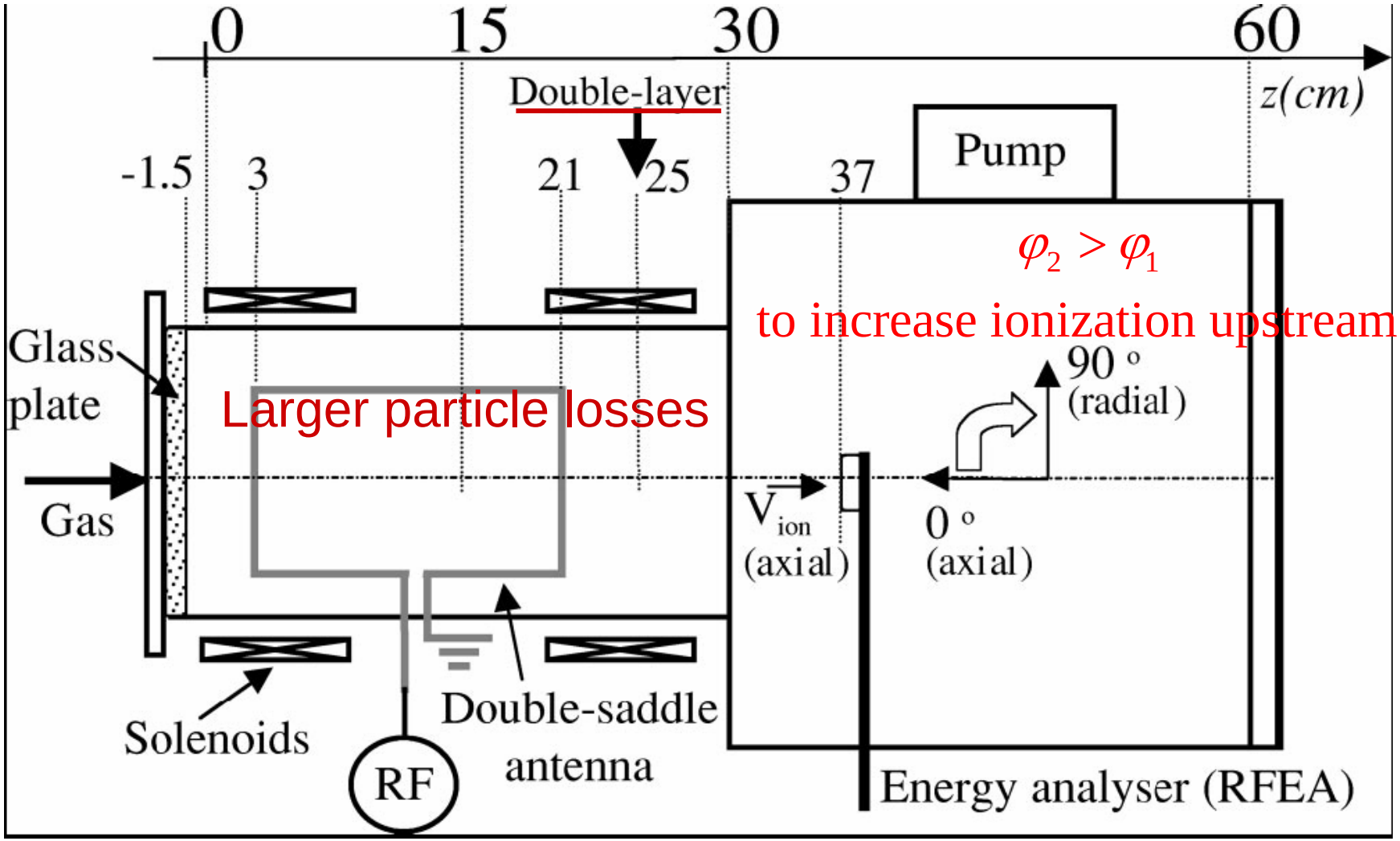
- No electrodes

Two different plasmas attached - Double Layer measured



Charles and Boswell (2003), Cohen *et al.* (2003), Sun *et al.*(2005)

Two different plasmas attached



Lieberman and Charles, PRL (2006)

LCB – Lieberman Charles Boswell – JPD (2006)

Thruster requirements

- Velocity (specific impulse)
- Efficiency
- Thrust

Thrust and Double Layer

Gauss law: $\rho = \varepsilon_0 \vec{\nabla} \cdot \vec{E}$

Force per unit volume: $\rho \vec{E} = \varepsilon_0 \vec{\nabla} \cdot \vec{E}\vec{E}$

force per unit area: $\frac{T}{A} = \int_{z_1}^{z_2} \rho E dz = \frac{\varepsilon_0}{2}\left[E(z_2)^2 - E(z_1)^2 \right]$

Double Layer $\rightarrow E(z_1) = 0 = E(z_2)$

The net force and the net momentum

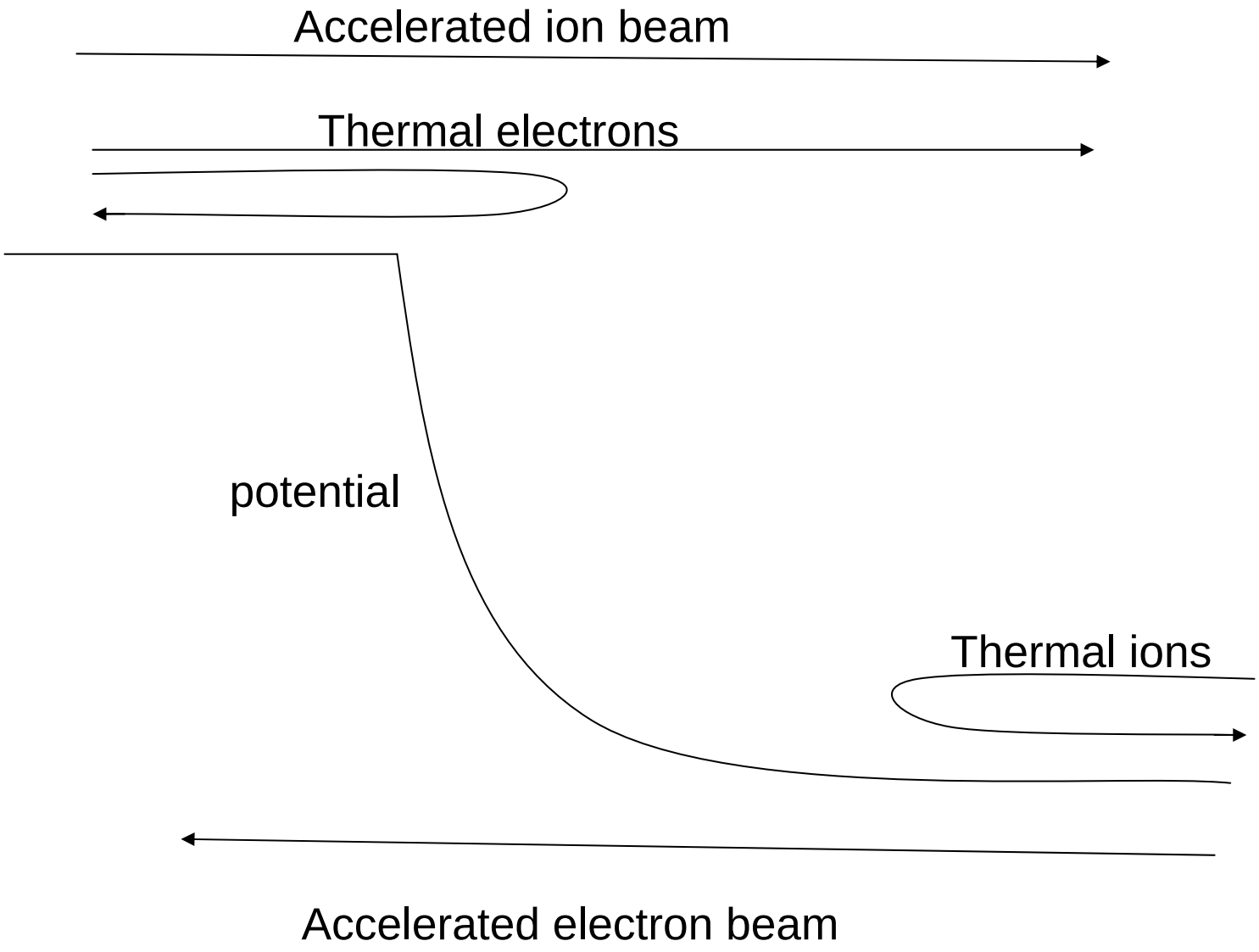
delivered by the electric field are zero $\int_{z_1}^{z_2} \rho E dz = 0$

Electric-field pressure – Double layer

- The electric force per unit area (the thrust density), the difference in the electric field pressure **is zero**
- The electric force is an internal force of the plasma ⟶ no momentum imparted
- **No electrodes** – advantage, **but**

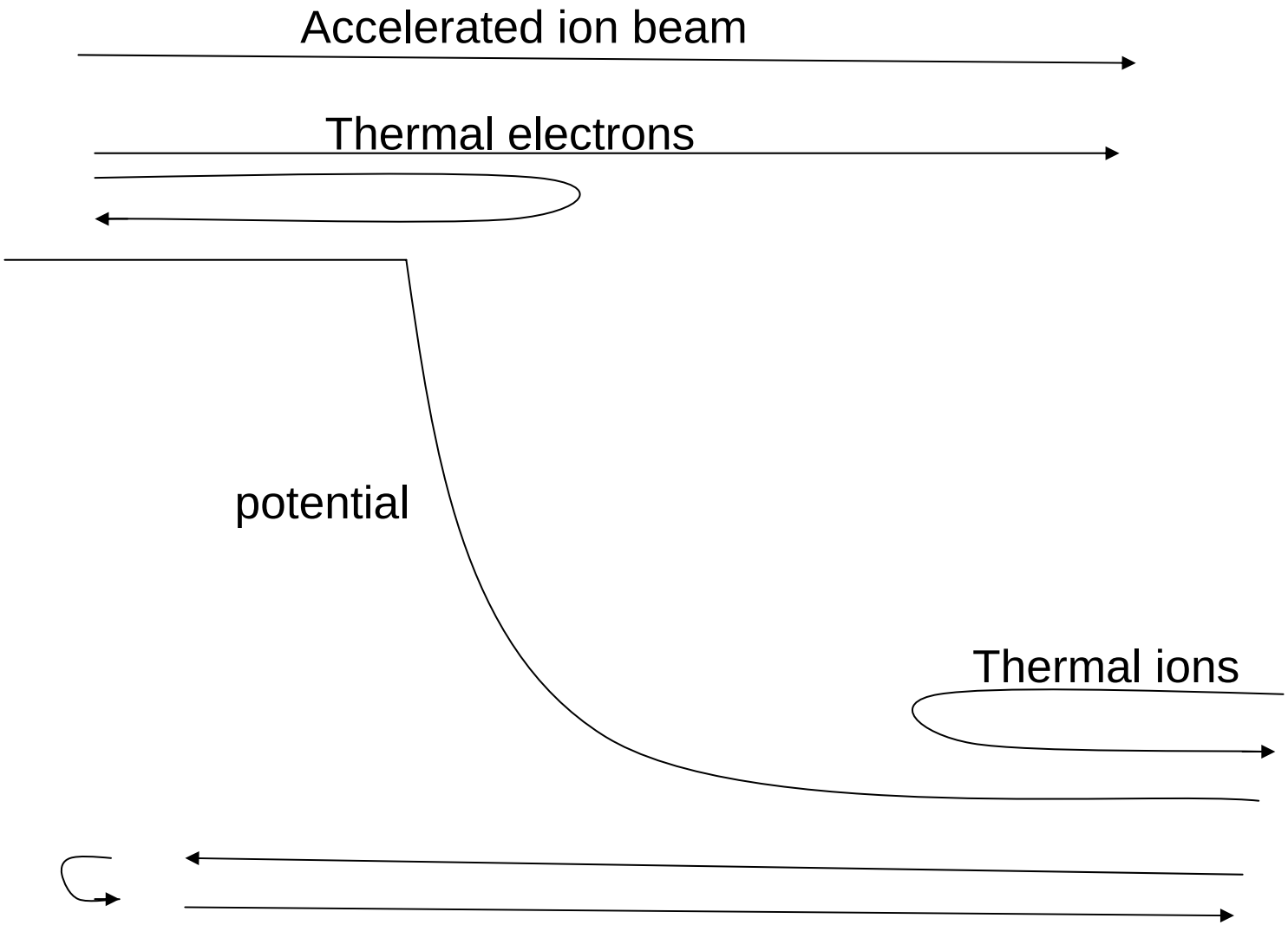
  the plasma edges carry the excess charge, an **internal force**
- The net force and momentum imparted by the strong electric fields of a DL are zero.

double layer, LCB (2006)



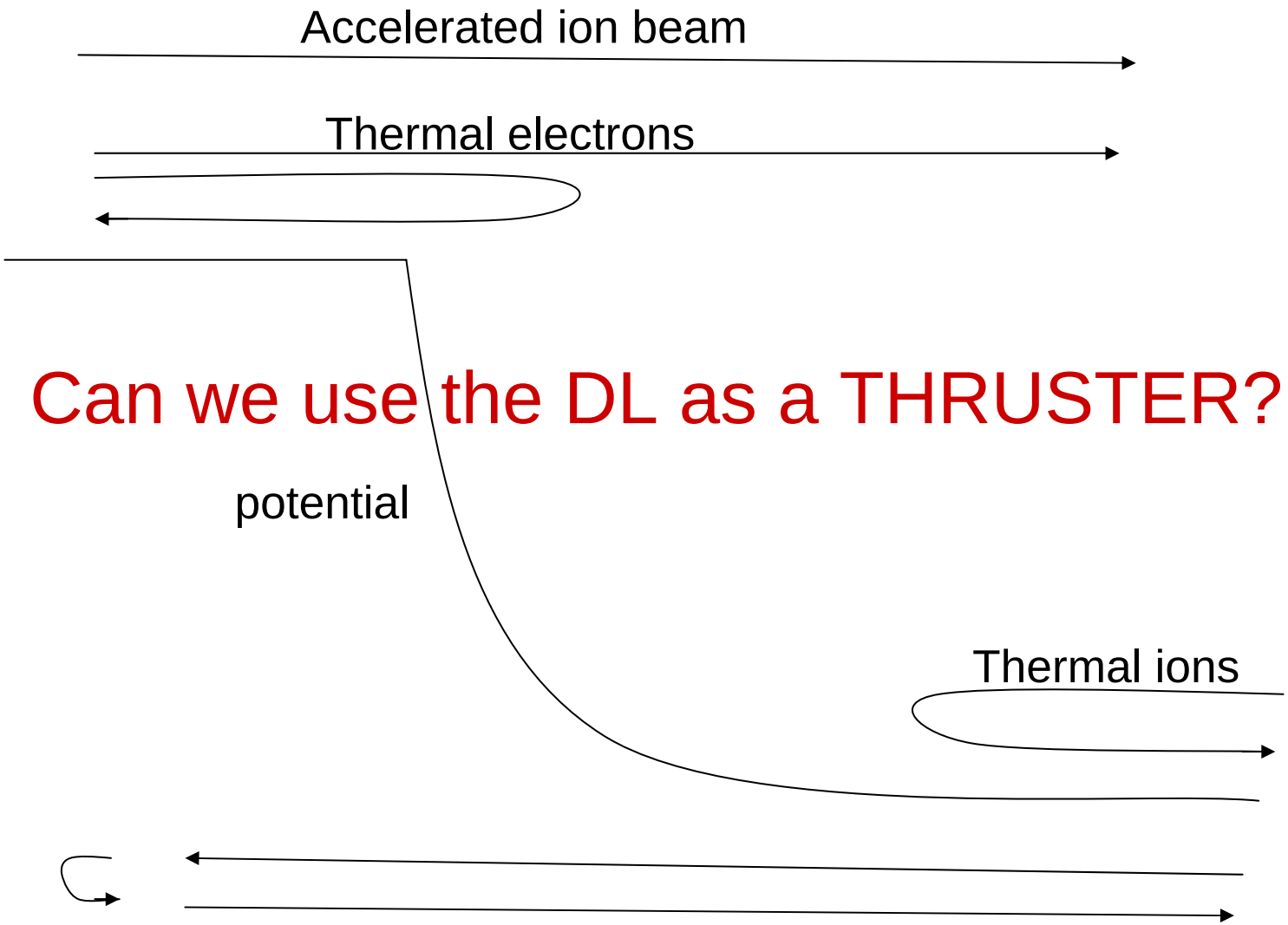
Electrons gain the same momentum to the left as ions acquire to the right – no net momentum to the plasma

Current-free double layer, LCB (2006)



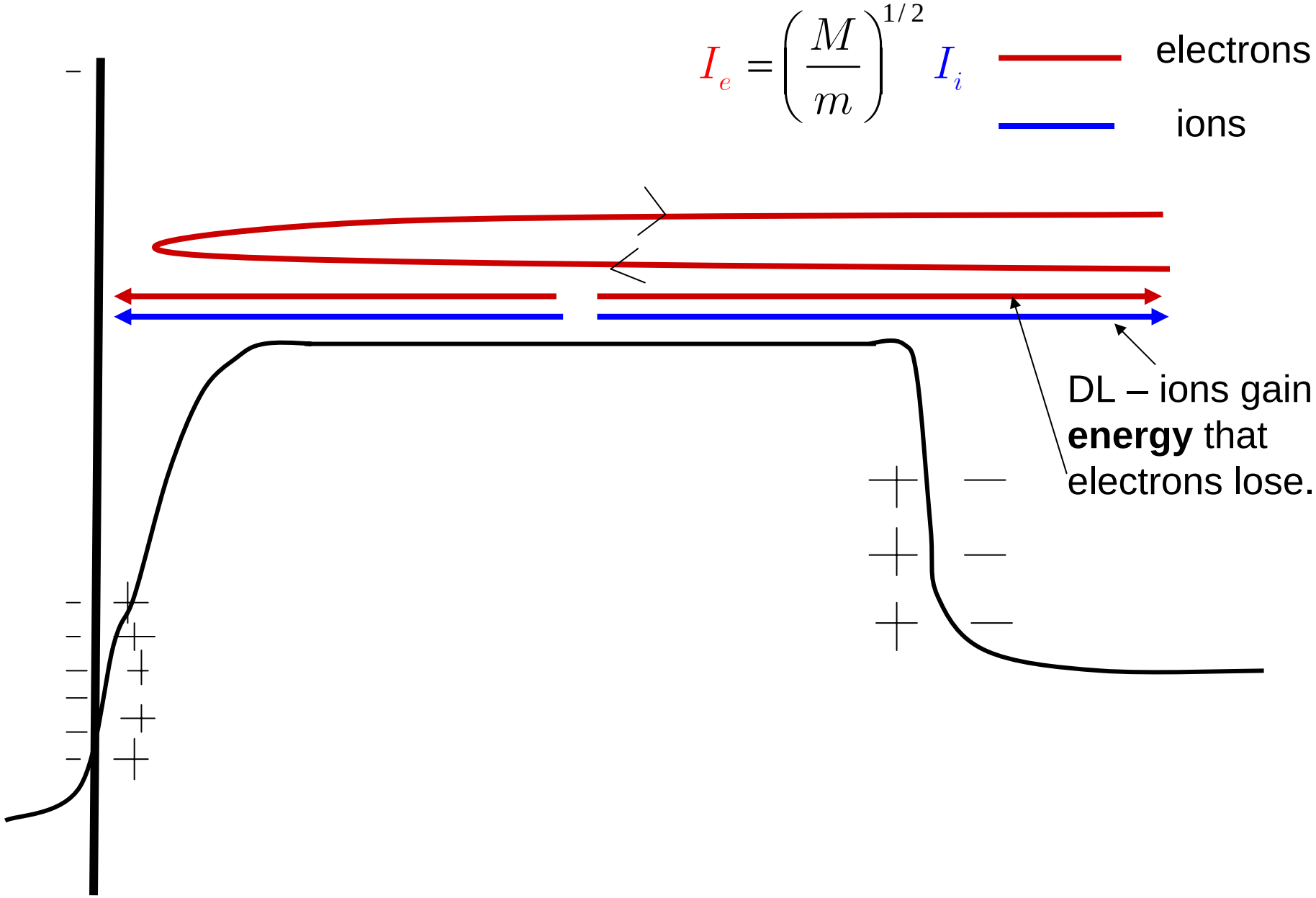
Electrons gain the same energy as ions acquire –
no net energy deposition in the plasma

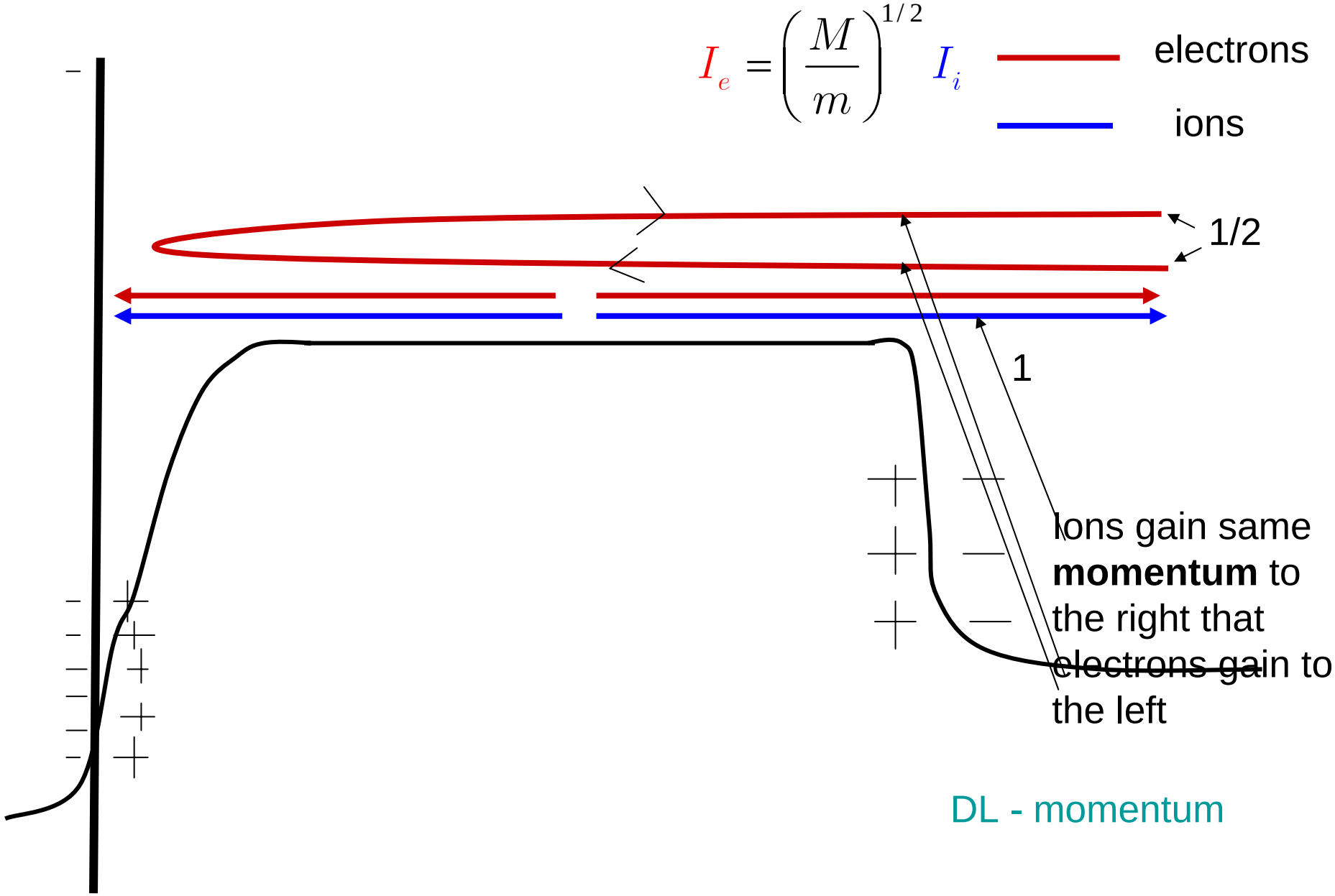
Current-free double layer, LCB (2006)



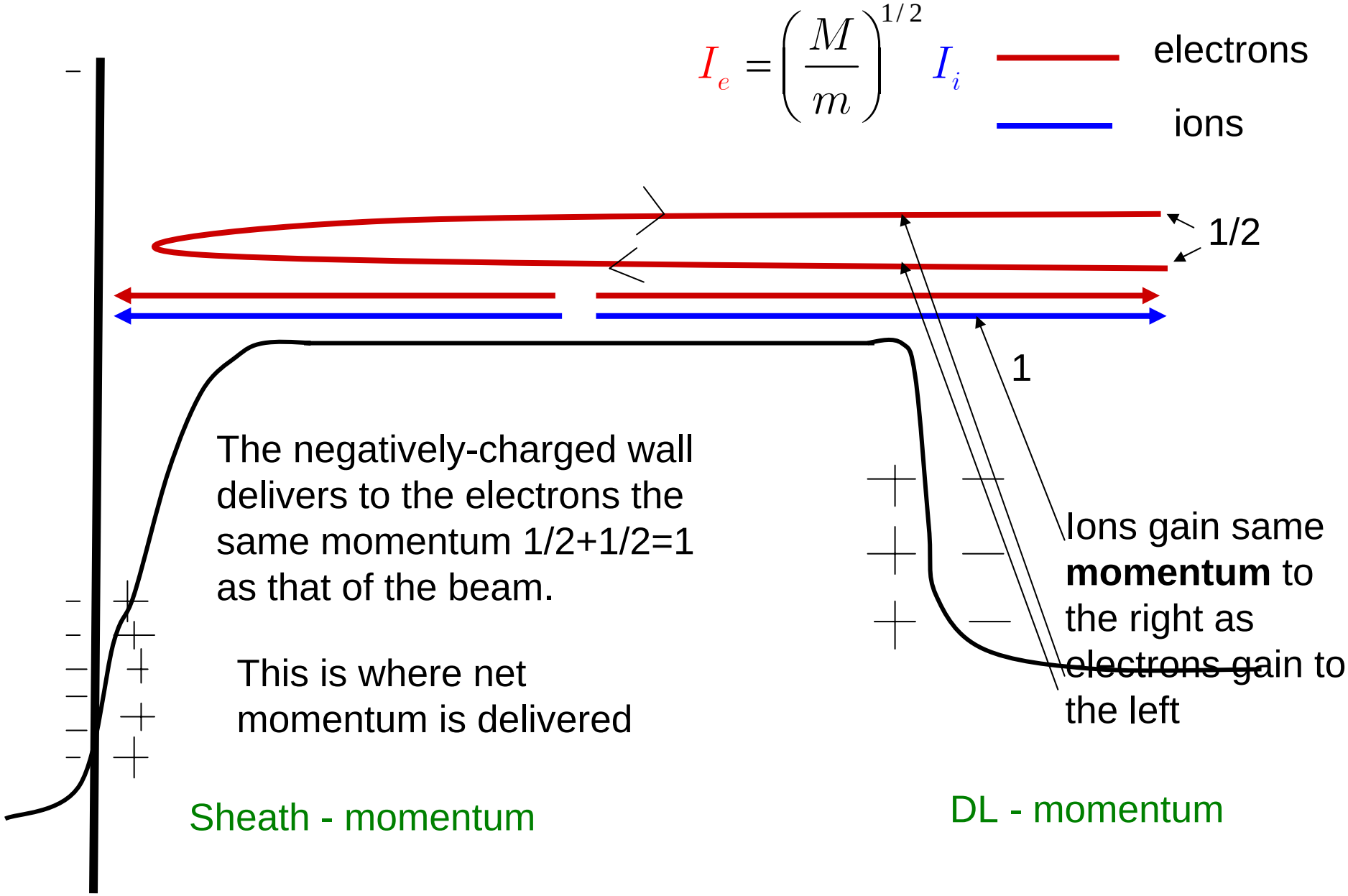
Can we use the DL as a THRUSTER?

Electrons gain the same energy as ions acquire –
no net energy deposition in the plasma


$I_e = \left(\frac{M}{m}\right)^{1/2} I_i$
electrons
ions
DL – ions gain **energy** that electrons lose.


$I_e = \left(\frac{M}{m}\right)^{1/2} I_i$
electrons
ions
1/2
1
Ions gain same **momentum** to the right that ~~electrons gain~~ to the left

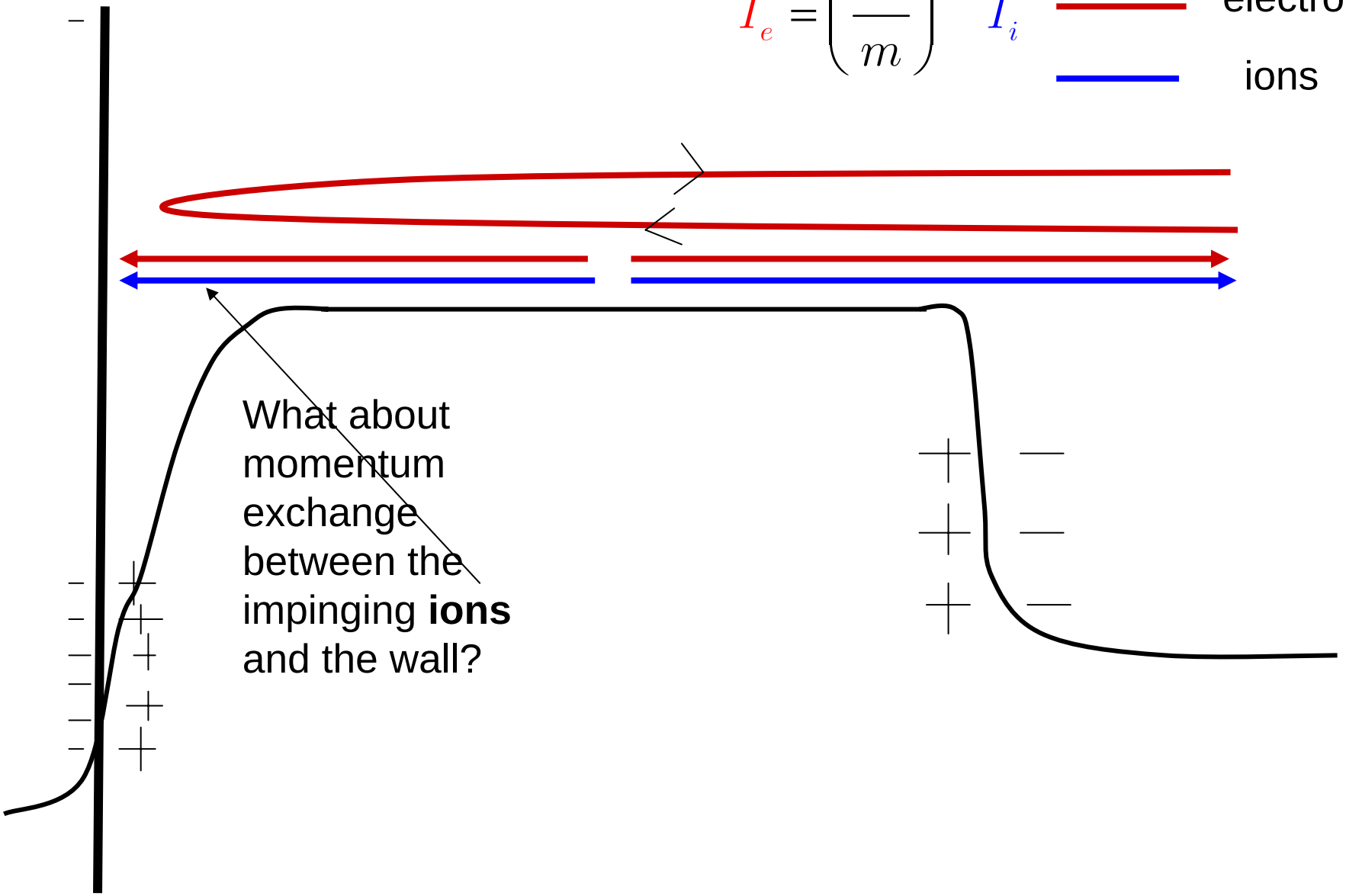
DL - momentum

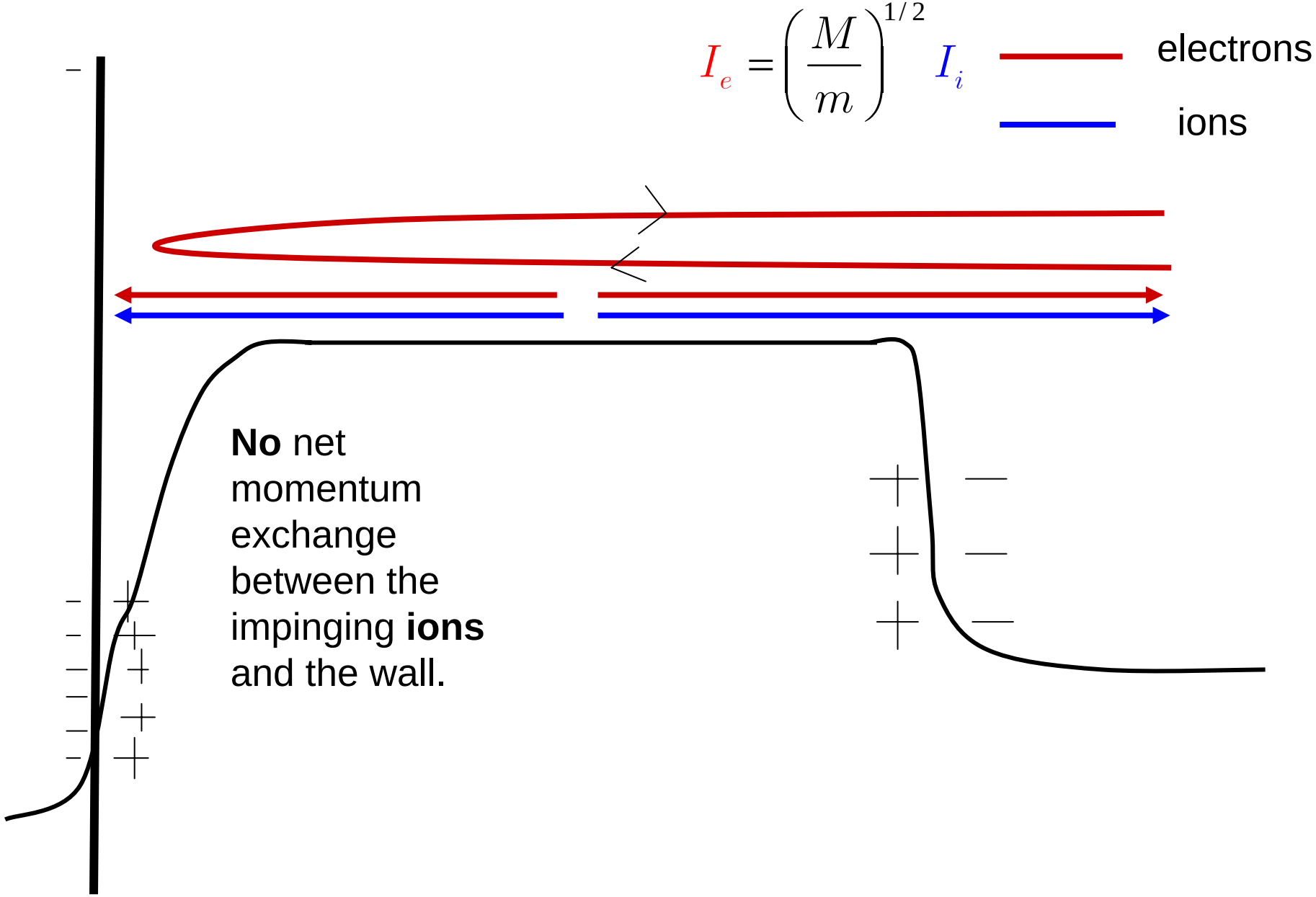

$I_e = \left(\frac{M}{m}\right)^{1/2} I_i$
electrons
ions
1/2
1
The negatively-charged wall delivers to the electrons the same momentum 1/2+1/2=1 as that of the beam.
This is where net momentum is delivered
Ions gain same **momentum** to the right as ~~electrons gain~~ to the left
Sheath - momentum
DL - momentum

$$I_e = \left(\frac{M}{m}\right)^{1/2} I_i$$

electrons

ions

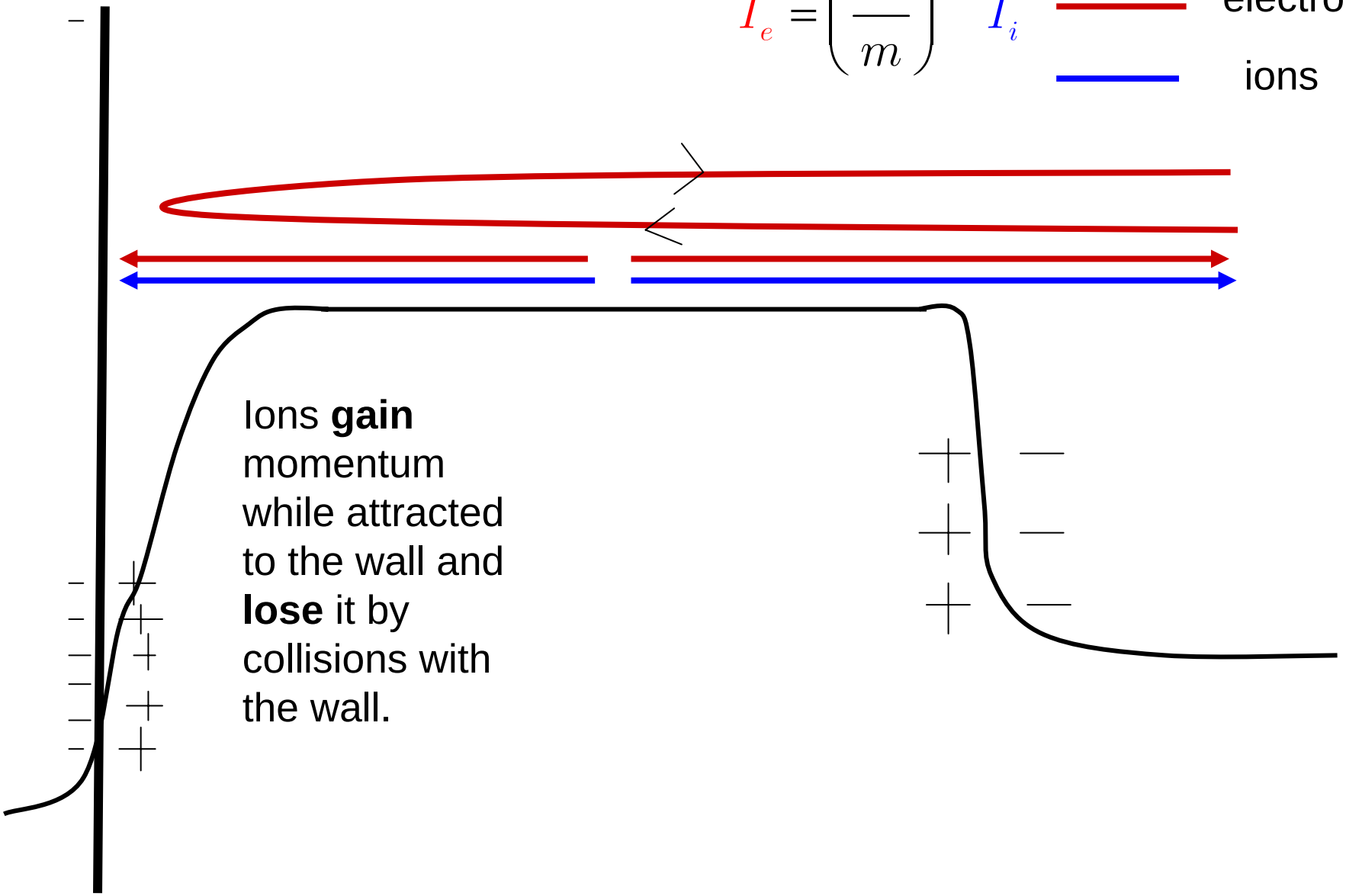



$I_e = \left(\frac{M}{m}\right)^{1/2} I_i$
electrons
ions
No net momentum exchange between the impinging **ions** and the wall.

$$I_e = \left(\frac{M}{m}\right)^{1/2} I_i$$

electrons

ions



Ions **gain** momentum while attracted to the wall and **lose** it by collisions with the wall.

- The ions impinging on the wall deposit energy at the wall that is similar to the kinetic energy of the ion beam to the right.
- This could cause **erosion** and is a source of **inefficiency**.

Efficiency

There is no free l(a)unch

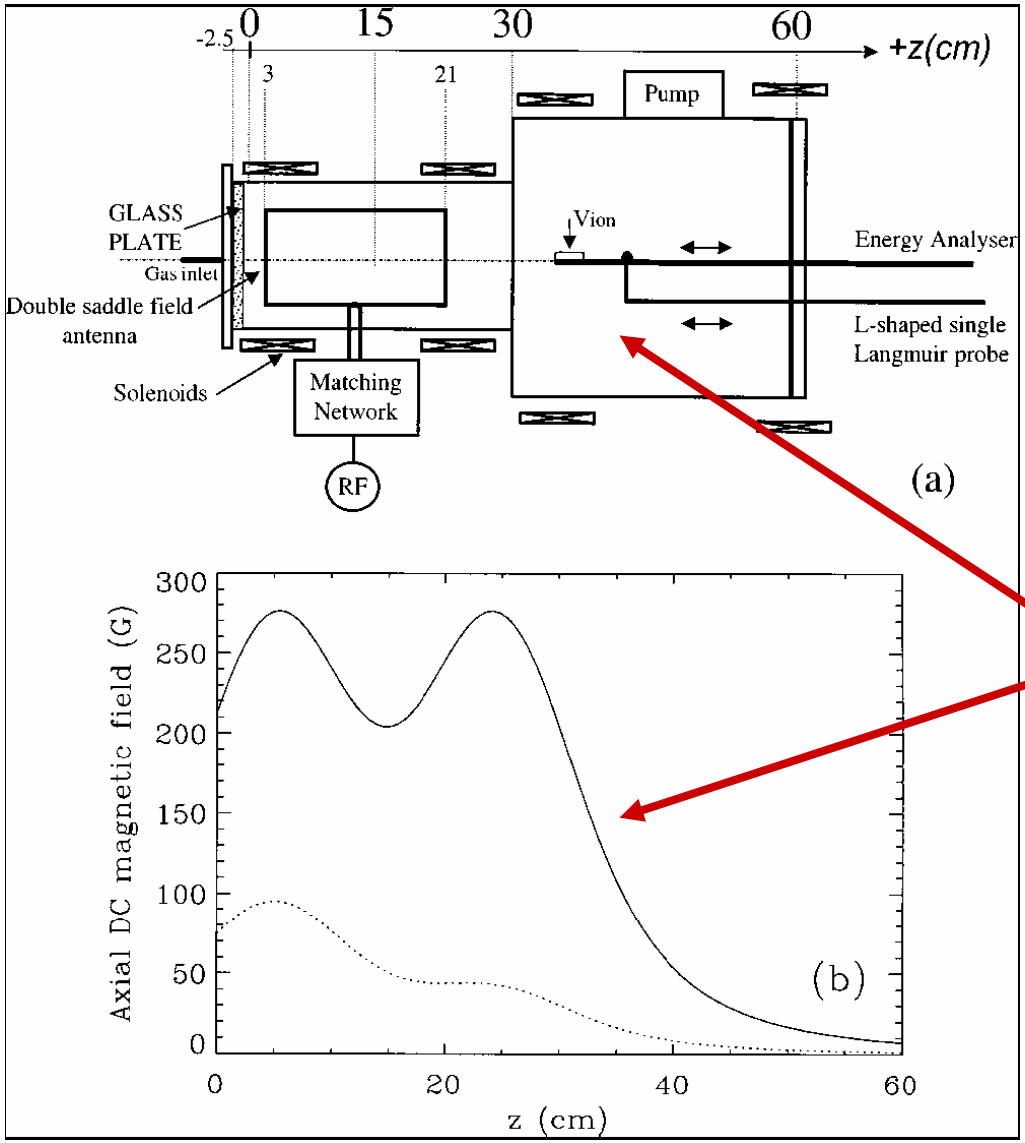
Wall

- Momentum is exerted at the wall
- Resurrection of electrode problems
- Bad news: erosion….

Can we replace the wall?

Magnetic field pressure and thrust

- **Electric** field pressure **does not** impart thrust to a quasi-neutral plasma
- **Magnetic** field pressure **does** impart thrust to a quasi-neutral plasma
- In fact in the helicon a divergent magnetic field is an inherent component.



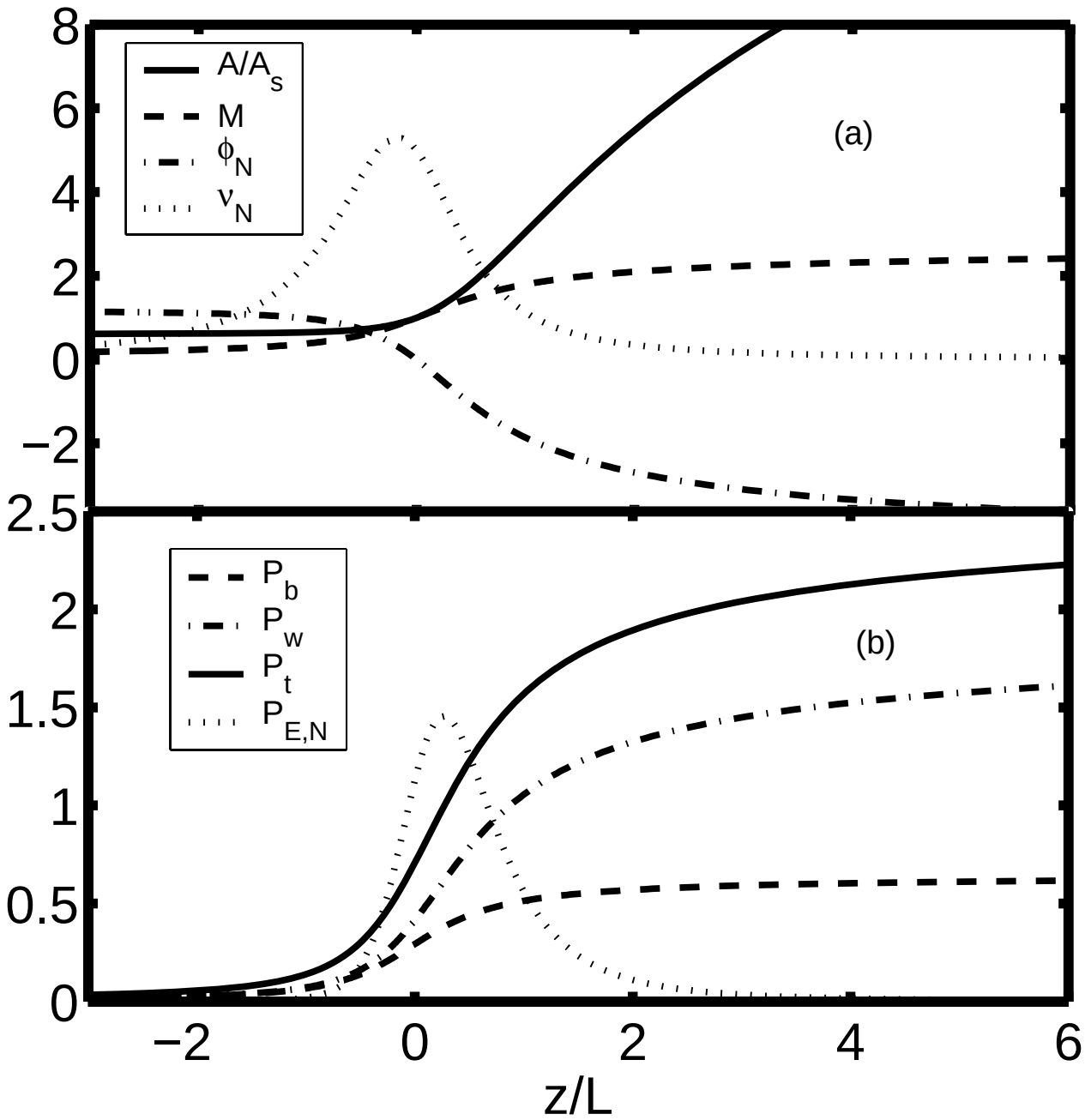
Divergent magnetic field

Charles and Boswell, APL (2003)

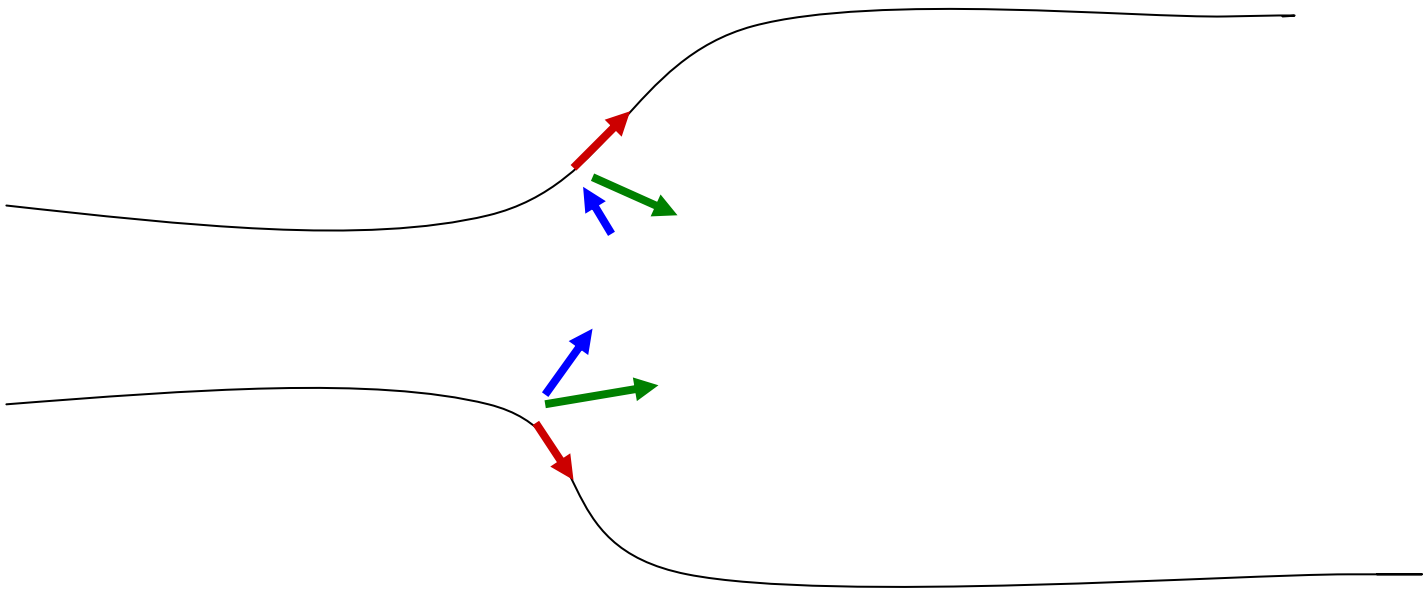
Magnetic DL model (AF, PRL, 2006)

In parallel to the LCB model for the DL, a model in which thrust is imparted to the plasma by the magnetic field pressure was proposed.

Divergent magnetic field – AF, PRL (2006)



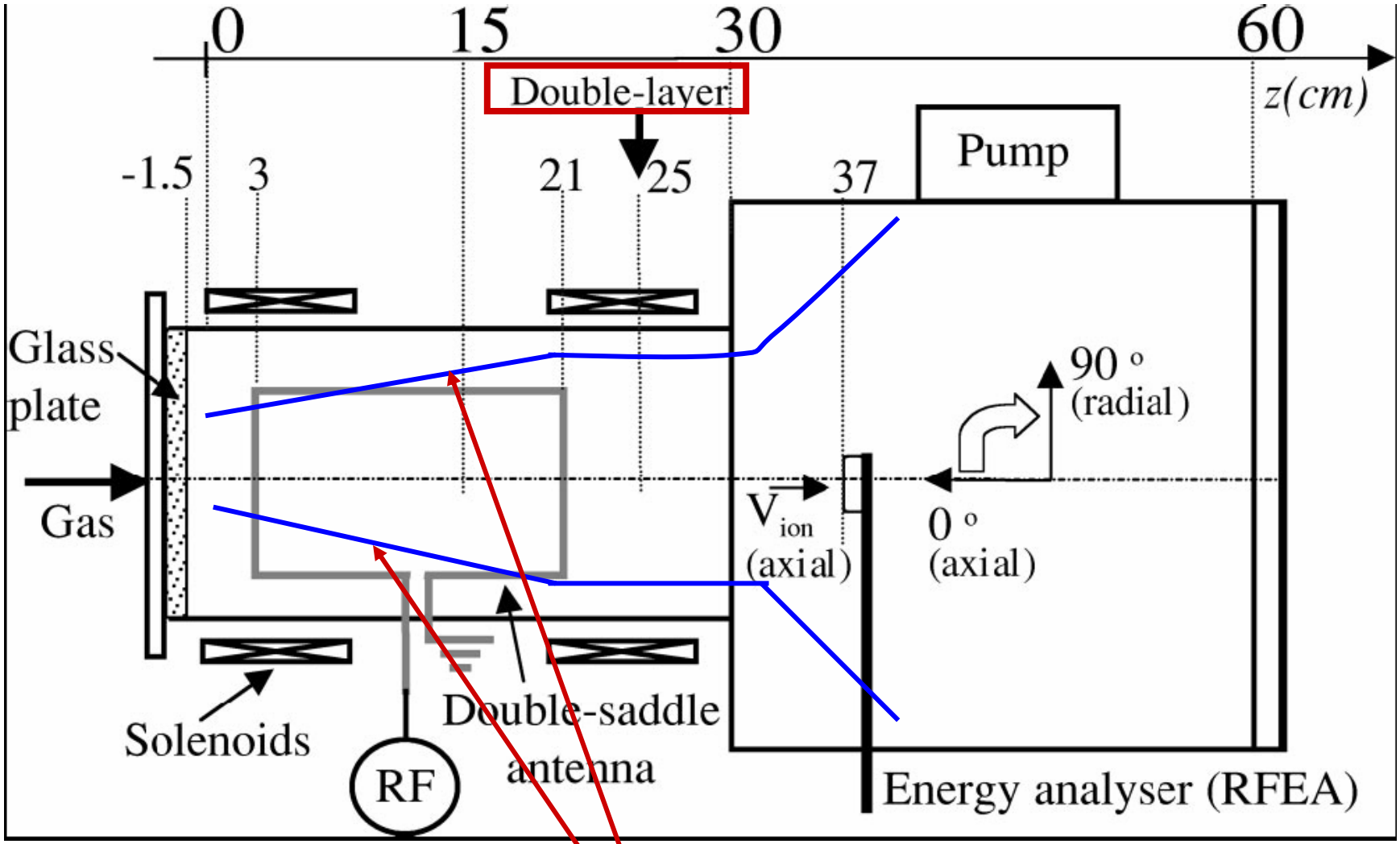
In the divergent magnetic field the JXB force that balances the plasma pressure has an axial accelerating component



The mf force is similar to the force of the wall, but without erosion. The force is exerted through the magnetic field on the coils. (Related to the **solar wind** acceleration along diverging field lines)

Magnetic Mirror

- Converging magnetic field lines could replace the wall in delivering thrust to the plasma upstream the double layer.
- Mirror not effective against beams !
- Takahashi *et al.* (This meeting, yesterday): the accelerated electrons are not parallel beam.
- Maybe the mirror mf will be effective.


0
15
30
60
z(cm)
Double-layer
-1.5
3
21
25
37
Pump
Glass plate
Gas
90 o (radial)
V ion (axial)
0 o (axial)
Solenoids
RF
Double-saddle antenna
Energy analyser (RFEA)
Magnetic mirror

Summary

- The mechanism of excitation of the DL in the helicon experiments is not clear yet.
- In particular, the role of the magnetic field has to be understood.
- The relation to DL in space is intriguing.
- With regard to propulsion, one has to keep in mind that

The sky is not the limit!