

New Developments in Combustion Technology

Part III: Making oxy-fuel combustion an advantage

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Course Length: 6 hrs

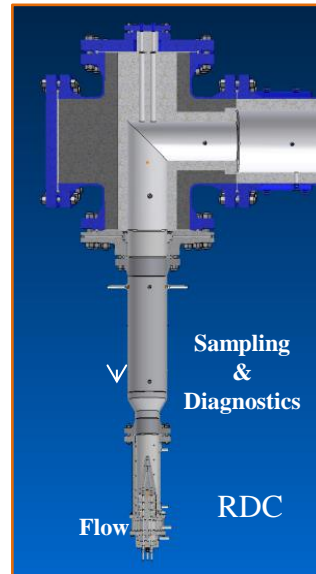
June 22-23, 2014



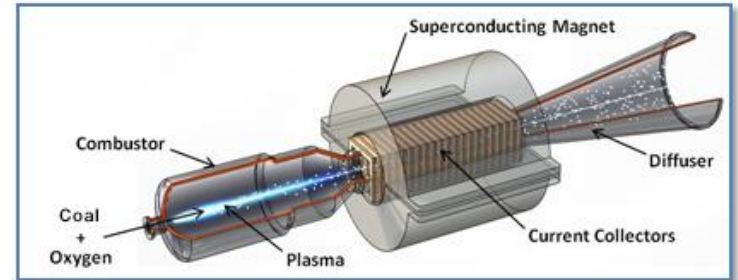
This presentation

Updated, expanded from 2012 CEFRC lecture:

- Inherent carbon capture: chemical looping combustion (Day 1)
- Step-change in generator efficiency: pressure gain combustion (Day 2)
- Frontier approach (?!): making oxy-fuel an efficiency advantage (Day 2)

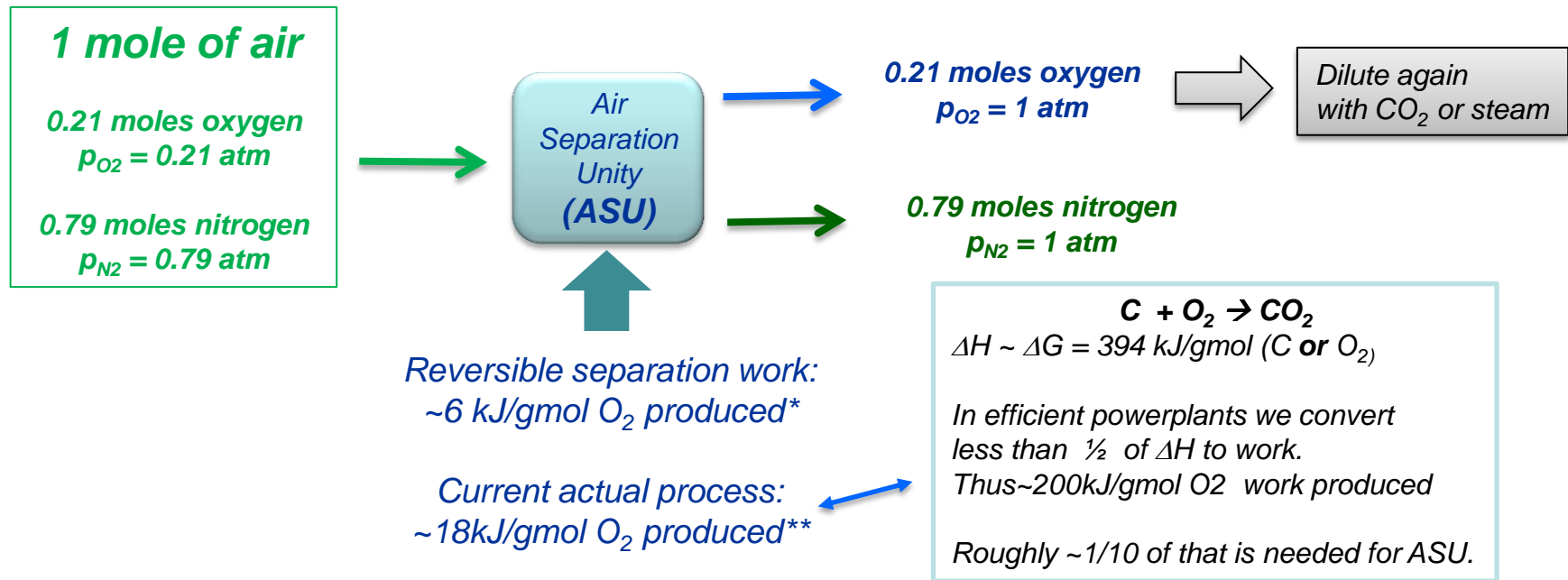


P-gain rig @ NETL



Making oxygen for oxy-fuel ...reprise

- Oxygen can be supplied today by commercial Air Separation Units (ASU) based on established cryogenic separation.
- The energy needed to separate oxygen from air is significant (see below)
- In conventional oxy-combustion, we dilute the purified oxygen to maintain the same boiler flame temperature as in air-combustion.

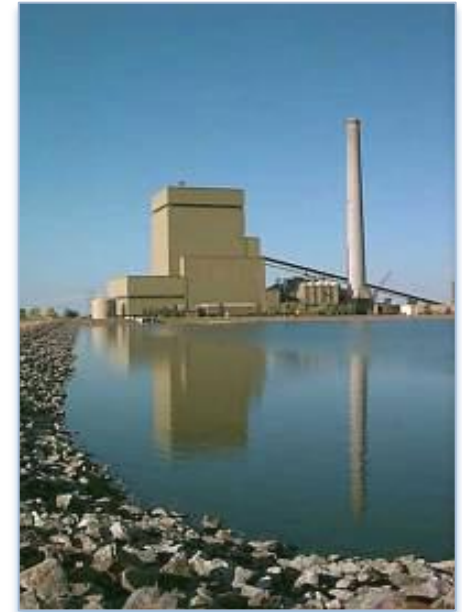
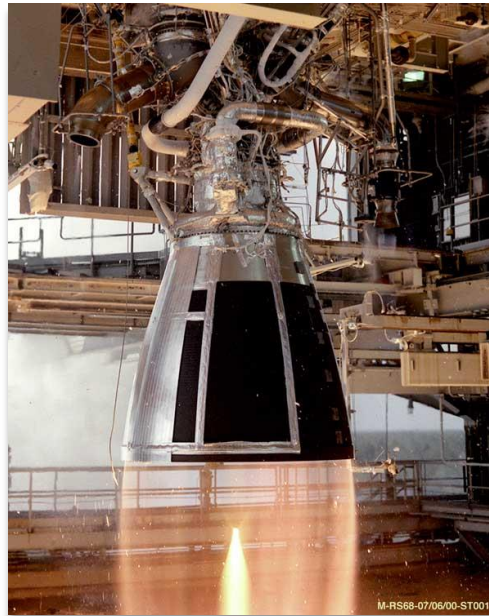


*e.g, the change in gibbs energy for ideal mixing (Sandler, Chemical Engineering Thermodynamics (1989) pp. 313.

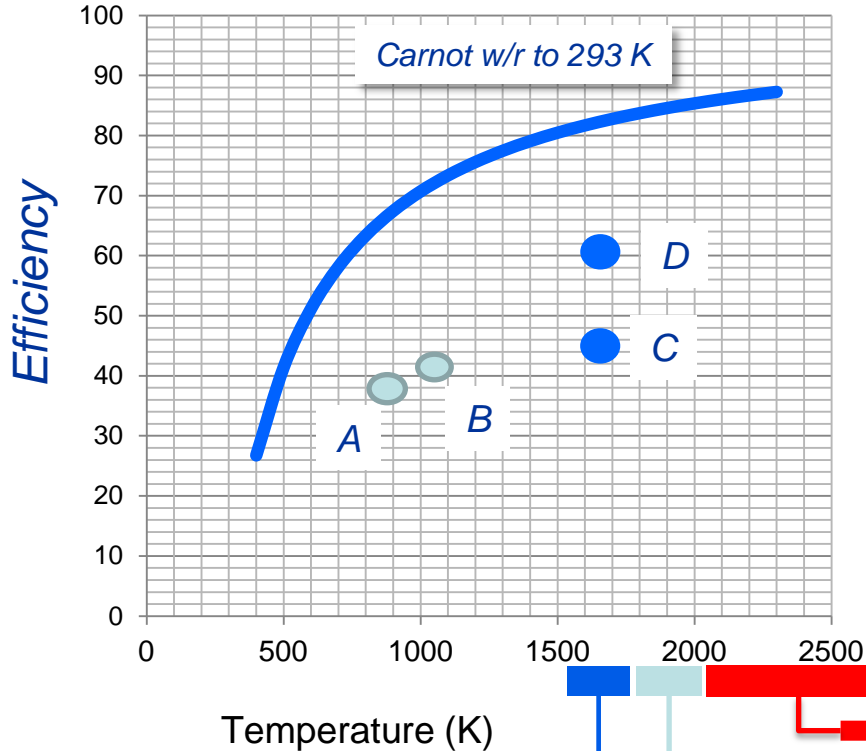
**See Trainier et al., "Air Separation Unit....." Clearwater Coal Conference, 2010.

Making Oxy-fuel an Advantage

- Producing pure oxygen requires a lot of energy!
- If one could find a way to make significant extra power because of the available oxygen, oxy-fuel would be an advantage.
- Oxy-fuel already provides an advantage for process industries that benefit from high temperatures (e.g., glass making, steel).
- Oxy-fuel already provides advantages in propulsion (rocket engines)
- How can you make oxy-fuel an advantage for power generation?

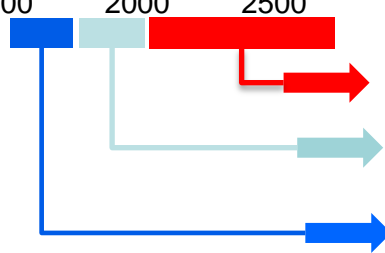


Efficiency



- A) Existing Supercritical Pulverized Coal (23.9MPa/866K/866K steam)¹
- B) Advanced Ultra-Supercritical Pulverized Coal (34.5 Mpa/1005K/1033K steam)¹
- C) Simple Cycle Gas Turbine (as reported, LMS 100, working fluid temp estimated from exhaust and pressure ratio)²
- D) Combined Cycle Gas Turbine (as reported, MPCP2(M501J), working fluid temp estimated similar to case C)³

Approximate combustion temperatures



Oxy-fuel Combustion Temp. >>> Working fluid temp.

PC Coal Combustion Temp. >> Working fluid temp.

Gas Turbine Combustion Temp. = Working fluid temp.

Note: boilers report HHV efficiency; turbines report LHV

[1] Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture, DOE/NETL-2012/1557

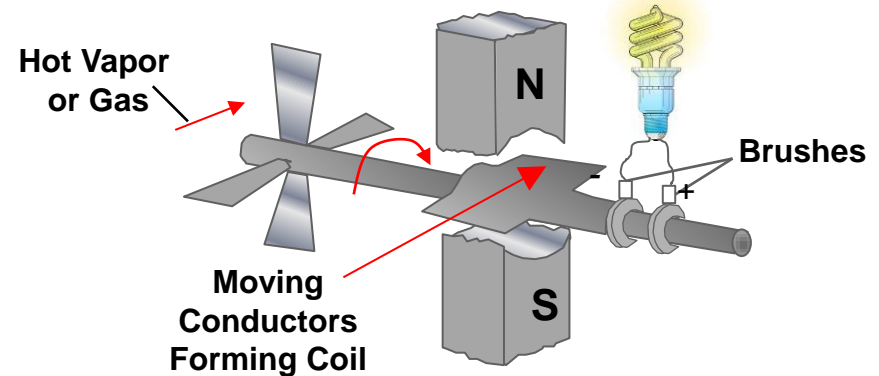
[2] Gas Turbine World 2012 GTW Handbook, Vol. 29, Pequot Publishing pp74

[3] Gas Turbine World 2012 GTW Handbook, Vol. 29, Pequot Publishing pp89

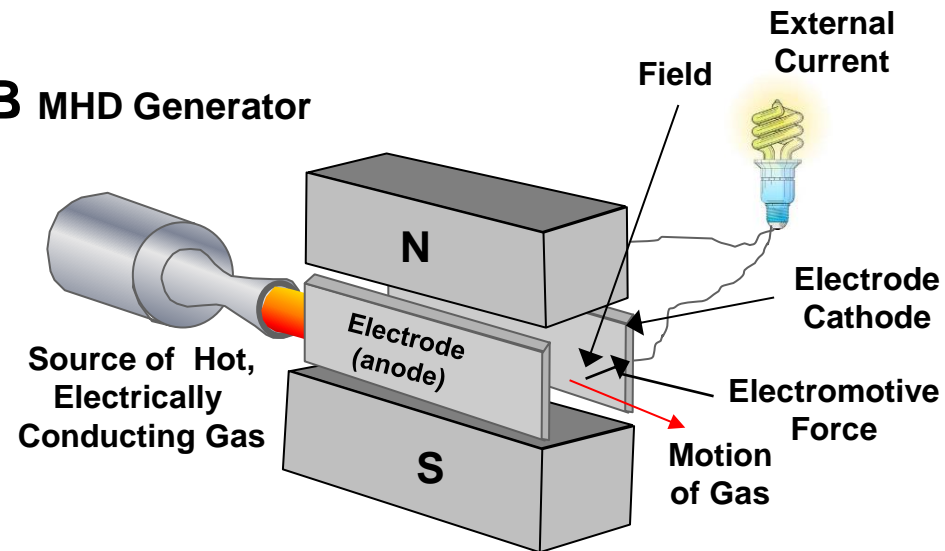
Magnetohydrodynamic Power Generation

- The high temperatures possible with oxy-fuel can be used to operate an MHD “topping” cycle:
 - Topping cycle power possible *because of the oxygen*
 - MHD exits to conventional steam boiler system (“bottoming cycle”).
- How does MHD work?
 - Conductive, high-temperature gases play the role of an electrical conductor moving through a magnetic field.
 - Generates power directly from the moving gases.

A Turbogenerator

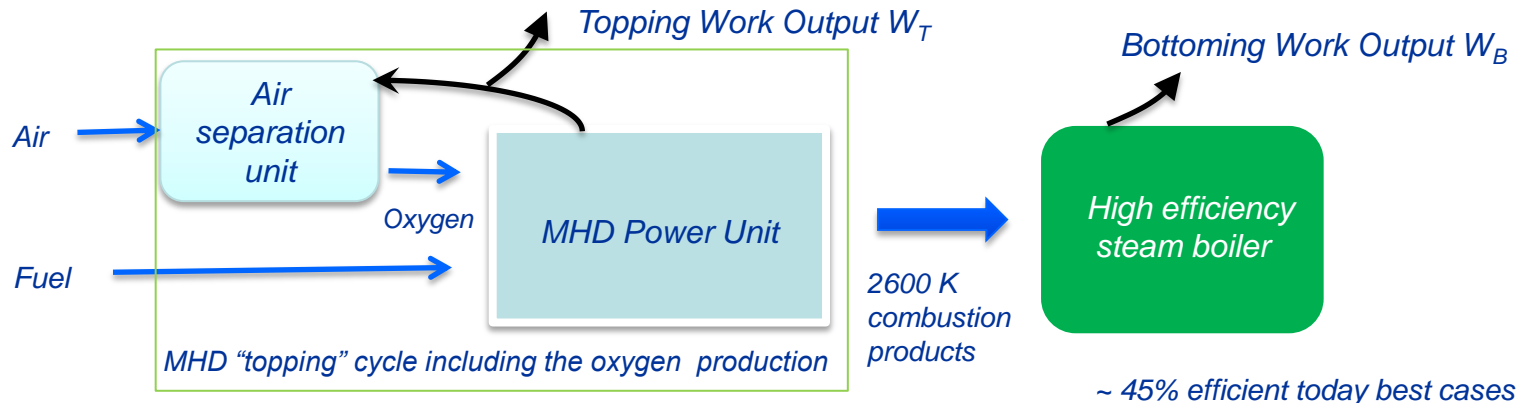


B MHD Generator



A combined cycle

- For reasons that will be clear later, most MHD concepts only produce power ABOVE ~ 2600K (which is....HOT!).
- Thus, it *needs to be* a combined cycle to extract energy from the whole temperature spectrum.



Enthalpy into the "top" = mass flow of fuel x HHV = Q

Work from the top : $W_T = \eta_T Q$

Enthalpy into the "bottom" = $Q - W_T = Q (1 - \eta_T)$

Work from the bottom: $W_B = \eta_B (\text{Enthalpy into the bottom}) = Q (\eta_B - \eta_T \eta_B)$

Combined cycle efficiency: $(W_T + W_B)/Q = \eta_T + \eta_B - \eta_T \eta_B$

Example

$$\eta_T = 0.1 \text{ (10\%)}$$

$$\eta_B = 0.45 \text{ (45\%)}$$

Combined

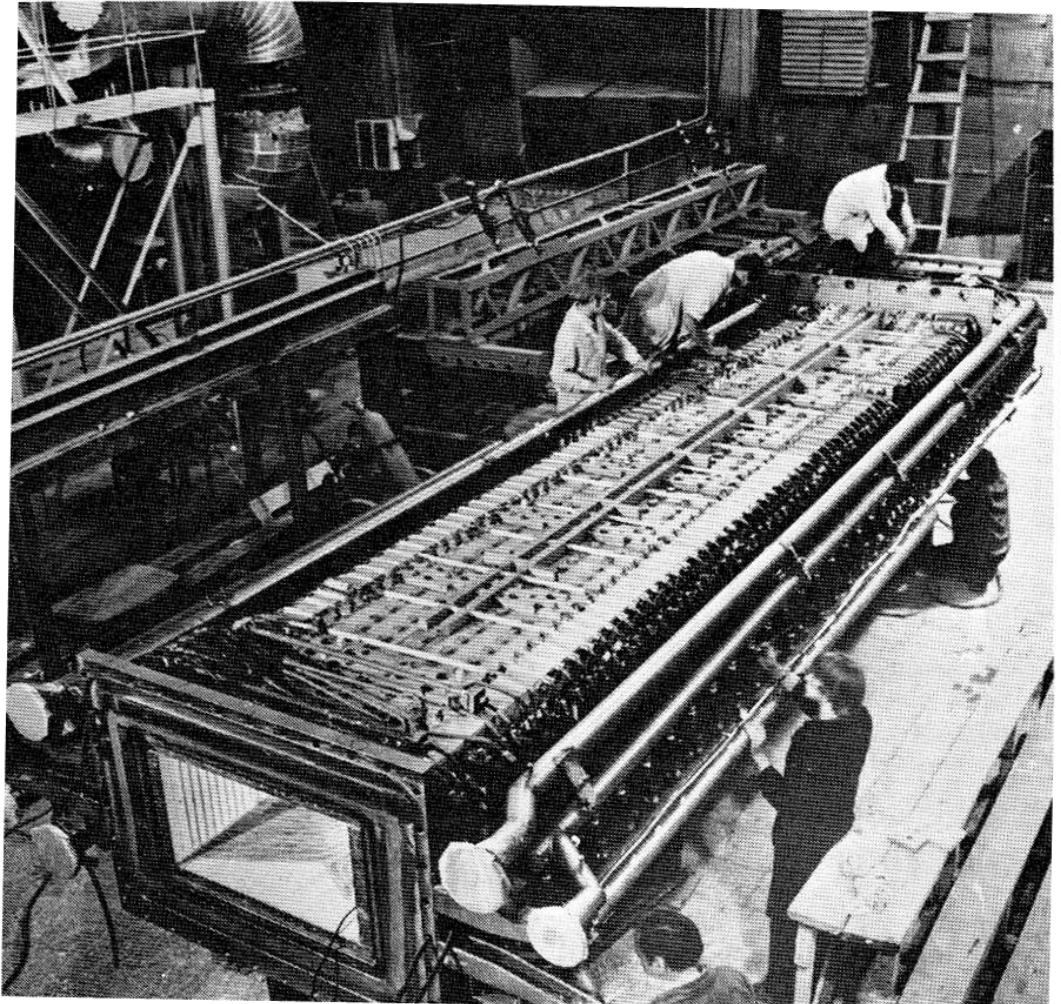
Efficiency:

$$.1 + .45 - (.1)(.45)$$

$$= 0.50 \text{ (50\%)}$$

Past MHD topping efforts

- **Concept proven in both U.S. and USSR in 70s and 80s**
 - US DOE 1978-1993
 - Electricity transferred to grid
- **Economic downfall : key factor being materials**
 - Electrode damage
 - Seed material use



*MHD U25RM diffuser channel (USSR) 1970s
From Petrick & Shumyatsky 1978.*

Direct Power Extraction

The “new” MHD: making oxy-fuel an advantage

New benefits, new approaches, new technology:

Legacy MHD program	Today	Comments
No CO ₂ capture	CO ₂ Capture	Oxy-fuel combustion developed for capture enables MHD.
Large demos	Simulation & validation	Validated models for different generator concepts, not demos.
Pre-heated air	Efficient oxygen production	ASU power requirements have dropped 40% since 1990.
SOx and NOx control	Capture GPU	No emissions! Use oxy-fuel gas processing unit (GPU).
Magnets < 6 Tesla	Magnets > 6 Tesla	Advanced magnets exist today.
Analog electronics	Solid-state inverters/control	Electrode arcing could be controlled with digital devices.
Linear generator	Radial, Linear, others	Simulations can compare multiple geometries.
Conventional manufacturing	Advanced manufacturing	New channel construction approaches.
Seeded flows	New goal: injected plasma	Aspirational – use nanosecond pulse discharge to ionize gas ?

Related technology – combustion, ionized flames, and plasma

- **Non-equilibrium plasma may benefit new aspects of combustion:**

Starikovskiy, A. Aleksandrov, N. (2013). *Plasma-Assisted Ignition and Combustion*, Progress in Energy and Combustion Science, Vol. 39, pp. 61-110.
Ignition in demanding applications - Pulse detonation engines, gas turbine re-light, HCCI engines, others

- **Alternating current excitation of flames has recently demonstrated significant hydrodynamic changes in flame structures:**

Drews, A. M., Cademartiri, L., Chemama, M. L., Brenner, M. P., Whitesides, G. M., Bishop, K. J. M (2012).
AC Electric Fields Drive Steady Flows in Flames, Physical Review E 86, pages 036314-1 to 4.

“...AC fields induce steady electric winds....localized near the surface of the flame....these results suggest that ac fields can be used to manipulate and control combustion processes at a distance....”

- **Flame ionization can be used for sensors and diagnostics.**

Benson, K., Thornton, J. D., Straub, D. L., Huckaby, E. D., Richards, G. A. (2005). Flame Ionization Sensor Integrated Into a Gas Turbine Fuel Nozzle,
ASME J. Eng. Gas Turbines and Power, Vol. 127, No. 1, pp. 42-48.

Proposes detection of dynamics and combustion conditions with flame ionization

- **New propulsion concepts include plasma - MHD “bypass” or electric thrust propulsion:**

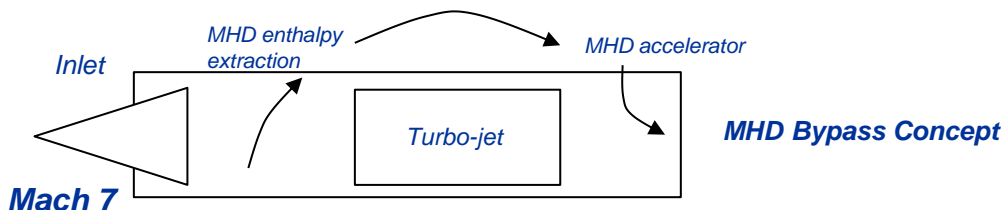
Schneider, S. (2011). *Annular MHD Physics for Turbojet Energy Bypass*, AIAA-2011-2230.

Longmeier, B. W., Cassady, L. D., Ballenger, M. G., McCaskill, G. E., Chang-Diaz, F. R., Bering, E. A. (2014). *Improved Efficiency and Throttling Range of the VX-200 Magnetoplasma Thruster*, Journal of Propulsion and Power, Vol. 30, No. 1 pp. 123 – 132.

- **Non-equilibrium plasma: a key technology for the future?**

Plasma Science: Advancing Knowledge in the National Interest (2010). <http://www.nap.edu/catalog/11960.html>

This National Academies report provides status and motivation to use plasma – including combustion applications.

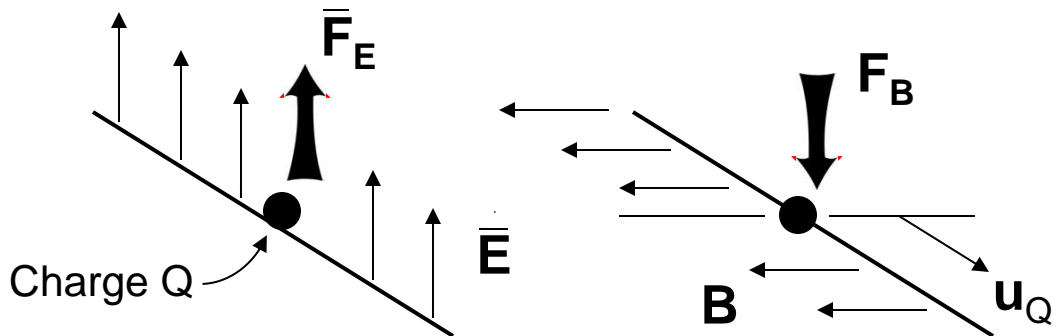


Plasma television display

http://en.wikipedia.org/wiki/Plasma_display

Fundamentals of Electromagnetics

- Electric field \mathbf{E} is a vector (units: volt/meter)
- \mathbf{E} can be described by the voltage potential V ; $\mathbf{E} = -\nabla V^*$
- By convention, minus sign means \mathbf{E} points to low voltage
- Magnetic Induction \mathbf{B} is a vector (units: Tesla = volt·sec/m²)



Experimental observations of charge Q in electric Field \mathbf{E} (left) and moving at velocity \mathbf{u}_Q in \mathbf{B} (right).

$$\mathbf{F}_E = Q \bar{\mathbf{E}}$$

Electric Force on Q

$$\therefore \mathbf{E} = \mathbf{F}_E / Q$$

$$\mathbf{F}_B = Q (\mathbf{u}_Q \times \mathbf{B})$$

Magnetic Force on Q

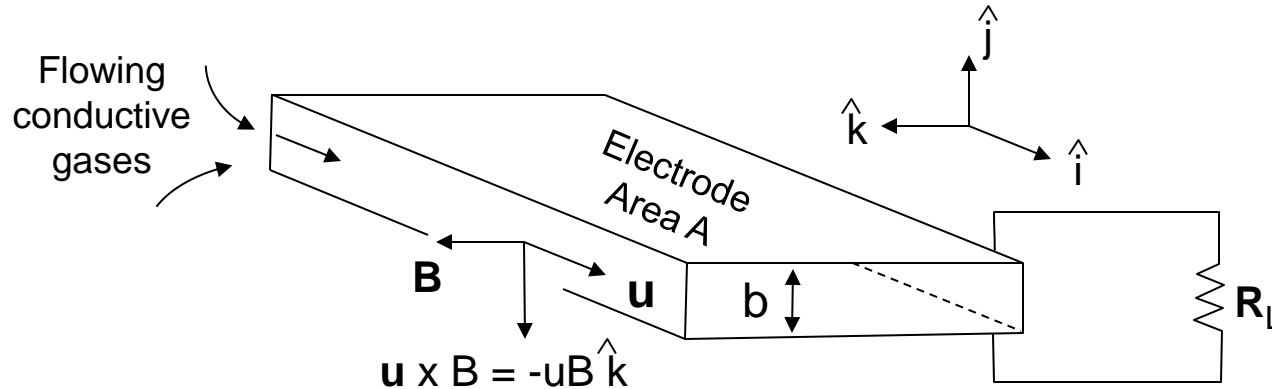
$$\therefore \mathbf{u}_Q \times \mathbf{B} = \mathbf{F}_B / Q$$

“Another” \mathbf{E} !

$$\mathbf{E}_{NET} = \mathbf{E} + \mathbf{u}_Q \times \mathbf{B}$$

* Thus in 1-D $E = -V/L$
 $L = \text{distance.}$

A Simple Generator



- Gas (conductive) flows with bulk velocity $u \hat{i}$
- Magnetic field $B \hat{k}$ is applied as shown.
- The resulting “induced” electric field is $-uB \hat{k}$
- This field can drive a current flow in the external circuit.
- How is this similar to a conventional generator?

How Much Current Flows?

The current flux is proportioned to E_{NET} :

$$\mathbf{J} = \sigma \mathbf{E}_{NET} ; \quad \sigma = \text{conductivity of media} \quad [\text{Amps}/(\text{volt}\cdot\text{meter})]$$

$$\mathbf{J} = \text{current flux vector} \quad [\text{Amps}/\text{meter}^2]$$

$$A = \text{electrode area} \quad [\text{meter}^2]$$

$$\mathbf{J} = \sigma \mathbf{E}_{NET} = \sigma (\mathbf{E}_0 + \mathbf{u} \times \mathbf{B}) = \sigma (E_0 - uB) \hat{j}$$

$R_i = b/\sigma A$ is the resistance to current flow through the plasma – shown “oddly” disconnected since uB drives current in the same place.

$$\text{From } \mathbf{E}_0 = -\nabla V \quad E_0 = - (V_L - V_H) / b$$

$$(V_L = \text{Low Voltage} \quad V_H = \text{High Voltage})$$

$$E_0 = (V_H - V_L) / b = IR_L / b \quad (\text{Ohm's Law})$$

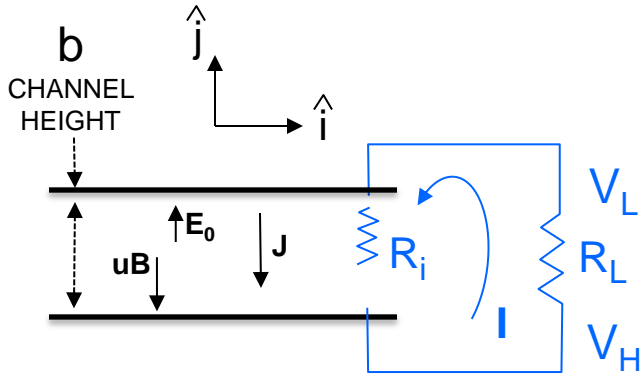
Define open circuit $R_L \rightarrow$ infinite, then $J = 0$ implies $E_0 = uB$ from above.

Then, $V_{oc} = uBb$ (open circuit voltage)

$$I = \frac{uBb}{b/\sigma A + R_L} = \frac{V_{oc}}{R_i + R_L} ; \quad R_i \equiv \text{internal resistance}$$

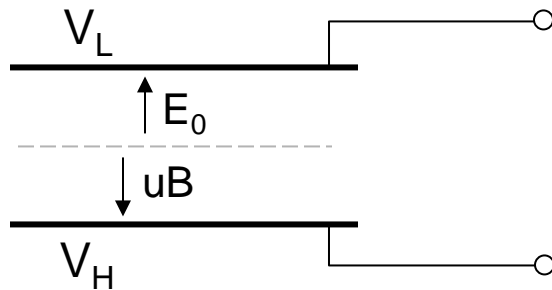
Note : as typical, V_{oc} is a voltage difference while V_H and V_L are measured relative to ground

Important Nomenclature Note:
 E_0 (zero sub) is applied by the external load & does not include magnetic induced field



SIMPLE GENERATOR FROM PREVIOUS PAGE

Limiting Cases

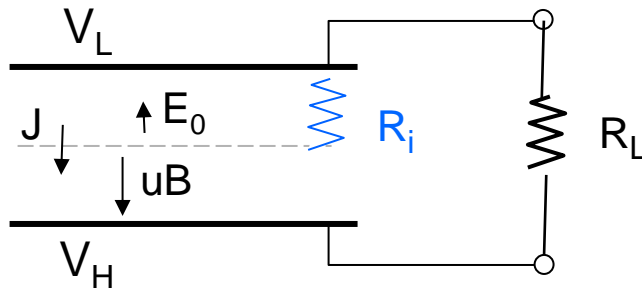


Open Circuit

$$0 = J = \sigma (E_0 - uB) \rightarrow E_0 = uB$$

$$(V_H - V_L)/b = E_0 = uB$$

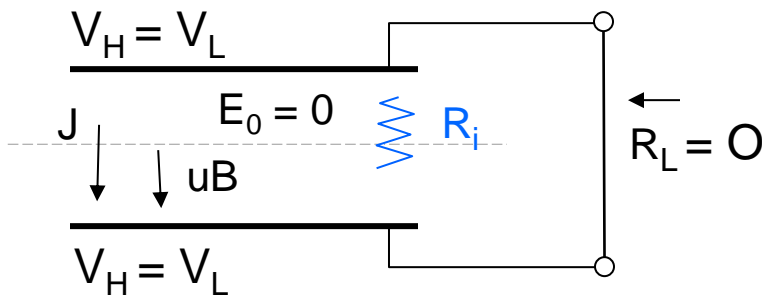
$$\therefore V_{oc} \equiv uBb$$



Generating Circuit

$$E_0 < uB; J = \sigma (E_0 - uB)$$

$$\therefore I = V_{oc} / (R_i + R_L)$$

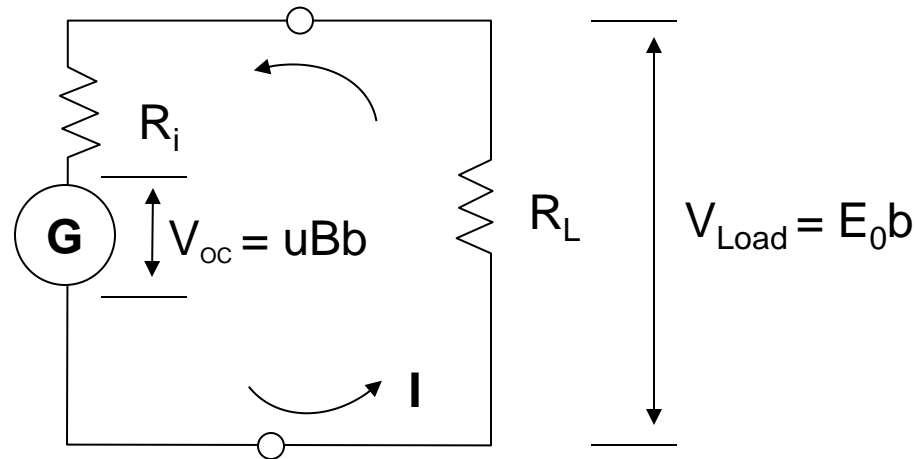


Short Circuit

$$E_0 = (V_H - V_L)/b = 0$$

$$I = \frac{V_{oc}}{R_i + R_L = 0} = \frac{V_{oc}}{R_i}$$

Electrical Analogy

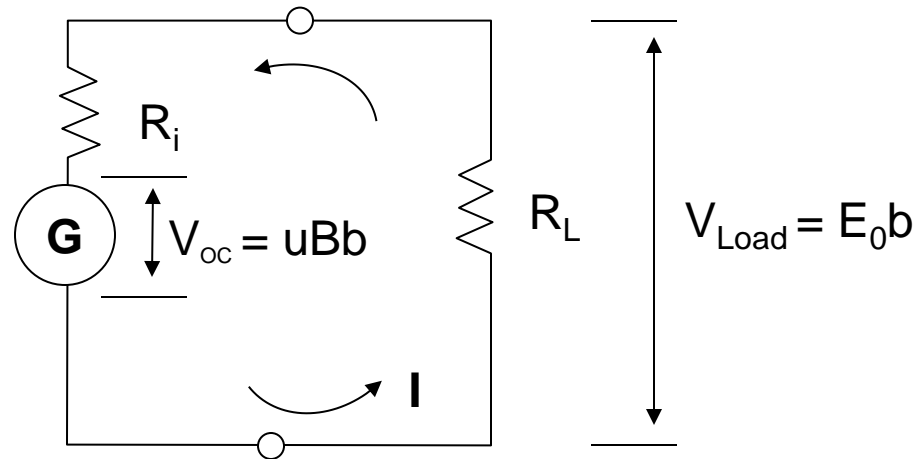


Define $K = \frac{V_{\text{Load}}}{V_{\text{oc}}} = \frac{IR_L}{I(R_i + R_L)} = \frac{R_L}{R_L + R_i} = \frac{E_0}{uB}$

Several interpretations for K:

1. Ratio of load to O.C. voltage
2. Ratio of load resistance to total resistance
3. An efficiency (why ? Multiply by $I/I \Rightarrow$ load power/total power)
4. A ratio of the “applied” field E_0 to “generated” field uB

Electrical Analogy – Power Produced



Define $K = \frac{V_{Load}}{V_{oc}} = \frac{IR_L}{I(R_i + R_L)} = \frac{R_L}{R_L + R_i} = \frac{E_0}{uB}$

The power to the load is power = (current x load voltage):

$$I = A J \quad ; \quad I = A \sigma (E_0 - uB) = A \sigma uB (K - 1)$$

$$V_{Load} = b E_0 = b uB K$$

$$\text{Power} = I \times V; \quad \text{Power} = Ab \sigma u^2 B^2 K (K - 1)$$

$$\text{Power density} = \text{Power}/(Ab) = \sigma u^2 B^2 K (K - 1)$$

Next slides - overview

What you just heard:

$$J_y = \sigma (E_0 - uB) \rightarrow \text{a simple generator}$$

What you will hear next:

- A complication arises from the Hall Effect
...the flowing current also interacts significantly with B
- Thus, we find:

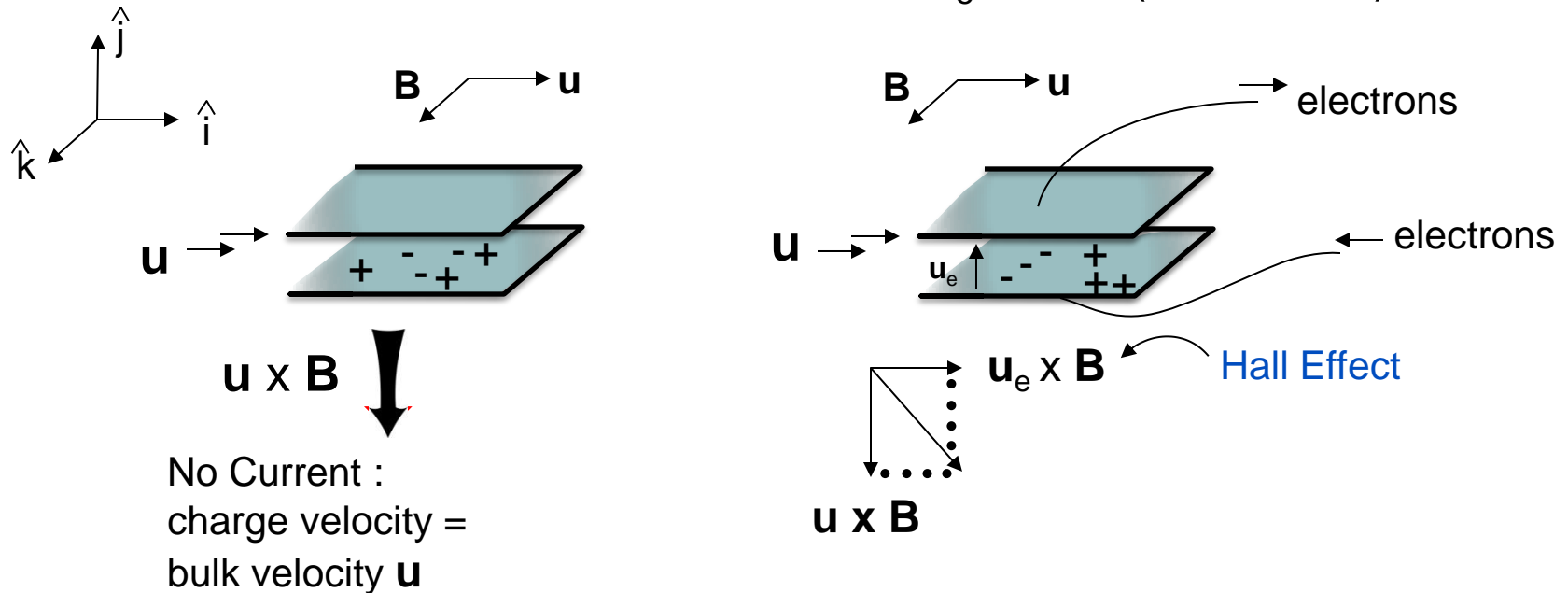
$$J_x = \frac{\sigma}{1 + \mu_e B^2} (E_{0x} - \mu_e B \{E_{0y} - uB\})$$

$$J_y = \frac{\sigma}{1 + \mu_e B^2} (\{E_{0y} - uB\} + \mu_e B E_{0x})$$

- You can impose E_{0x} or E_{0y} by applying different electrical boundary conditions via electrode geometry

Complications From the Hall Effect

- Most MHD: charge is carried by electrons
- By convention, electrons move against \mathbf{E}
- The electron current flow has an associate charge velocity \mathbf{u}_e
- Must account for the interaction between \mathbf{u}_e and \mathbf{B} (Hall Effect)

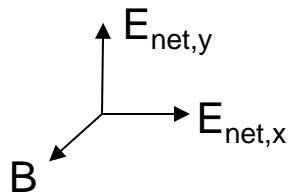


Hall Effect “Tilts” the Field – How Much?

Caution: note this is a simplification for clarity; \mathbf{u}_e may not be aligned with the y-axis

Some Cyphering

- The velocity of electrons in a field is $\bar{\mathbf{u}}_e = -\mu_e (\mathbf{E}_{\text{net}} + \mathbf{u}_e \times \mathbf{B})$ (i)
- The mobility μ_e is related to conductivity as $n_e e \mu_e = \sigma$
- The \mathbf{B} field is assumed independent of current flow $\mathbf{B} = B \hat{\mathbf{k}}$



$$\mathbf{u}_e = -\mu_e (\mathbf{E}_{\text{net},x} \hat{\mathbf{i}} + \mathbf{E}_{\text{net},y} \hat{\mathbf{j}} + \mathbf{u}_e \times \mathbf{B})$$

Also assume $\mathbf{u}_e = u_{ex} \hat{\mathbf{i}} + u_{ey} \hat{\mathbf{j}}$
 $\mathbf{J} = J_x \hat{\mathbf{i}} + J_y \hat{\mathbf{j}}$



Straightforward algebra and substitutions in equation (i).

- Notice that $J_x = -n_e e u_{ex}$; $J_y = -n_e e u_{ey}$

$$J_x = \frac{\sigma}{1 + \mu_e^2 B^2} (\mathbf{E}_{\text{net},x} - \mu_e B \mathbf{E}_{\text{net},y})$$

$$J_y = \frac{\sigma}{1 + \mu_e^2 B^2} (\mathbf{E}_{\text{net},y} + \mu_e B \mathbf{E}_{\text{net},x})$$

$$\begin{aligned} \mathbf{E}_{\text{net},x} &= \mathbf{E}_{0x} \\ \mathbf{E}_{\text{net},y} &= \mathbf{E}_{0y} - u B \end{aligned}$$

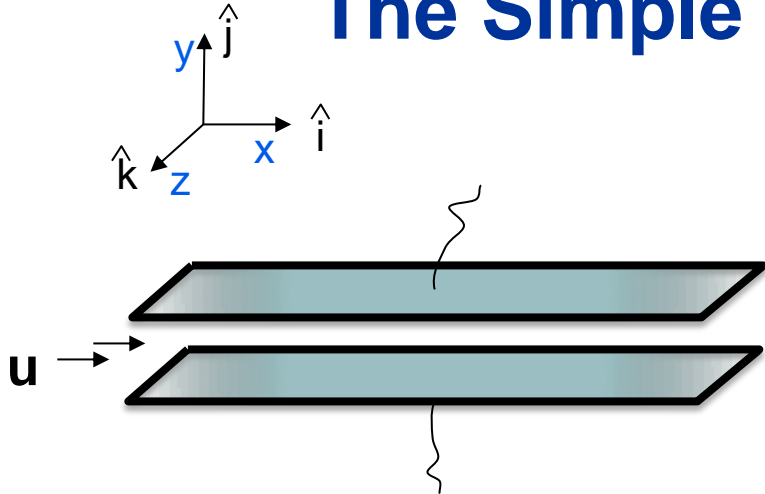
Nomenclature

n_e = electron # density (per m^3)

e = fundamental charge $1.602 \text{ E-}19 \text{ C/electron}$

μ_e = electron mobility $\frac{\text{m}}{\text{s}} / \frac{\text{V}}{\text{m}}$

The Simple Faraday Generator



- The electrodes are long, continuous
- Thus, $E_{0x} = 0$

$$J_y = \frac{\sigma}{1 + \mu_e^2 B^2} (E_{y,\text{net}}) = \frac{\sigma}{1 + \mu_e^2 B^2} (E_{0y} - uB)$$

Notice that the simple generator analysis (without Hall Effect) gave

$$(J_y)_{\text{No Hall}} = \sigma (E_{0y} - uB)$$

Thus, the Hall Effect reduces the y- current by: $\frac{1}{1 + \mu_e^2 B^2}$

What is the magnitude of meaning of J_x ?

$$J_x = \frac{\sigma}{1 + \mu_e^2 B^2} (0 - \mu_e B E_{\text{net},y}) = \frac{\sigma}{1 + \mu_e^2 B^2} (-\mu_e B [E_{0y} - uB]) = -\mu_e B J_y$$

The Hall effect leads to an x-current that is $\mu_e B$ times the y-current.

How big is $\mu_e B$? (Next Slide)

The Magnitude of $\mu_e B$

Consider the x-direction force on the electron between collisions time τ

$$F_e = m_e \frac{du_e}{dt} ; -eE_x \cong m_e \left(\frac{\mu_e u_{e, \text{mean}}}{\tau} \right) \quad \text{(i)}$$

But, we also write: (ii)

$$- \mu_e E_x = u_{e, \text{mean}}$$

Combining (i) and (ii) : $\mu_e = \tau e / m_e$ (iii)

We can also express a magnetic field in terms of a “cyclotron frequency” ω , next:

$$\mathbf{F}_B = -e(\mathbf{u}_e \times \mathbf{B})$$

In the absence of other forces/collisions, the electron will experience a force at right angles to its motion \Rightarrow circular orbit r_L , consider the force:

$$F_B = - m_e u_e^2 / r_L$$

$$-e u_e B = -m_e u_e^2 / r_L \Rightarrow \frac{u_e}{r_L} \frac{m_e}{e} = B$$

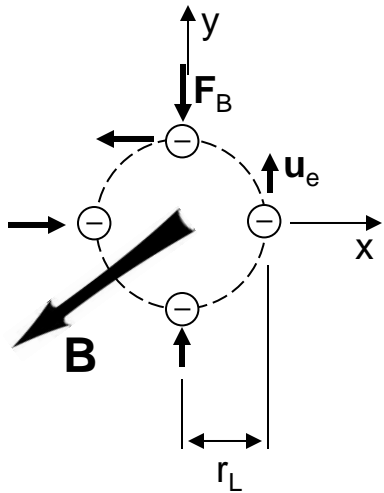
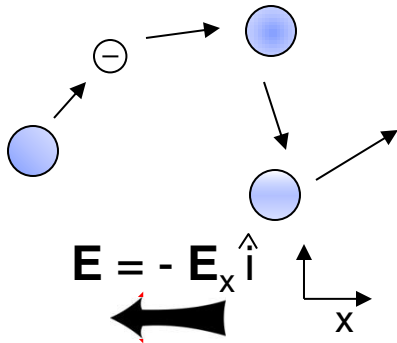
Define cyclotron frequency
 $\omega = u_e / r_L \Rightarrow B = \omega m_e / e$ (iv)

Combine (iii) and (iv) : $\mu_e B = \omega \tau$ *“Hall parameter”*

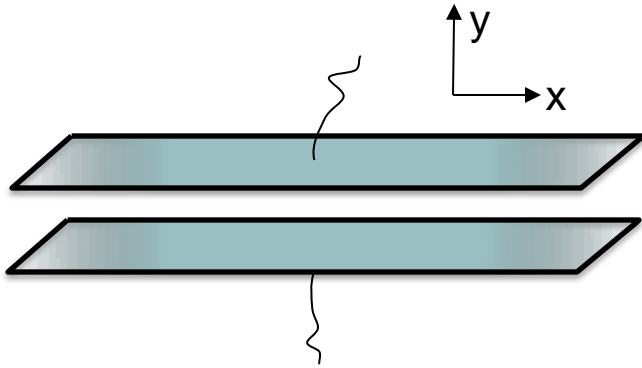
$\omega \tau \gg 1 \Rightarrow$ lots of cycles before collisions

$\omega \tau \sim 1 \Rightarrow$ collide \sim one cycle

$\omega \tau \ll 1 \Rightarrow$ lots of collisions before a cycle is complete



Return to Faraday Generator



With $\mu_e B = \omega\tau$: Recall $K = \frac{E_{0y}}{uB}$

$$J_y = \frac{\sigma}{1 + (\omega\tau)^2} [E_{0y} - uB] = \frac{\sigma uB}{1 + (\omega\tau)^2} (K - 1)$$

$$J_x = \omega\tau (J_y)$$

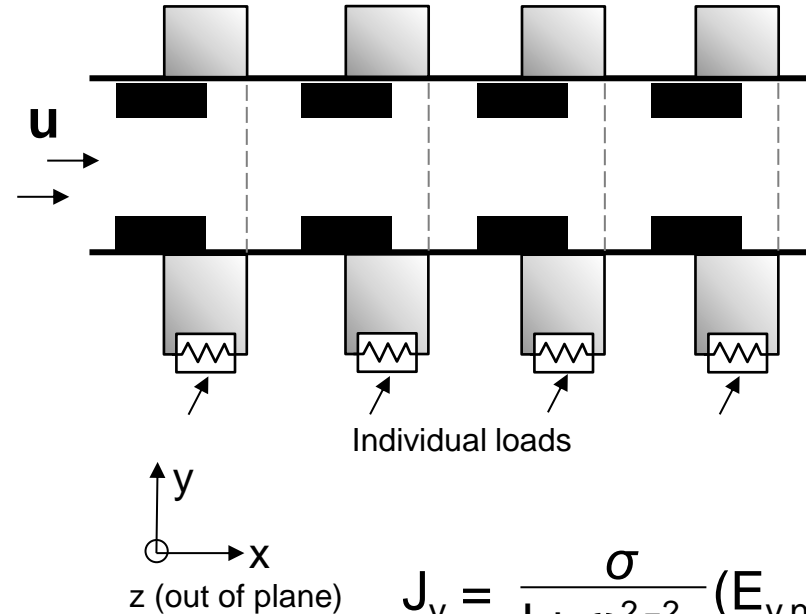
For practical MHD $1 < \omega\tau < 10\dots$ implies:

- 1) Significant reduction in J_y versus “simple” model
- 2) Large axial (x) current flow – creates ohmic losses

How could you improve this situation?

Segmented Electrodes

Break up the x-current so that $J_x = 0$:
(why does this stop the Hall current?)*



$$J_x = \frac{\sigma}{1 + \omega^2 \tau^2} (E_{x,\text{net}} - \omega \tau E_{y,\text{net}}) = 0 \quad (1)$$

$$J_y = \frac{\sigma}{1 + \omega^2 \tau^2} (E_{y,\text{net}} + \omega \tau E_{x,\text{net}}) \quad (2)$$

$$\text{From (1): } E_{x,\text{net}} = \omega \tau E_{y,\text{net}} \quad (3)$$

\Rightarrow

$$J_y = \frac{\sigma}{1 + \omega^2 \tau^2} (E_{y,\text{net}} + \omega^2 \tau^2 E_{y,\text{net}}) = \frac{\sigma E_{y,\text{net}}}{1 + \omega^2 \tau^2} (1 + \omega^2 \tau^2)$$

$J_y = \sigma E_{\text{net},y} = \sigma (E_o - uB)$ Same as “simple” generator

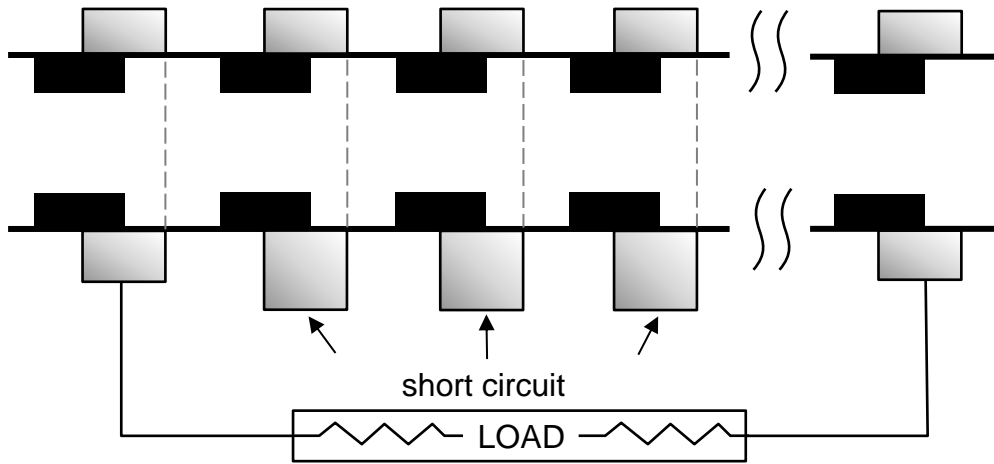
Notice that the axial voltage gradient is potentially very large (eqn. 3)

What practical disadvantages exist with this concept?

* It has no return path.

Hall Generators

Here, you use the axial hall current for power. Notice $E_{y0} = 0$ by short circuit.

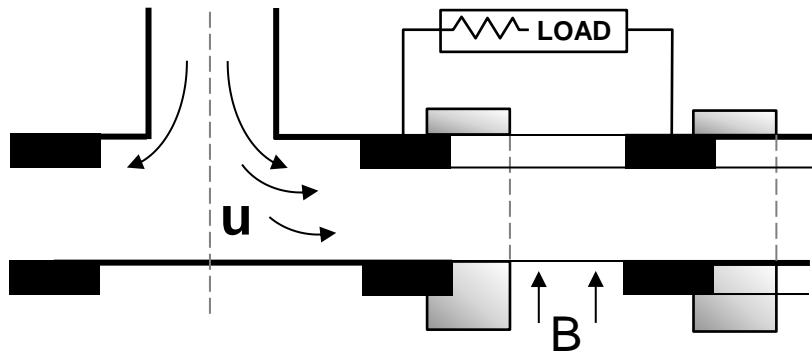


(applied) $E_{y,net} = E_{y0} - uB$

Solve for currents and voltage as before.

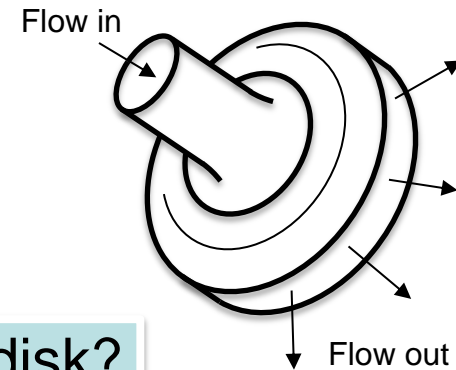
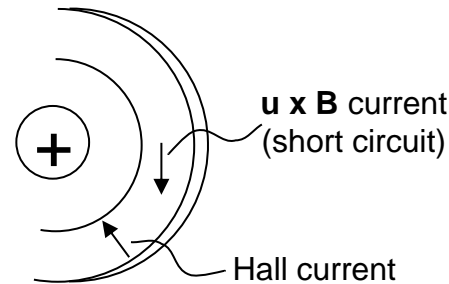
$E_{oc} = -\omega\tau uB$ open circuit

Disk Geometry (very clever!)



Notice the open circuit voltage is larger than uB

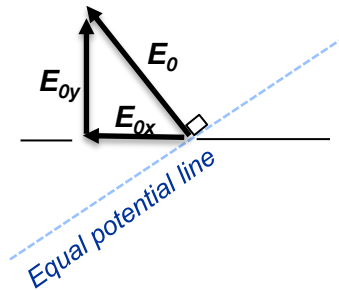
$\therefore K_H = -E_{ox} / \omega\tau uB$ (Defined)



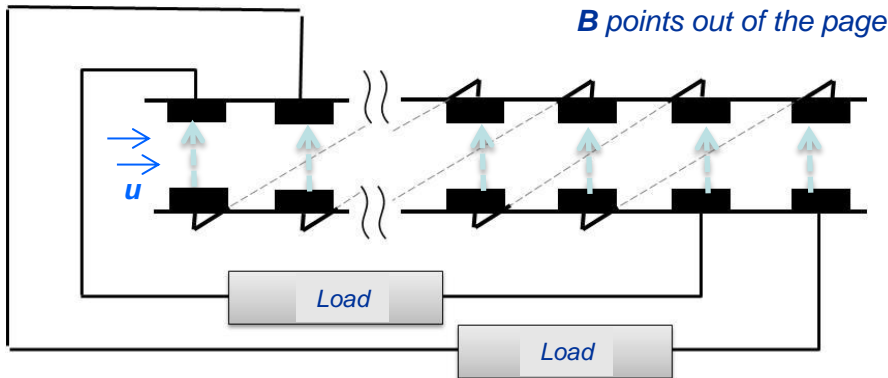
State one huge practical advantage of the disk?
(Hint: count the number of wires)

An intermediate approach: Slanted (diagonal) electrode connections

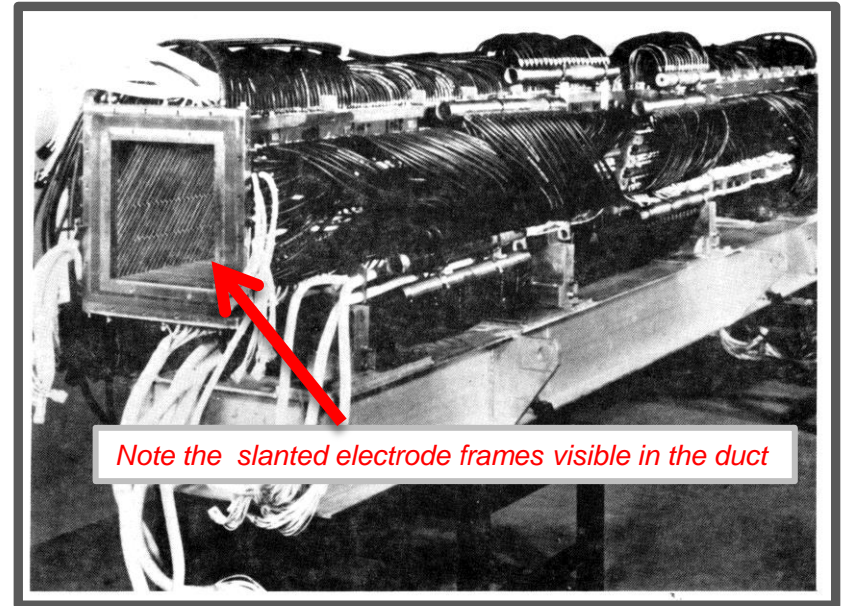
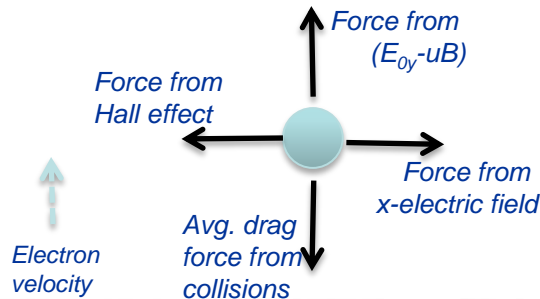
- Electrode connections establish E_{0x} and E_{0y} so that the electrons experience a force from the Hall field that is balanced by the E_{0x} imposed by the electrodes.
- Thus, the current only flows vertically in the channel.
- This balance exists at just one operating condition.



Note that the E_{net} includes $-uB$ in the y-direction. The electrons move vertically in response to $(E_{0y}-uB)$



See Hill and Peterson
"Mechanics and
Thermodynamics of
Propulsion" Third Printing,
1970, Addison-Wesley
Publishing, pp. 122. Helpful
discussion of the force
balance.



Note the slanted electrode frames visible in the duct

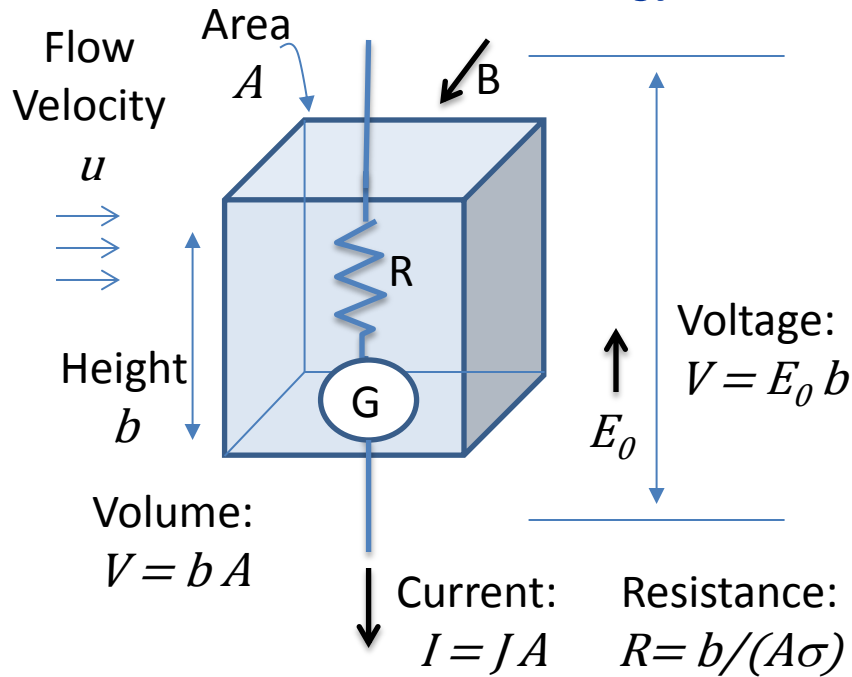
From: Quarterly Technical Progress Report, July 1 – Sept 30, 1985, Component Development and Integration Facility
Work performed under DOE DE-AC07-781D01745; Original Reports currently available only at NETL.

Fluid mechanics and thermodynamics



1-D Energy Balance

Treating J as a negative scalar (current flowing down):



Ohmic loss:

$$I^2 R = \frac{A^2 J^2 b}{A \sigma} = V \frac{J^2}{\sigma} \quad \begin{array}{l} \text{per} \\ \text{unit} \\ \text{volume:} \end{array} \quad \frac{J^2}{\sigma} \quad (i)$$

Electrical power output from the volume:

$$I V = A (-J) E_0 b \quad \begin{array}{l} \text{per} \\ \text{unit} \\ \text{volume:} \end{array} \quad -J E_0 \quad (ii)$$

Note: in a 2 or 3D problem the output is the dot product of vectors $-J \cdot E_0$. Care must be used on the sign of scalars in simple balance laws, and distinguishing output (MHD generator) versus input (MHD pump)

Mechanical energy input to the volume (x-body force times x-velocity u):

$$\begin{array}{l} \text{x-body force} \\ \text{per unit volume:} \end{array} \quad (n_e(Q)\{\mathbf{u}_e + \mathbf{u}\} \times \mathbf{B} \cdot \hat{\mathbf{i}}) = (n_e(Q)\mathbf{u}_e \times \mathbf{B} \cdot \hat{\mathbf{i}}) = \mathbf{J} \times \mathbf{B} \cdot \hat{\mathbf{i}}$$

Charges per unit volume *Force on a charge $Q = (-e)$* *Note \mathbf{u} has only x-component;* *The vector product points left*

$\mathbf{u} \times \mathbf{B} \cdot \hat{\mathbf{i}} = 0$

Thus, mechanical energy input per unit volume: $-J B u$ (iii)

Use the earlier definition of load factor K ; recall $0 < K < 1$, use (i - iii)

$$K = E_0 / (u B) ; J = \sigma u B (K - 1)$$

$$\begin{array}{l} (1) \text{ohmic loss} = \sigma u^2 B^2 (K - 1)^2 \\ (2) \text{electrical power out} = -\sigma u^2 B^2 K (K - 1) \\ (3) \text{mech power input} = -\sigma u^2 B^2 (K - 1) \end{array}$$

As expected : (1) + (2) = (3)

A summary of mass, momentum and energy

(1-D simplification, steady flow, constant area duct, neglect thermal conduction and viscous effects)
For a comprehensive development of the governing equations, see for example: Hughes W.F., Young, F. J. (1989). *The Electrodynamics of Fluids*, 2nd Edition, Robert E. Krieger Publishing.

Again, treat J as a negative scalar

$$\frac{d(\rho u)}{dx} = 0 \quad \text{Continuity: Familiar}$$

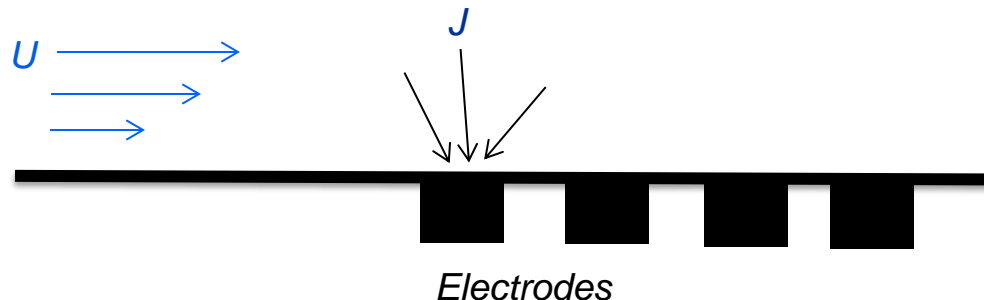
$$\frac{dP}{dx} + \rho u \frac{du}{dx} = J B \quad \text{Momentum eqn: Note } JB \text{ is the body force from last page.}$$

With negative J , what does this do to pressure along X ?

$$\rho u C_p \frac{dT}{dx} + \rho u^2 \frac{du}{dx} = -(-J E_0)$$

= - (output)

Energy eqn: note this is written with the source term (right side) as the negative of the output defined on the last page. What does the source term do to the enthalpy of the flow along X ?



The real situation:
Describe the flow near the electrodes?

Conductivity in the gaseous media

- In conventional electrical generators, a long copper wire moves at a relatively slow speed through a modest magnetic field.
- The conductivity of the gases in MHD is comparatively low, even when “seeded”, next slide.
- MHD power extraction is practical only because of the high velocity U , strong field B , large volume conductor, and “adequate” conductivity

$$\text{Power output density} = -J \cdot E_0 = -\sigma U^2 B^2 K (K-1)$$

$$\text{Copper} \quad \sigma \quad \sim = 6 \times 10^7 \text{ Siemen/m}$$

$$\text{Seeded MHD} \quad \sigma \quad \sim = 10 \text{ Siemen/m}$$

Siemen = 1/ohm

Gas Conductivity: Seeding

Current flow depends on conductivity $J = \sigma E$

Simple generator: Power density

$$P = -J \cdot E_0 = -\sigma U^2 B^2 K (K-1)$$

The power density is maximum at

$$K = 1/2 \quad \therefore \quad P_{\max} = \sigma U^2 B^2 / 4$$

Reasonable Design:

$$10\text{MW/m}^3 = P_{\max}; \quad UB = 2000\text{V/M}$$

$$\sigma \approx 10 \text{ S/m} \quad (\text{S=Siemen} = 1/\text{ohm})$$

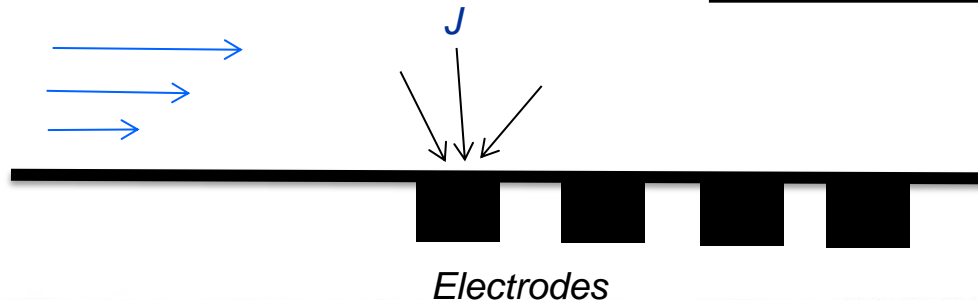
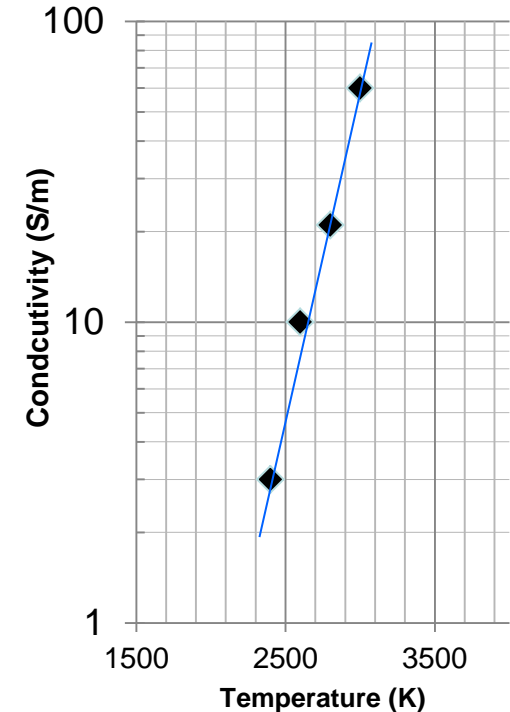
Two points:

1. The magnitude of the conductivity with temperature: operating temp $\sim > 2600\text{K}$
2. The slope versus temperature: very sensitive

Ionization Potentials

Species	Ionization potential E_i (eV)
Li	5.39
Na	5.14
K	4.34
Cs	3.89
He	24.58
Ne	21.56
A	15.76
H ₂	15.6
O ₂	12.05
O	13.61
N ₂	15.6
NO	9.26
CO	14.1
CO ₂	14.4
H ₂ O	12.6
OH	13.8
U	6.1

Data from Swithenbank, J, (1974), *Magnetohydrodynamics and Electrodynamics of Combustion Systems*, in "Combustion Technology: Some Modern Developments" Palmer, H.B., Beer, J.M. [eds] Academic Press. Conductivity is for JP4-oxygen combustion products with 1% K seed.

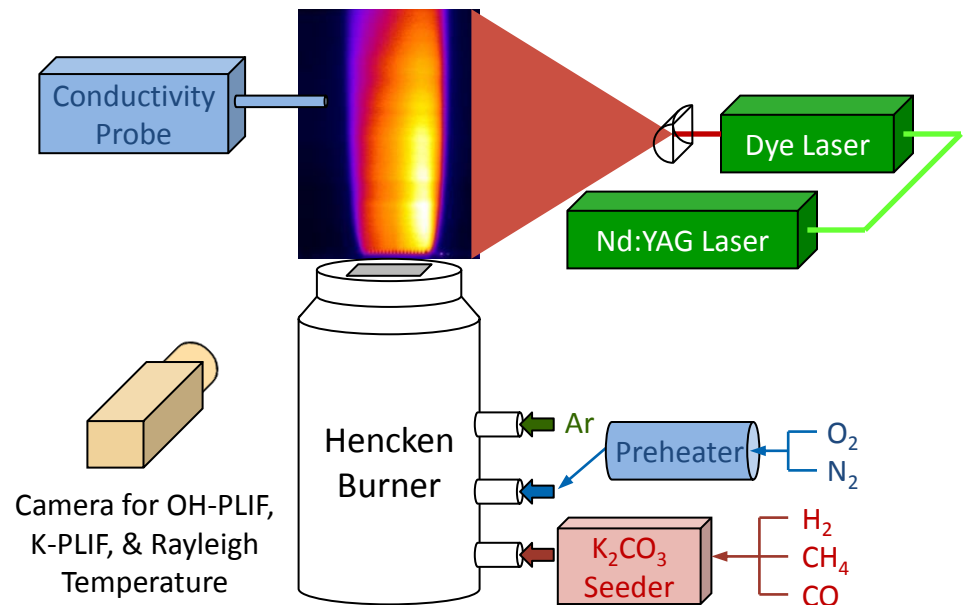
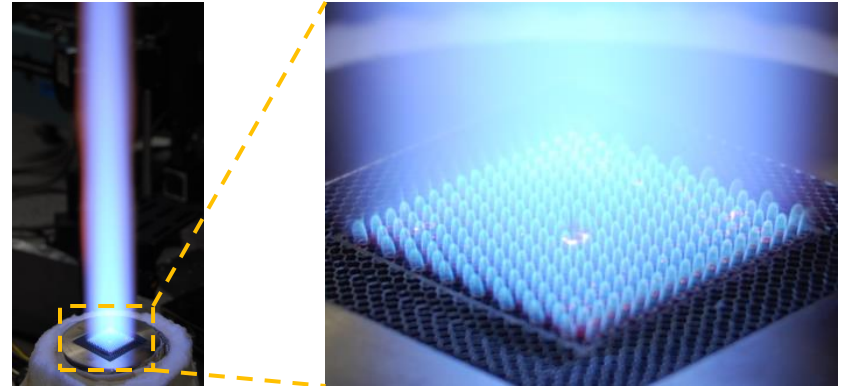


The real situation:
Describe the conductivity near the electrodes?

Plasma Conductivity Experiments

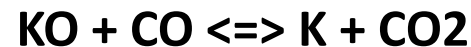
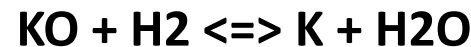
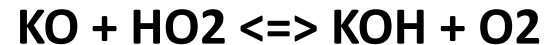
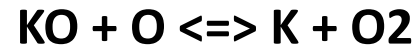
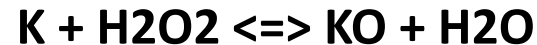
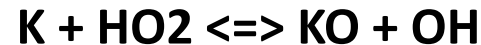
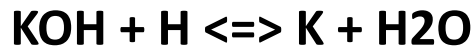
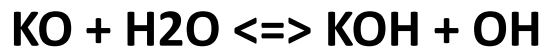
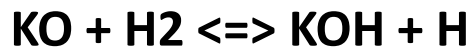
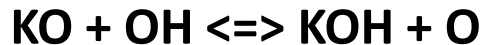
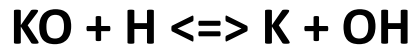
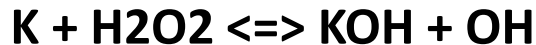
Fundamental Combustion Lab – NETL

- **Oxy-methane Hencken burner used for high temperature (~3000 K) flame generation**
 - Began operation in Feb 2014
- **K_2CO_3 seeded in fuel ionizes to create thermal plasma**
 - K seed density quantified via K-PLIF or spectroscopy
- **Conductivity measured point-wise with Langmuir probe**
- **Nd:YAG and dye lasers for optical diagnostics**
 - Rayleigh thermometry temperature measurement
 - Quantitative OH-PLIF



Reaction Mechanism

- Elements K and e (Electron) added
- Species K, K+, KO, KOH, OH-, and Electron added
- K/O/H reaction data added from: P. Glarborg, P. Marshall, “Mechanism and modeling of the formation of gaseous alkali sulfates”, *Combustion and Flame* 141, 22-39 (2005)

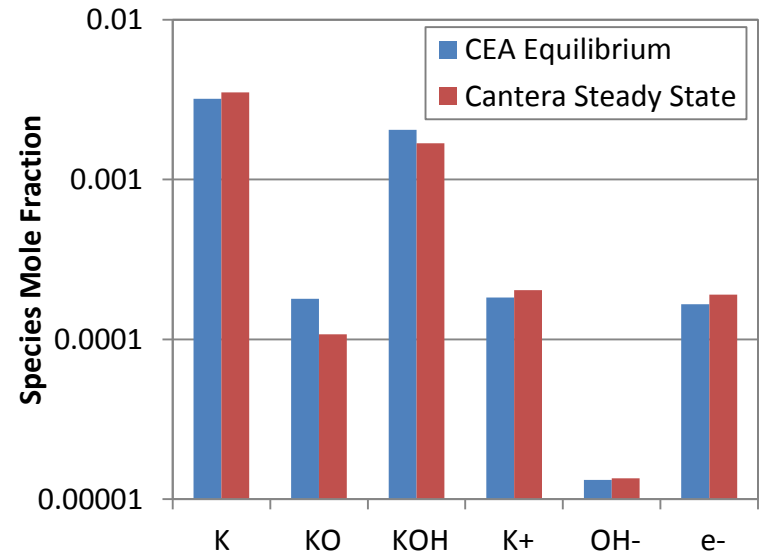
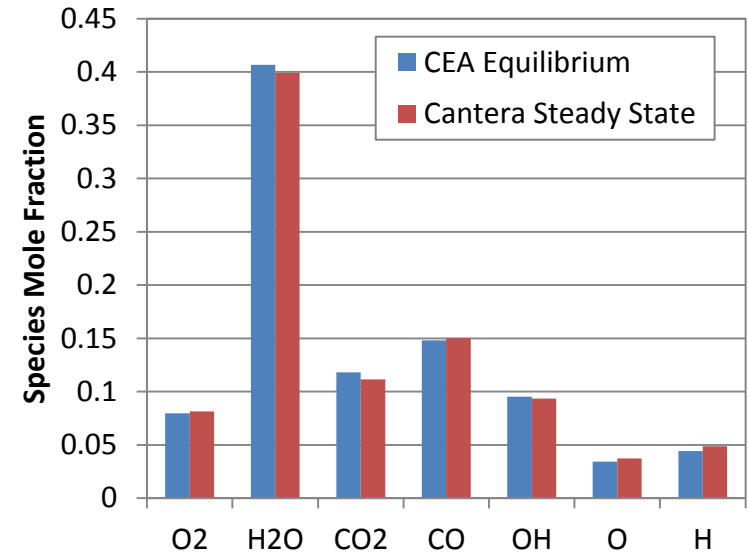
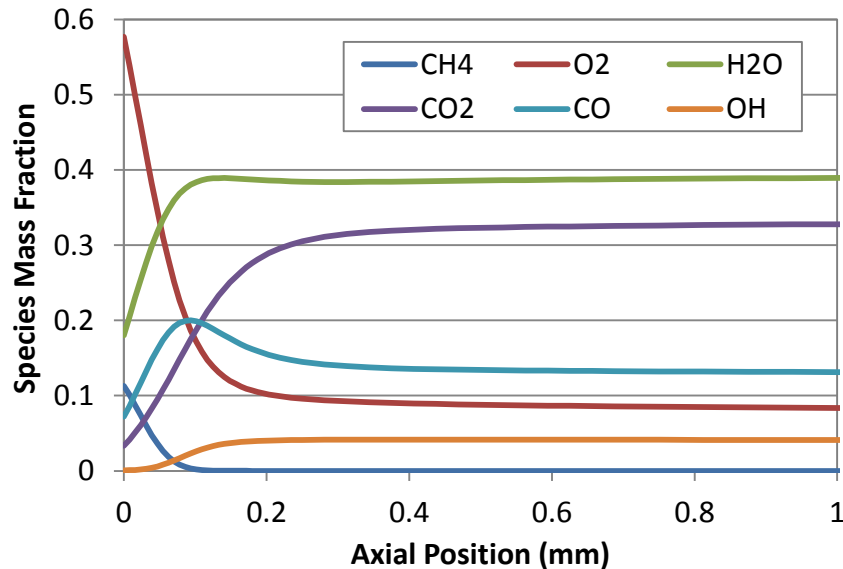


- Ionization reaction data added from: D.E. Jensen, G.A. Jones, “Reaction rate coefficients for flame calculations”, *Combustion and Flame* 32, 1-34 (1978)



1-D Flame Modeling in Cantera

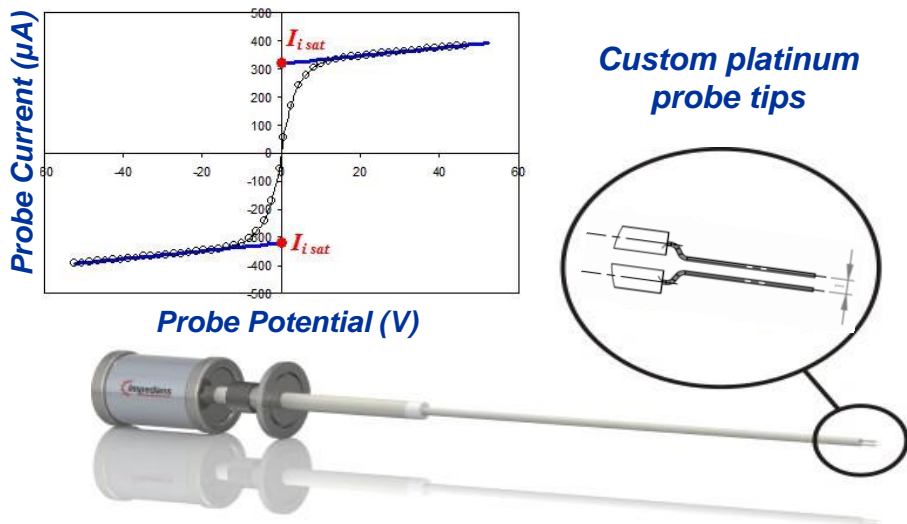
- **Steady state simulation composition matches CEA equilibrium fairly well; Cantera case is burner stabilized flame, noting $T < T_{ad}$:**
 - CEA: 3022 K
 - Cantera: 2815 K (burner stabilized heat loss)
- **Major species reach equilibrium in <1 mm**



Conductivity & Seed Density Measurements

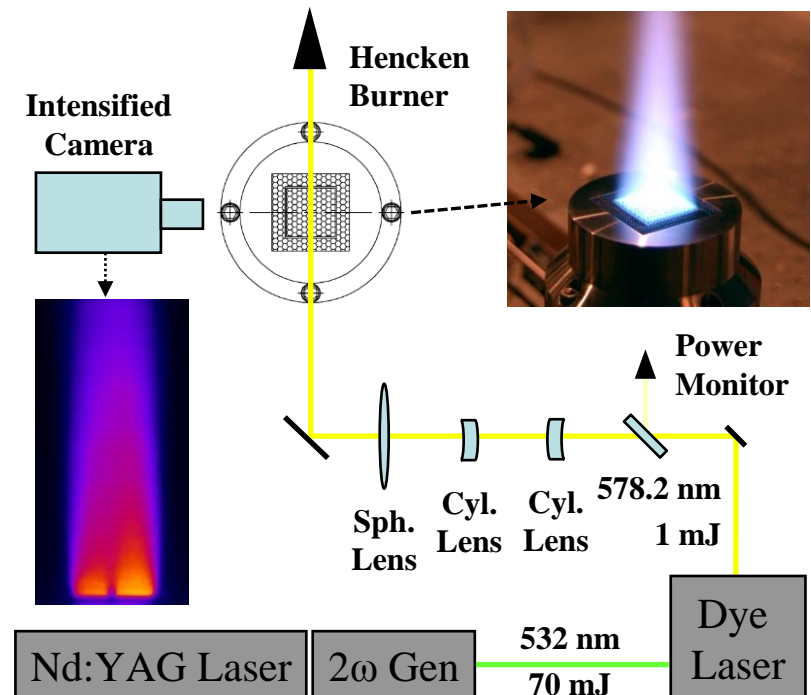
- **Conductivity Measurements**

- Using a commercial Langmuir Double Probe from Impedans, Ltd.
- Custom shaped platinum probe tips to achieve 1 mm² resolution in flame
- Shape of induced current profile vs. probe voltage differential used to obtain electrical conductivity, electron temperature, and ion density (Osaka, 2008; Wild, 2012)



- **K-PLIF Imaging**

- Need quantitative measure of seed density for correlation to plasma conductivity
- K-PLIF used by Lengel & Linder (1990)
- Use K-atom transition at 578.2 nm (Monts, 1995) with existing laser dye



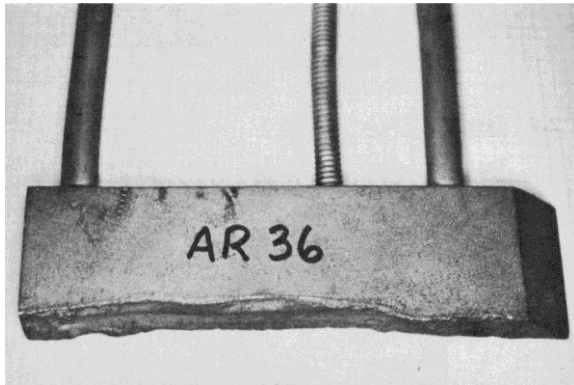
Seeding – not the same today?

- Seeding is used to raise the conductivity of the combustion products.
- The seed recovery was a major cost item and technical barrier in earlier MHD programs.
- Would this change in a carbon capture scenario where the entire flue gas was sought for capture?
- Non-equilibrium plasma generated would be a game changer if :
 - Energy to generate was low enough.
 - Recombination rate was low.
 - Studies for propulsion applications, using nano-second discharge pulses: about 2 order of magnitude greater ionization needed (?)*

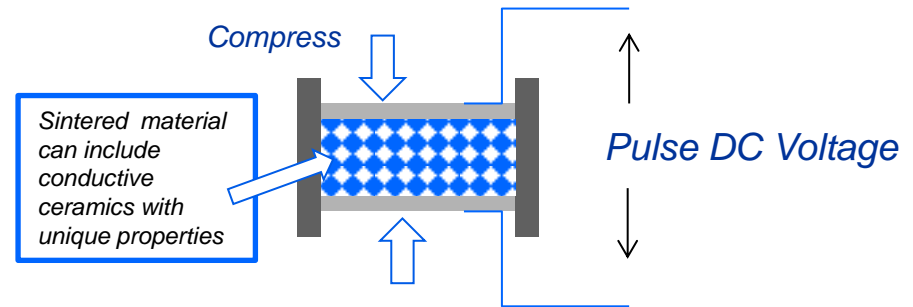
* Schneider, S. (2011). *Annular MHD Physics for Turbojet Energy Bypass*, AIAA-2011-2230

Electrodes

- Cooled electrodes must operate with high surface temperature to reduce quenching conductivity and heat loss near the walls.
- Complicated by thermal, chemical, and electrical attack.
- Some tests suggest reasonable life is possible in slag free (gas fuel operation) or with better slag removal.
- Advances in materials and material processing for conductive solid oxides – Field Assisted Sintering Technology- currently under investigation at NETL.
- Current instability can lead to arcing – concentrated current flows – burning the surface.
 - State of the art electronics may reduce this problem



Cooled electrode from legacy test program,
Damage from arcing evident.



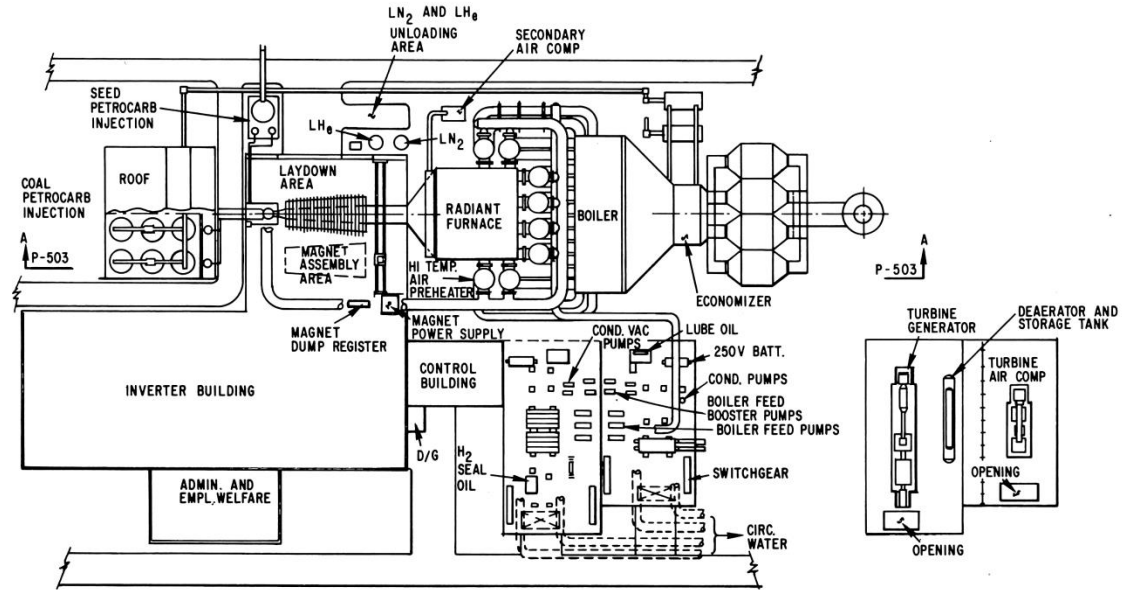
S. Chanthapan, A. Rape, S. Gephart, Anil K. Kulkarni, J. Singh (2011). Industrial Scale Field Assisted Sintering Is an Emerging Disruptive Manufacturing Technology *ADVANCED MATERIALS & PROCESSES*, pp. 21-26, Published by ASM.

Layout of a Power Plant Configuration

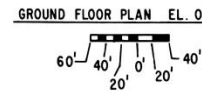
What would be different in a carbon capture scheme?

What might be removed for future electric grids?

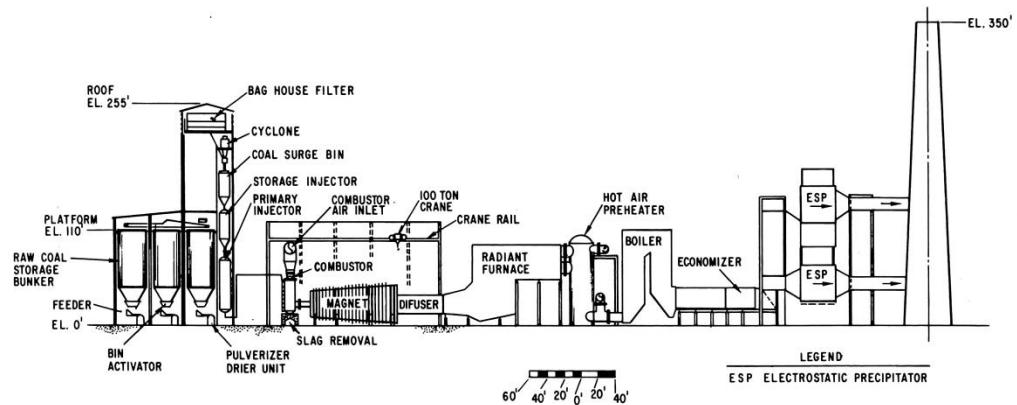
General arrangement plan and elevation view for the MHD plant



- LEGEND
- ESP ELECTROSTATIC PRECIPITATOR
 - D/G DIESEL GENERATOR
 - COMP. COMPRESSOR
 - LN₂ LIQUID NITROGEN
 - LH₆ LIQUID HELIUM



PLAN AT EL. 51'
ONLY TURBINES SHOWN



- LEGEND
- ESP ELECTROSTATIC PRECIPITATOR

Petrick, M., Shumyatsky, Y.A. (1977)

Research issues/ideas

- **Various literature citations suggest different efficiency benefits of the concept.**
 - *Enthalpy extraction* from the combustor to MHD exit is a key.
 - Conductivity vs. temperature in existing concepts limits on the enthalpy extraction.
 - Kayukawa (2004) reviews some interesting options for efficiency gains.
- **The actual component behavior and performance needs to be understood before development is pursued.**
 - A ideal application for cybercombustion!
 - Validated simulations – where do we get the data to validate?
- **Can we develop a different approach for *Direct Power Extraction*?**
 - Unsteady flow (e.g. – periodic)?
 - Non-equilibrium plasmas – how about behind a detonation?

Kayukawa, N. (2004). Open-Cycle magnetohydrodynamic power generation: a review and future perspectives. Progress in Energy and Combustion Science, Vol 30, pp. 33-60.

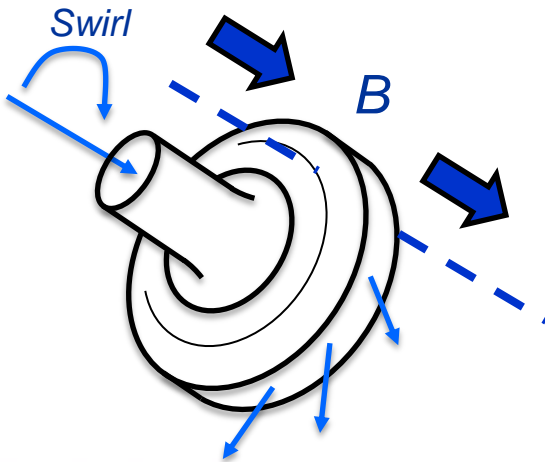
MHD literature background – A source of validation data?

- **The legacy MHD program was managed by DOE's PETC (NETL predecessor).**
 - In 1994, Congress wanted DOE to archive the information learned in the program so “costs and time to reestablish a viable MHD effort could be minimized”
 - Ninety boxed documents scanned and digitized at NETL during 2013.
 - This may be the largest set of information on MHD (for power) anywhere.
 - Contact NETL for information/access.

Discussion/thinking/homework

1. Using a simple drawing, show what can happen to the Hall current in a Disk Generator what you add swirl to the inlet flow?
2. Go to the internet and find the account of Michael Faraday trying to measure MHD voltage in the Thames river.
 - Estimate the voltage he should have measured?
 - Can you think of any other situations in nature where MHD physics might be significant?

Disk generator



Summary

- **Direct Power Extraction** from high-temperature oxy-fuel flames is possible using magnetohydrodynamics.
- The concept has been explored in the past.
- New drivers of CO₂ capture and progress in oxy-fuel combustion suggest a “new look” may be worthwhile.
- **In a combined cycle, the efficiency could be very high, but:**
 - Power extraction is limited by conductivity versus lower temperature for traditional seeded flows
 - Need to address technical challenges of seed recovery, electrode life....or find a new innovation!
- **Computational models offer a new approach to development that did not exist in earlier programs.**
- **In progress: Simulations and validating experiments with new technologies, material processes.**