UNIVERSITY OF WASHINGTON 1861

Physical boundary conditions

To

Annual PSI-Center meeting
8-17-10

Outline

- Creating and sustaining plasma
- Surface current distribution
- Neutral dynamic
- Possible boundary conditions
- Summary

Inputing power to create plasma

Neutral gas

+

Paschen breakdown conditions ⇒Plasma

+

E×**B**/μ_o input power
[B^2/μ_o(enthalpy) at velocity **E**×**B**/B^2]

+

Magnetic confinement ⇒Hot plasma

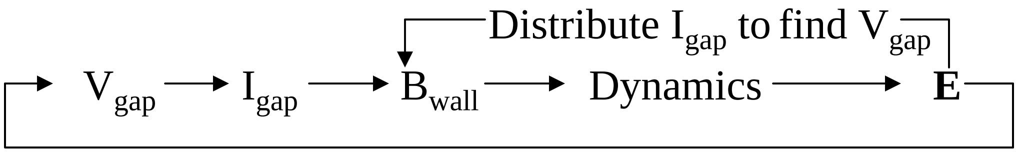
+

Continuous Fueling and Power input

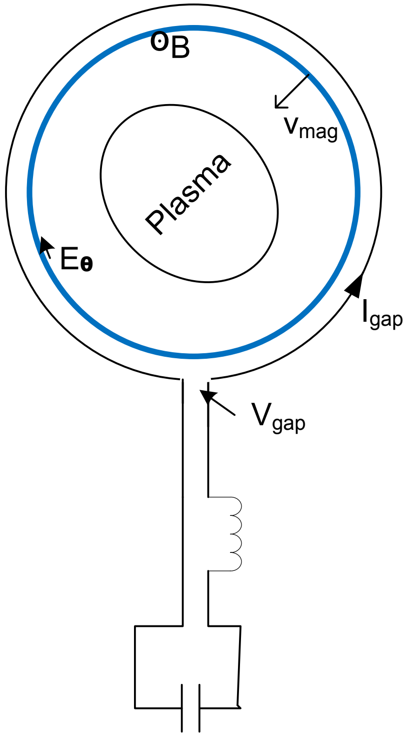
⇒Hot sustained plasma

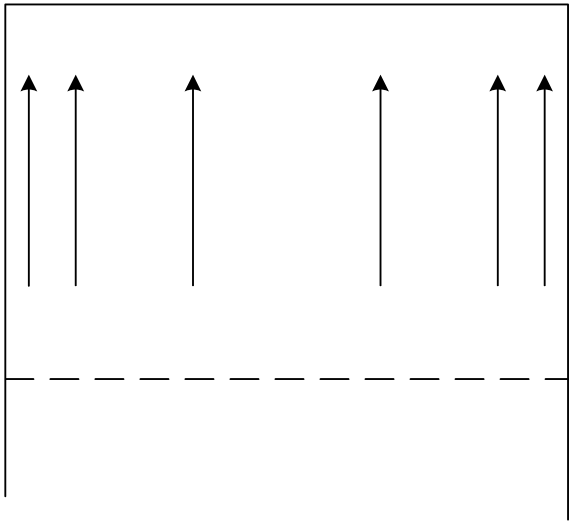
E&B at wall are determined by plasma motion, resistivity, and the external circuit

- $\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta\mathbf{j} = -\mathbf{v}_{mag} \times \mathbf{B}$
- Magnetic field moves in by diffusion or plasma motion leading to **E**-field.
- Plasma motion is caused by the magnetic field.
- At the wall the external circuits (including eddy current in the wall) supply the current that makes this B-field
- Usually currents enters through a uniform-voltage gaps. This constrains the **E** at the boundary but do not define it.
- Currents are distributed and the values of the voltage across the gaps, V_{gap}, are determined such that: $-\oint \mathbf{E}\cdot d\mathbf{l} = \sum V_{gap}$ (of the gaps crossed) for all paths.
- V_{gap} reacts back on the circuit impacting I_{gap}



Theta pinch illustrates physical E&M boundary conditions

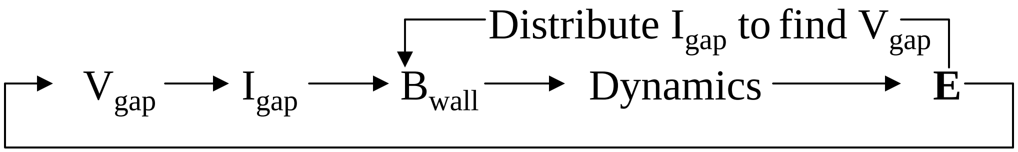




Side view plus current stream lines

- Current distributes to make V_{gap} uniform

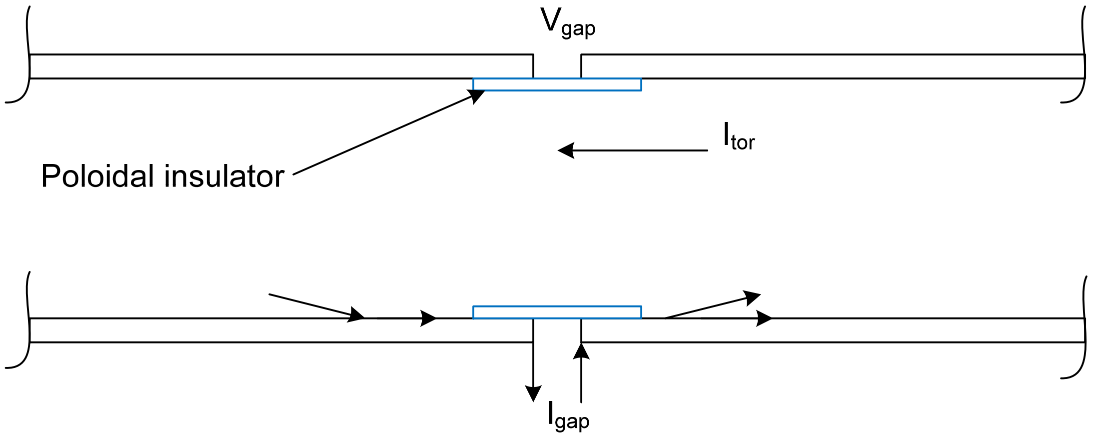
- For higher non-symmetric modes:
  - E is not zero
  - $\oint E\cdot dl = 0$ for $m \neq 0$
  - Can affect surface current pattern



Distribute I_{gap} to find V_{gap}

$V_{gap} \rightarrow I_{gap} \rightarrow B_{wall} \rightarrow$ Dynamics $\rightarrow$ **E**

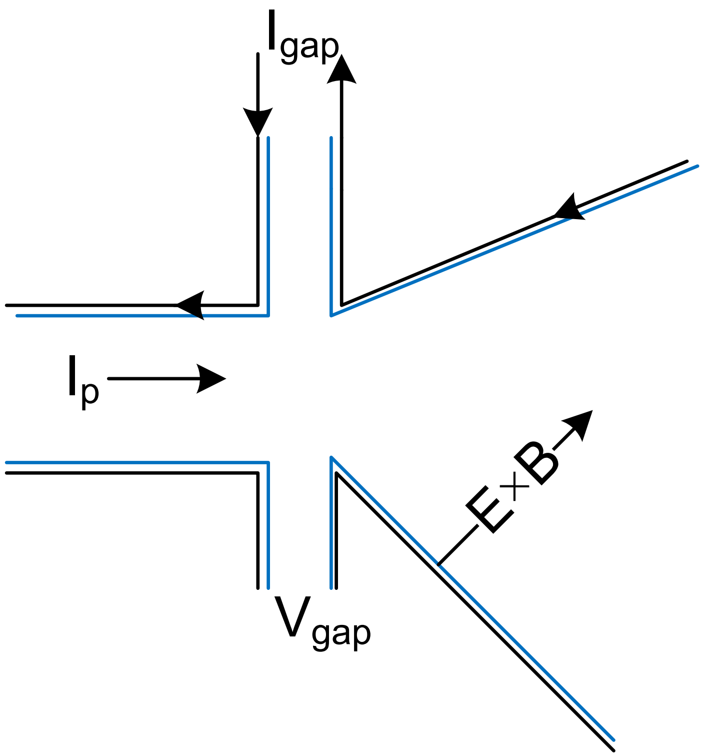
MST may need Sheath BC


Segment of MST at the poloidal break

- Uniform voltage gap is exaggerated
- I_{gap} is from circuit
- $\oint \mathbf{E}\cdot\mathbf{dl} = -V_{gap}$
- Current in and out of wall can be found from sheath BC
- With sheath BC, $E_{||} \neq 0$, $E_{||} \neq$ Constant
- Again $E_{||} \neq 0$ for $n > 0$ modes

In HIT-SI plasma dynamics dominates BC

HIT-SI around injector voltage break



- Geometry requires BC to be calculated
- Achieved in NIMROD with resistive layer
- Insulating boundary has simple E&M physics
- $-\oint E\cdot dl = \sum V_{gap}$ crossed

Velocity BC: Plasma moves toward the wall

- If neutral density at the wall is high, little plasma will reach the wall. Plasma still moves toward the wall at the wall.
- The density of the plasma reaching the wall depends on heating versus cooling of the plasma at the wall and plasma flow to the wall.
  - Heating: flow into the wall, plasma diffuse to the wall, plasma heating (by thermal conduction and electro-magnetic heating) that ionizes the gas at the wall, radiation ionizing the gas at the wall
  - Cooling: radiation, convection, and conduction cooling and recombination

Plasma sets up a thin sheath when it contacts the wall and moves into the wall at the sound speed giving a resistive electrical connection

- With insulating walls, electron and ion flow into wall at the same rate with a sheath voltage of about $4kT_e/e$ to lower the electron density at the wall. Both electrons and ions flow into the wall at the sound speed.
- For conducting walls the sheath drop depends on the plasma current to the wall since the ion and electron flows would not, in general, be the same locally.
- A simple sheath impedance, based on Langmuir probe equations, depends on the temperature and density of the plasma at the wall. In the limit of zero plasma density or temperature the impedance is infinite. This is a glow discharge.
- Plasma that reaches the wall flows into the wall at the plasma sound speed. A glow discharge can be weakly ionized
- Under high voltage an arc can form and generate plasma from wall material and glow theory is not valid. The simplest model is a constant voltage arc drop

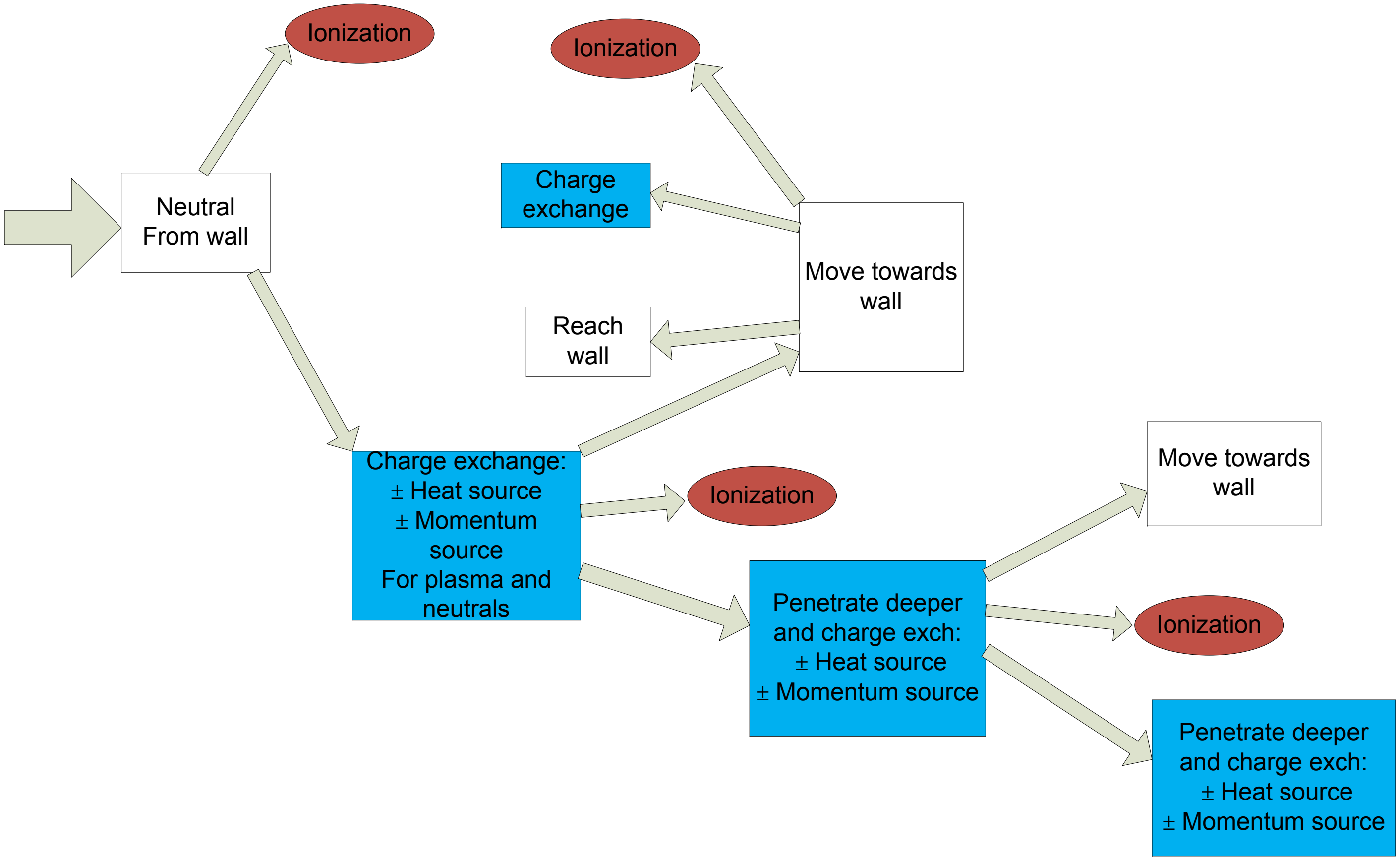
Neutral influx depends on many factors

- Wall conditions: depends on wall history including treatment and wall material
    - Amount of gas absorbed in the wall
    - Number of mono-layers on the wall
    - Wall material
- Wall Temperature: depends on heating history vs conduction, convection and radiation cooling
    - Large factor in out-gassing rate and mono-layer evaporation
    - A factor in absorption of neutral produced by plasma neutralization
- Rate of plasma neutralization at the wall:
    - Influx is often thought of as a recycling fraction, which would be near one after a long time of steady state operation (much longer than ICC experimental pulse lengths)
    - Recycling rate of one or zero are simple models
- Local gas injection: for fueling

Neutrals influx is at the neutral sound speed and wall temperature and density can be determined

- Heated neutral expand from the wall and the Chapman-Jouguet condition applies. The material comes off the wall at Mach I [$v_{infl} = (kT_{wall}/m)^{1/2}$]
- $n\ v_{infl}$ = function of T_{wall} and other known factors
- Net power/area into wall is convected away: $P_{net} = n\ v_{infl}\ \varepsilon_p$ where ε_p is the energy carried away per particle.
- Three equations determine wall temperature, density, and influx velocity
- For very high powers to the wall, such a laser irradiation or arcs, the wall temperature can be high enough so that the influx is ionized.

Neutral influx is important because charge exchange allows neutral to penetrate deeply and remove plasma energy



Neutral
From wall

Ionization

Charge exchange:
± Heat source
± Momentum source
For plasma and neutrals

Move towards wall

Ionization

Charge exchange

Reach wall

Ionization

Penetrate deeper and charge exch:
± Heat source
± Momentum source

Move towards wall

Ionization

Penetrate deeper and charge exch:
± Heat source
± Momentum source

The effects of neutrals can be captured by a neutral-fluid that interacts with a fluid plasma model

- Neutral density is often very low even though it has large effects
- Neutral-neutral mean free paths are very long and *Monte Carlo* approach is often used
- However, this probably is not necessary since neutral-plasma mfps are not long
- Fluid models seem to work very well if you do it right*

* Private Communication Tom Rognlien of UEDGE, LLNL

The effects of neutrals may be captured by a neutral-fluid that interacts with a fluid plasma model Cont-

Neutral effect	Fluid mechanism
Charge exchange penetration of plasma	Pressure gradient driven flows of neutral-fluid that is heated by charge exchange
Random walk nature of penetration prevents penetration	There is a force on the neutral fluid due to momentum exchange that similarly inhibits neutral fluid penetration.
Escaping hot neutrals cool plasma	Temperature gradient driven thermal conduction of the neutral fluid can capture this effect
Ionization and recombination	Source and sink terms in both fluids captures this physics

Charge exchange penetration of plasma is captured by pressure gradient driven fluid

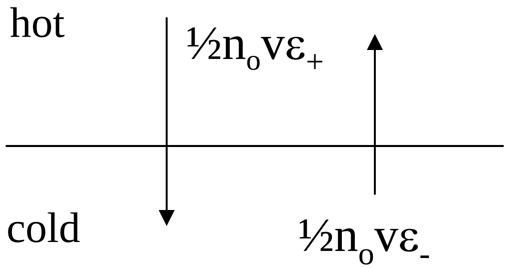
- Charge exchange is a large heating source for maintaining temperature gradients in the neutral fluid.

- Ionization helps to maintain the density gradient.

- Hot neutral penetration can be modeled as a hot low density fluid expanding into the plasma.

Temperature gradient driven thermal conduction of the neutral fluid can capture charge exchange cooling

- Thermal conductivity can be estimated



hot

$\frac{1}{2} n_o v \varepsilon_+$

cold

$\frac{1}{2} n_o v \varepsilon_-$

$Q = - \frac{1}{2} n_o v \varepsilon_+ + \frac{1}{2} n_o v \varepsilon_-$

$= - \frac{1}{2} n_o v(5/2\ kT_+ - 5/2\ kT_-)$

$= -5/4 n_o v k 2 l_{mfp} (T_+ - T_-)/2 l_{mfp}$

$= -5/4 n_o v k 2 l_{mfp} \nabla T_o$

$\kappa = 5/2 n_o v_{zt} k l_{mfp}$

Need l_{mfp}

$n_i \sigma_{cx} l_{mfp} + n_o \sigma_{oo} l_{mfp} = 1$

$$l_{mfp} = \frac{1}{n_i \sigma_{cx} + n_o \sigma_{oo}}$$

$$\kappa = \frac{5/2 n_o k}{n_i \sigma_{cx} + n_o \sigma_{oo}} \sqrt{\frac{kT_o}{m_o}}$$

Neutral boundary conditions are easy?

- **Temperature** of neutrals at the wall is the wall temperature computed from power balance. Inputs include plasma impact, radiation hitting wall, neutral thermal conduction. Losses include thermal conduction into the wall, convection away from the wall, radiation away. (discussed before)
- **Velocity** is Mach I (Chapman-Jouguet condition) away from the wall based on the wall temperature, as discussed. Non-slip parallel velocity BC.
- **Density** of neutrals at the boundary is such that the influx of particles is equal to the loss of plasma plus wall out gassing, gas injection, and evaporation , minus wall absorption as discussed.
- **Pressure** is from the density and temperature

At low powers the wall temperature is low enough that the influx is not ionized.

At high powers the influx is partially ionized so the neutral density is a fraction of the influx.

Low-power plasma boundary conditions

- **B-field:** Continuous across the boundary. Obtained B-parallel along with E-parallel from circuit I_{gap} which is distributed around the plasma to give uniform voltage at the voltage gaps as described.
- **Velocity:** Plasma at the wall moves into the wall at the sound speed. Zero normal derivative for parallel velocity.
- **Current density:** j into the wall is calculated from sheath boundary conditions and is zero for insulating boundaries. Zero normal-first-derivative for j parallel to the wall.
- **E-field** is calculated from the generalized Ohm’s law used in the simulation and the rate of change of B-normal. Resistivity must go to infinity as the density goes to zero. This allows B-parallel to enter as very low density plasma flows to the wall.
- **Density:** zero normal-derivative.
- **Temperature:** zero derivative for plasma velocity. Wall temperature from power balance for thermal conduction. Supersonic ions do not conduct heat to wall but ambipoler electrons can have temperature and can conduct heat to wall if there is emission from the wall. This is especially important when field lines go into the wall. Heat transport is flux limited.
- **Pressure:** Density times temperature

High-power plasma boundary conditions

- **B-field:** Continuous across the boundary. Obtained B-parallel and E-Parallel from circuit I_{gap} which is distributed around the plasma to give uniform voltage at the voltage gap as described.
- **Velocity:** Velocity is Mach I (Chapman-Jouguet condition) away from the wall based on the wall temperature. Non-slip parallel velocity BC.
- **Current density:** j into the wall is calculated from arc boundary conditions (V= const) and is zero for insulating boundaries. Zero normal-first-derivative for j parallel to the wall.
- **E-field** is calculated from the generalized Ohm's law used in the simulation and the rate of change of B-normal.
- **Density:** zero normal-derivative.
- **Temperature:** Wall temperature. Electrons conduct heat to wall since there is emission from the wall. This is especially important when field lines go into the wall.
- **Pressure:** Density times temperature

There are solutions to the low density regions produced by these BC

- For numerical reasons we use a density floor. The added density should be: as low as possible, as resistive as possible, with no pressure, and should only be loaned to the cell.
- Including the displacement current in Maxwell’s eq. with a lower speed of light is perhaps a more elegant way of dealing with very low density regions.

Summary

- Plasma dynamics dominates the E-field at the boundary
- Experimental constrains are often imposed as uniform voltage gaps that also have current that couples to a circuit.
- A 2D surface problem needs to be solved to find the surface E-field and B-field over the whole surface
- The effect of neutrals on the plasma can be modeled as neutral-fluid interacting with the plasma-fluid.
- At low power, plasma flows into the wall at its sound speed and neutrals flow away from the wall at their sound speed.
- At high power, partially ionized material flows away from the wall at the sound speed.