New Developments in Combustion Technology

Part III: Making oxy-fuel combustion an advantage

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Today's presentation

- **New approaches in three ways**
  - Inherent carbon capture: chemical looping combustion.
  - Step-change in generator efficiency: pressure gain combustion
  - Frontier approach (?): making oxy-fuel an efficiency advantage.

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.**

1 mole of air

0.21 moles oxygen
p_{O2} ***= 0.21 atm***

0.79 moles nitrogen
p_{N2} ***= 0.79 atm***

Air Separation Unity ***(ASU)***

0.21 moles oxygen
p_{O2} ***= 1 atm***

Dilute again with CO_2 or steam

0.79 moles nitrogen
p_{N2} ***= 1 atm***

Reversible separation work:
*~6 kJ/gmol O_2 produced**

Current actual process:
*~18kJ/gmol O_2 produced***

$$C + O_2 \rightarrow CO_2$$

*$\Delta H \sim \Delta G$ = 394 kJ/gmol (C **or** O_2)*

In efficient powerplants we convert less than ½ of ΔH to work.
Thus~200kJ/gmol O2 work produced

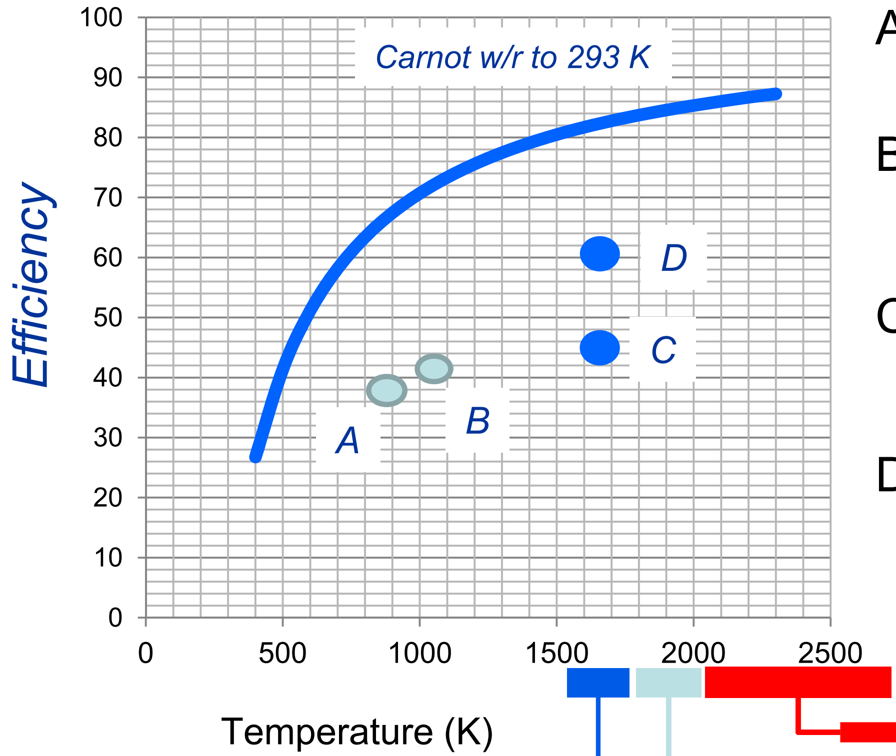
Roughly ~1/10 of that is needed for ASU.

**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.

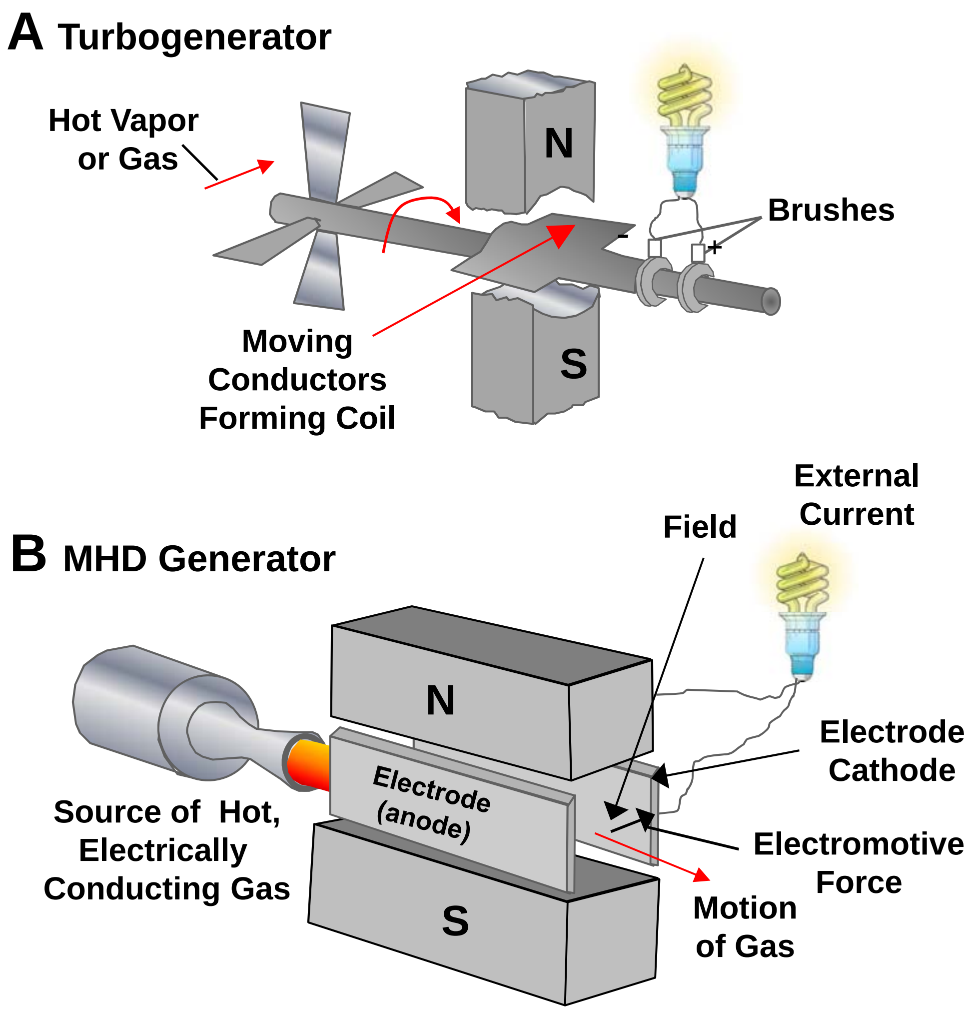
Gas Turbine Combustion Temp. = Working fluid temp.

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

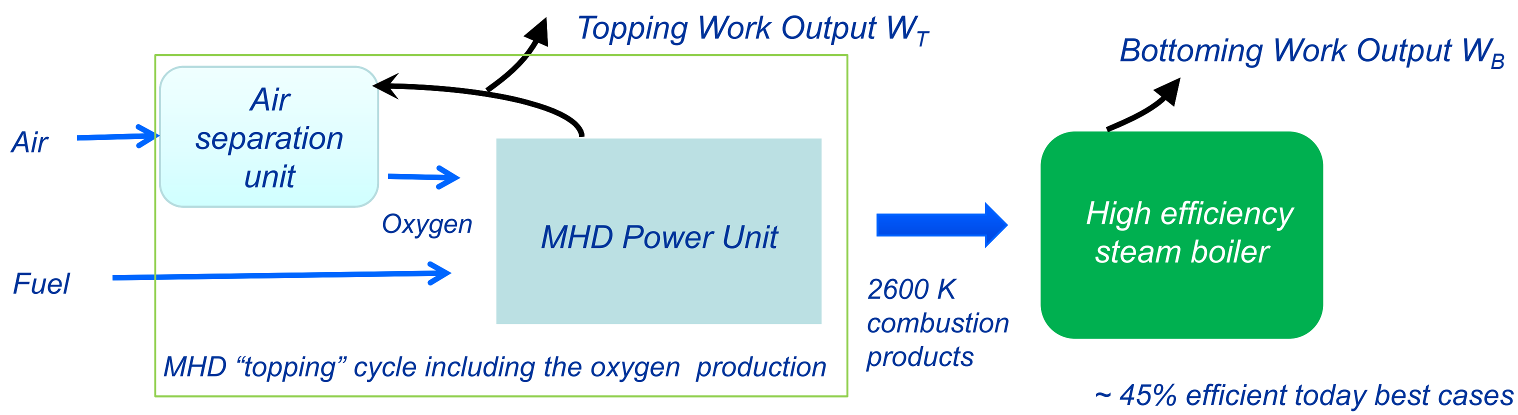
Magnetohydrodynamic Power Generation

- **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 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: $W_B = \eta_B$ (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

$\eta_T = 0.1$ (10%)

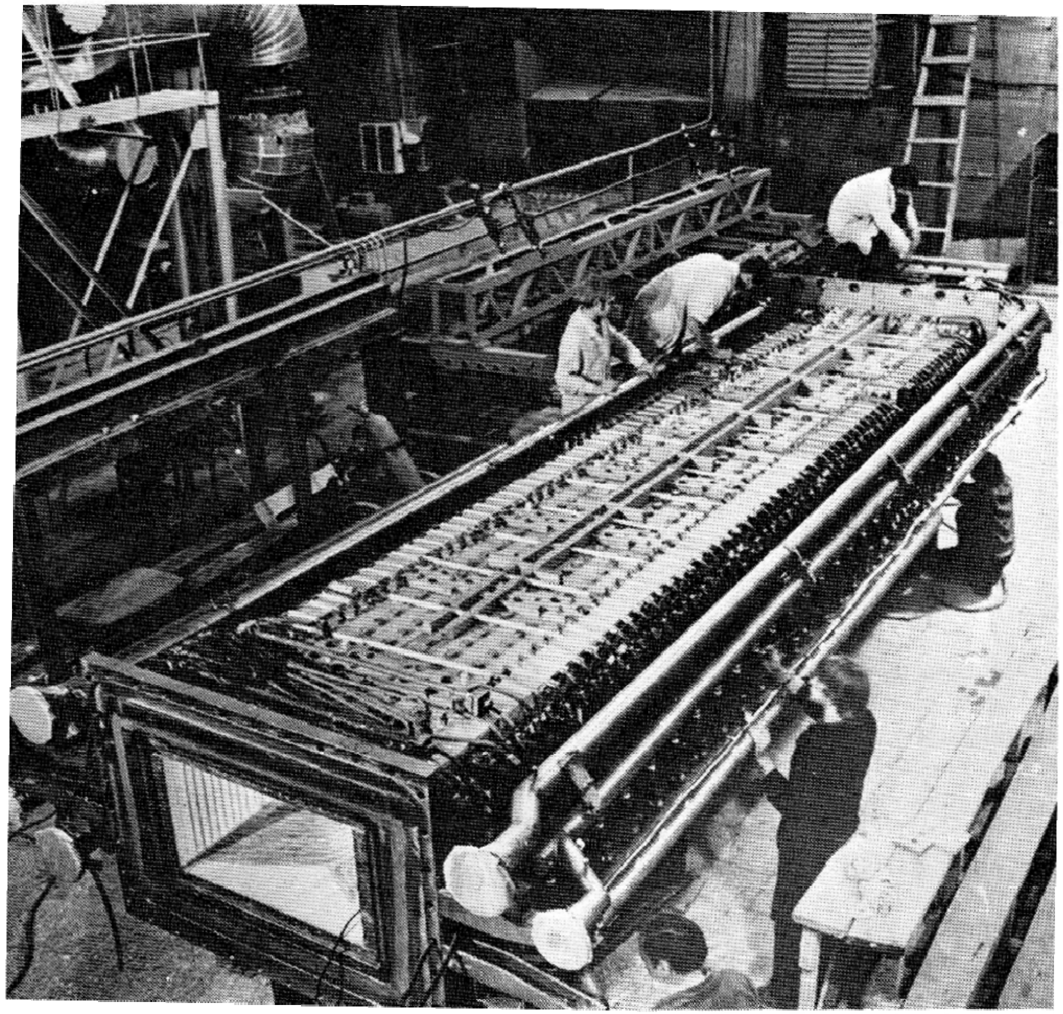
$\eta_B = 0.45$ (45%)

Combined Efficiency:

.1+.45 – (.1)(.45)
= 0.50 (50%)

Past MHD topping efforts

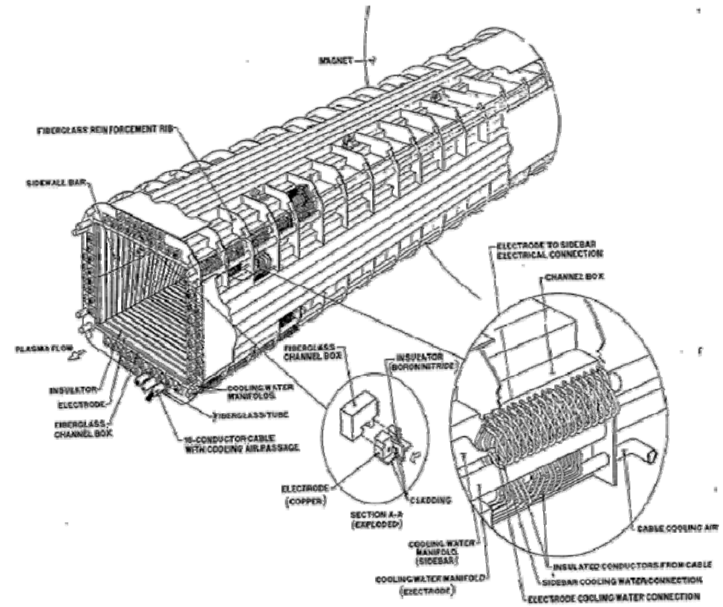
- **Concept proven in both U.S. and USSR in 70s and 80s**
  - US DOE ~680 million $ 1978-1993
  - Electricity transferred to grid
- **Economic downfall : key factor being materials**
  - Electrode damage
  - Seed material use



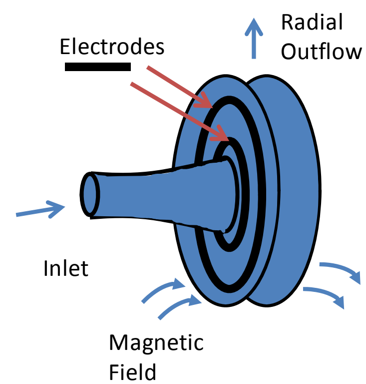
MHD U25RM diffuser channel (USSR) 1970s
From Petrick & Shumyatsky 1978.

Direct Power Extraction
- - - then, now, and next….

- **then:**
  - MHD concept proven in U.S. and USSR in 70s & 80s.
  - Electricity transferred to grid.
  - Economic downfall : Short electrode life.
  - Electrode damage from uncontrolled arcing.
  - Seed material use confounded by poor slag control.
- **now:**
  - CO_2-capture-ready is a desired goal.
  - Oxyfuel combustion ASU optimization - significant energy reduction versus 1980's.
  - Availability of magnets (10 Tesla instead of 4.5 Tesla) – power per tube ~B^2 implies **4x increase in power!**
  - Today's slagging combustors may meet slag control goals from 1980s.
  - **MHD CFD codes** enable optimization of generator design with reduced arcing, slag interaction.
- **next (?):**
  - Disk generator concept.
  - Novel power extraction from unsteady flows (?).



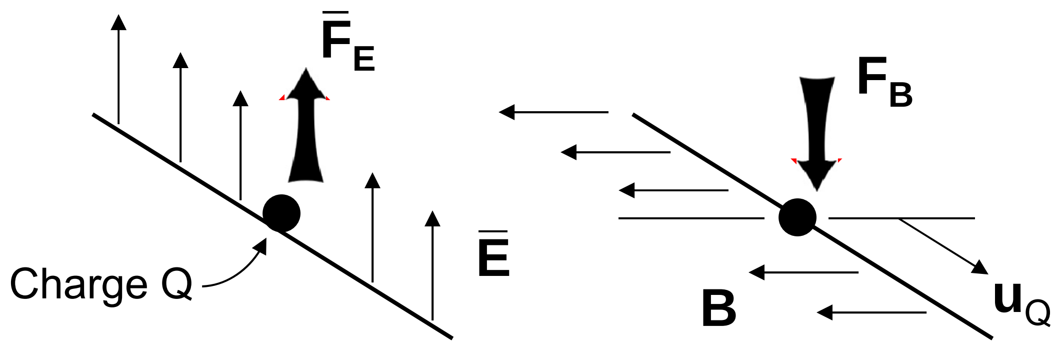
"Advanced MHD Power Train" coal topping generator, US DOE program, 1985



Disk Generator Concept: Simple design & high performance.

Fundamentals of Electromagnetics

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



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

$\mathbf{F_E} = Q\,\bar{\mathbf{E}}$
Electric Force on Q
$\therefore \quad E = \mathbf{F_E}/Q$

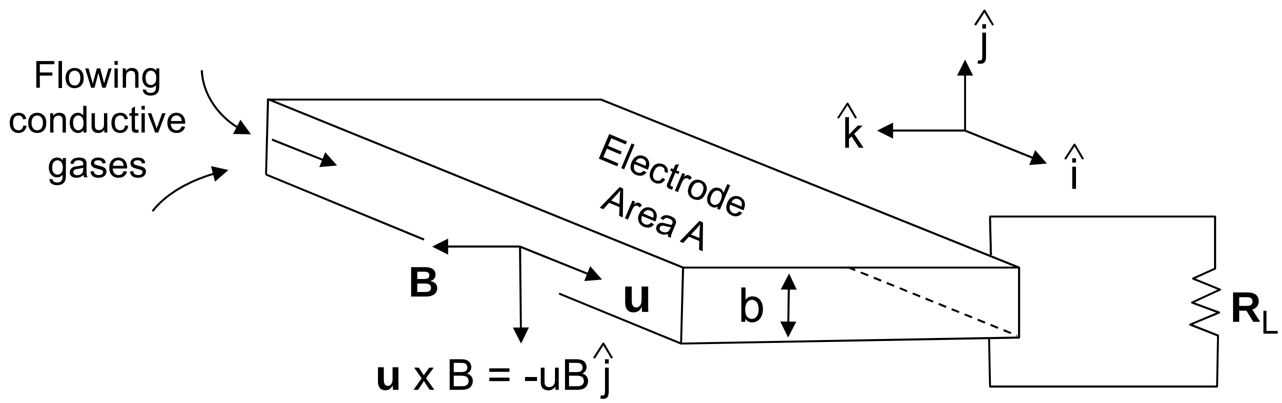
$\mathbf{F_B} = Q\,(\mathbf{u}_Q \times \mathbf{B})$
Magnetic Force on Q
$\therefore \quad \mathbf{u}_Q \times \mathbf{B} = \mathbf{F_B}/Q$

"Another" **E** !

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

* Thus in 1-D E = -V/L
L = distance.

A Simple Generator



- Gas (conductive) flows with bulk velocity $u\,\hat{i}$
- Magnetic filed $B\,\hat{k}$ is applied as shown.
- The resulting “induced” electric field is $-uB\,\hat{j}$
- 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}:

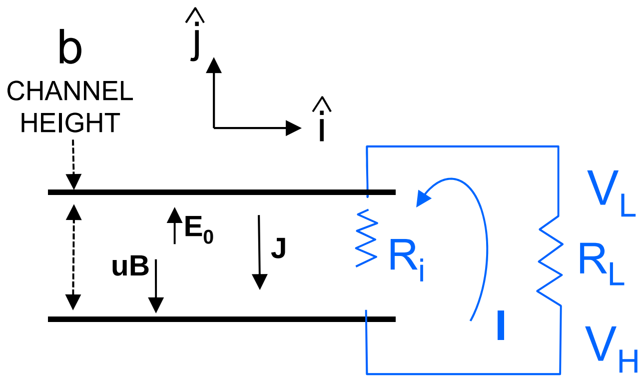
Important Nomenclature Note: *E_0 (zero sub) is applied by the external load & does not include magnetic induced field*

$\mathbf{J} = \sigma\, \mathbf{E}_{NET}$; σ = conductivity of media [Amps/(volt·meter)]

J = current flux vector [Amps/meter^2]

A = electrode area [meter^2]

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



SIMPLE GENERATOR FROM PREVIOUS PAGE

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

From $\mathbf{E_0} = -\nabla V$ $\qquad E_0 = -(V_L - V_H)/b$

(V_L = Low Voltage $\qquad V_H$ = High Voltage)

$E_0 = (V_H - V_L)/b = IR_L/b$ (Ohm's Law)

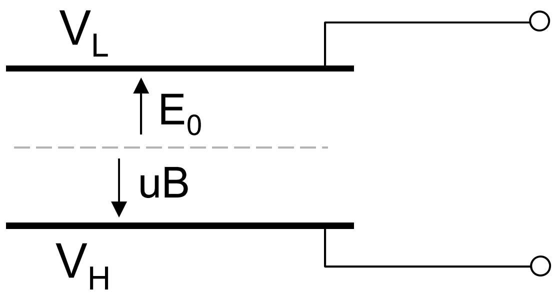
Define open circuit $R_L \rightarrow$ infinite, then J = 0 implies $E_0 = uB$ from above.

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

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

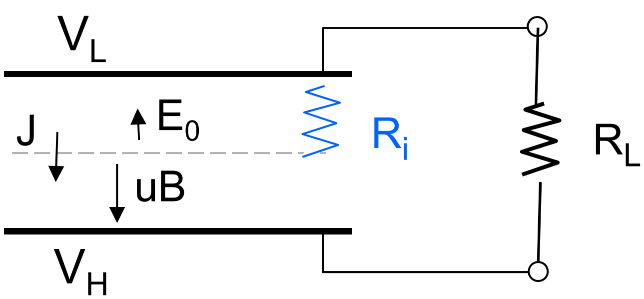
Note : as typical, V_{oc} is a voltage difference while V_H and V_L are measured relative to ground

Limiting Cases



Open Circuit

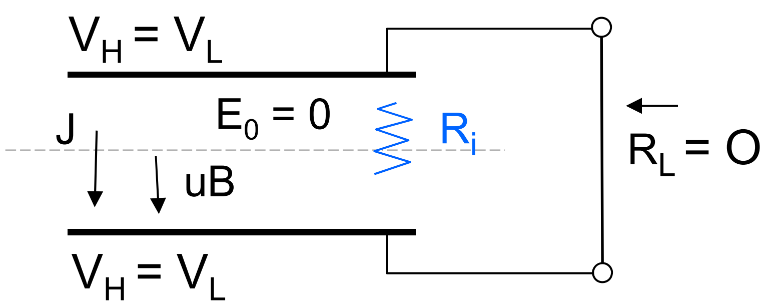
$$O = J = \sigma\,(E_0 - uB) \longrightarrow E_0 = uB$$
$$(V_H - V_L)/b = E_0 = uB$$
$$\therefore\ V_{OC} \equiv uBb$$



Generating Circuit

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

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

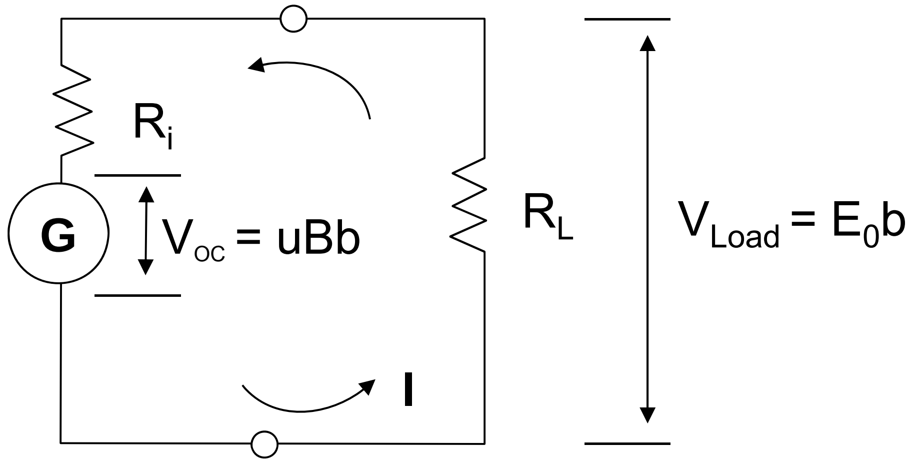


Short Circuit

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

$$I = \frac{V_{OC}}{R_i + R_L = O} = \frac{V_{OC}}{R_i}$$

Electrical Analogy

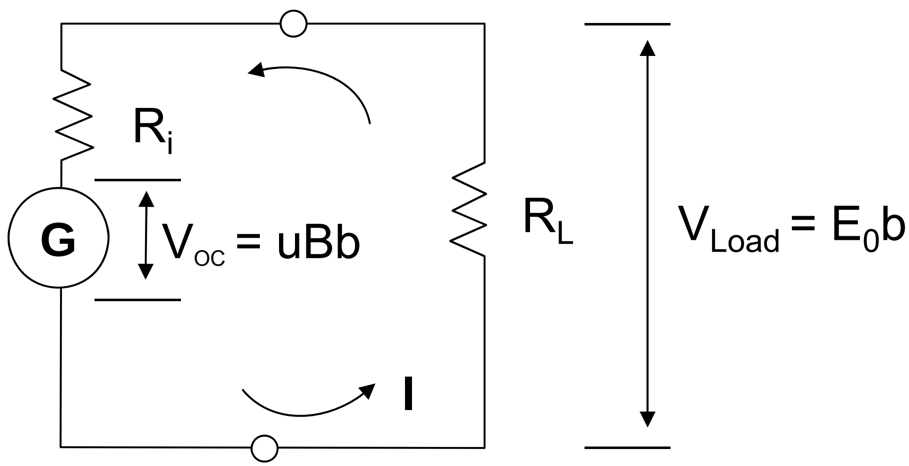


$$\text{Define} \quad K = \frac{V_{Load}}{V_{oc}} = \frac{IR_L}{I\,(R_i + R_L)} = \frac{R_L}{R_L + R_i} = \frac{E_0}{uB}$$

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



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

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

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

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

Power = I $\times$ V; Power = $Ab\,\sigma\,u^2B^2\,K\,(K - 1)$

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

Next slides - overview

What you just heard:

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

What you will hear next:

- A complication arises from the Hall Effect

  …the <u>flowing</u> <u>current</u> also interacts significantly with B

- Thus, we find:

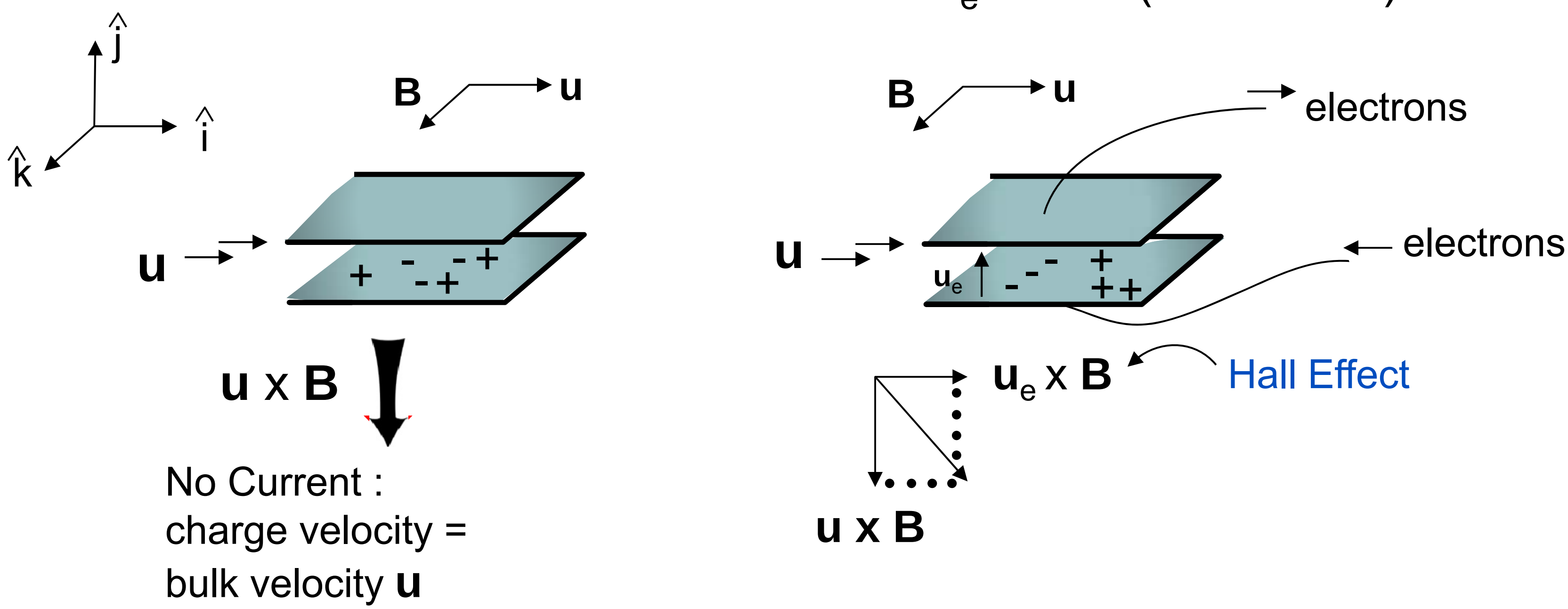
$$J_x = \frac{\sigma}{l + \mu_e B^2}\,(E_{0x} - \mu_e\, B\,\{E_{0y} - uB\})$$

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

- 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 **E**
- The electron current flow has an associate charge velocity $\mathbf{u}_e$
- Must account for the interaction between $\mathbf{u}_e$ and **B** (Hall Effect)

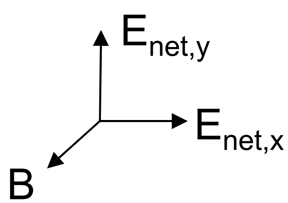


Hall Effect "Tilts" the Field – How Much?

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



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

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

$\mathbf{J} = J_x\hat{i} + J_y\hat{j}$

Straightforward algebra and substitutions in equation (i).

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

$$J_x = \frac{\sigma}{1 + \mu_e^2 B^2}\left(E_{net,x} - \mu_e B\, E_{net,y}\right)$$

$$J_y = \frac{\sigma}{1 + \mu_e^2 B^2}\left(E_{net,y} + \mu_e B\, E_{net,x}\right)$$

$$E_{net,x} = E_{0x}$$
$$E_{net,y} = E_{0y} - u\,B$$

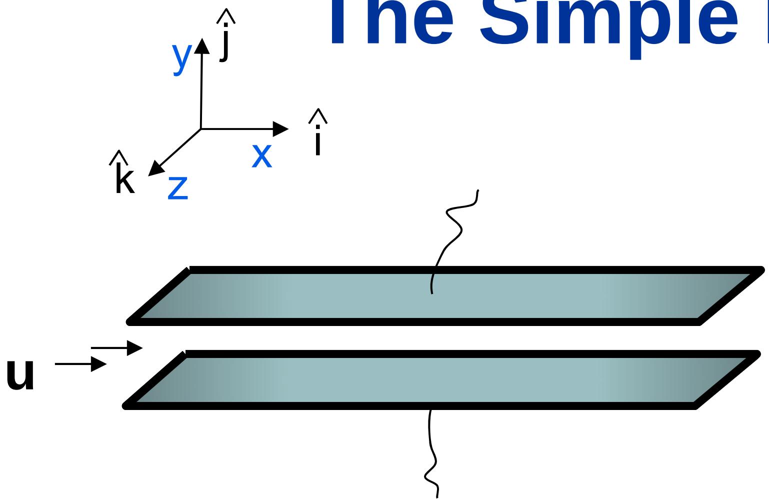
Nomenclature

n_e = electron # density (per m^3)

e = fundamental charge 1.602 E-19 C/electron

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

The Simple Faraday Generator



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

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

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: $\dfrac{1}{1+\mu_e^2 B^2}$

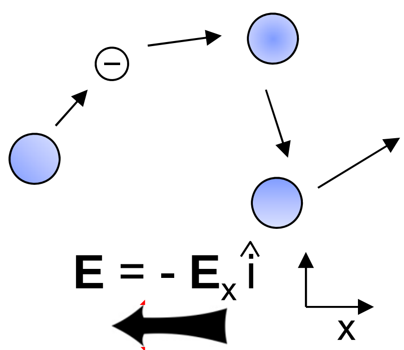
What is the magnitude of meaning of J_x?

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

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

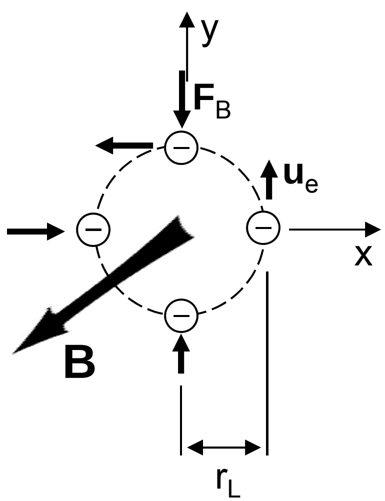
$$F_e = m_e \frac{du_e}{dt} \; ; \; -eE_x \cong m_e \left(\frac{u_{e,\,mean}}{\tau} \right) \qquad \text{(i)}$$

But, we also write: **(ii)**

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

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:

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

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

Define cyclotron frequency

$\omega = u_e / r_L \Rightarrow B = \omega\, m_e / e$ **(iv)**

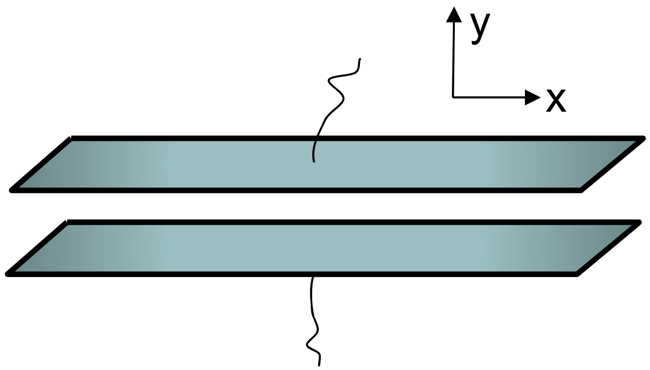
Combine (iii) and (iv) : $\boxed{\mu_e B = \omega\tau}$ *"Hall parameter"*

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

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

$\omega\tau << 1 \Rightarrow$ 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 $1 < \omega\tau < 10$… implies:

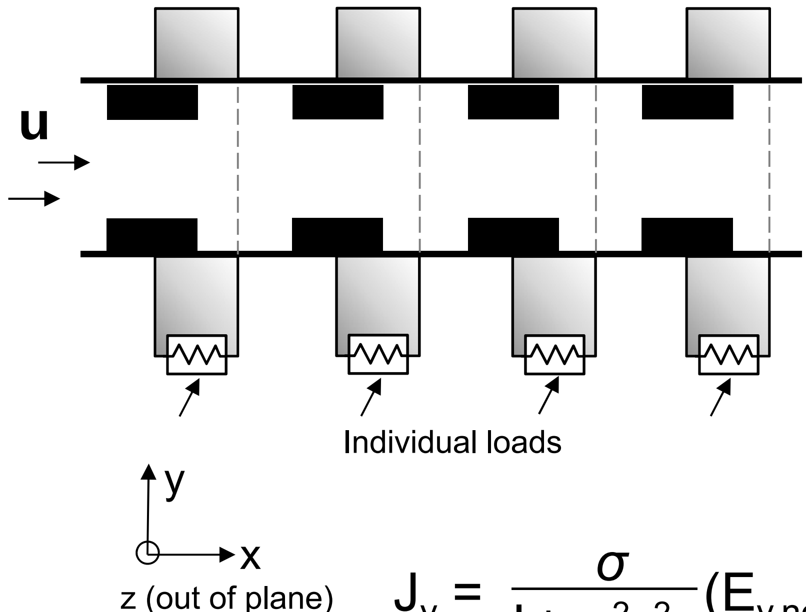
1) Significant reduction in J_y versus “simple” model

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?)*



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

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

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

$\Rightarrow$

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

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

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

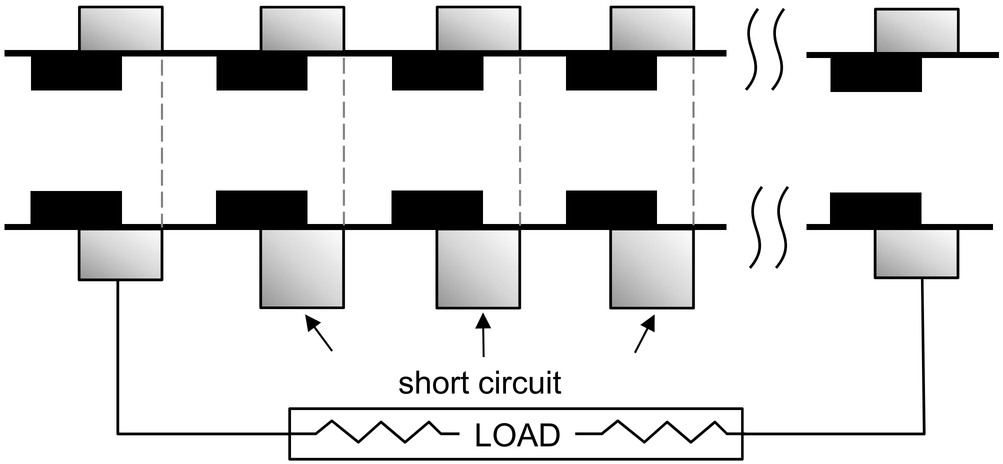
What practical disadvantages exist with this concept?

* It has no return path.

Hall Generators

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

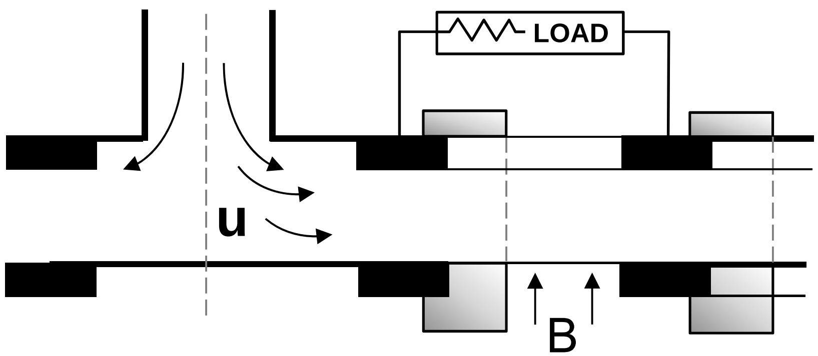
(applied) $E_{y,net} = E_{yo} - uB$



Solve for currents and voltage as before.

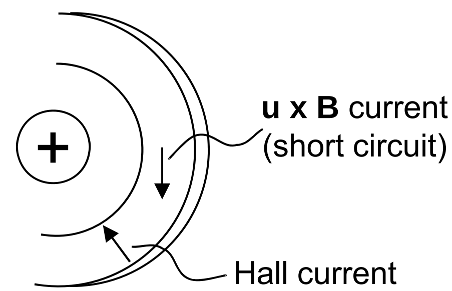
$E_{oc} = -\omega\tau\, uB$ open circuit

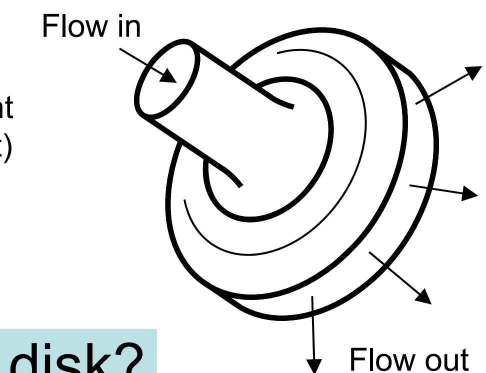
Disk Geometry (very clever!)



Notice the open circuit voltage is larger than uB

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

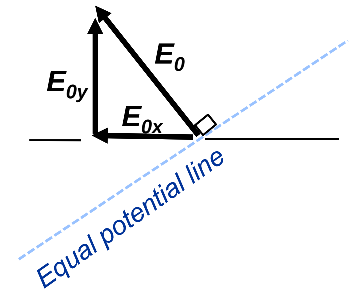




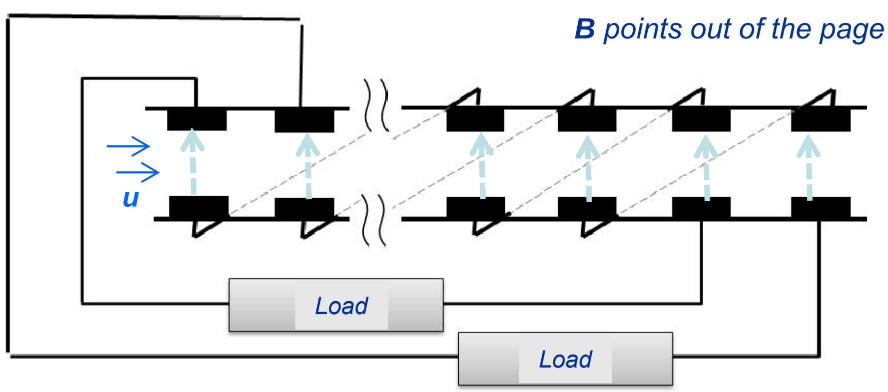
State one huge practical advantage of the disk?
(Hint: count the number of wires)

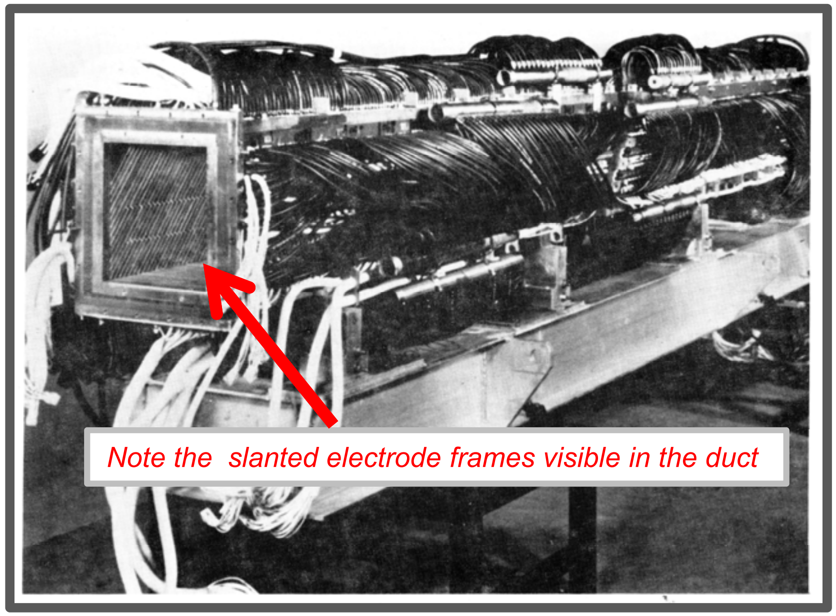
An intermediate approach:
Slanted (diagonal) electrode connections

- **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.**



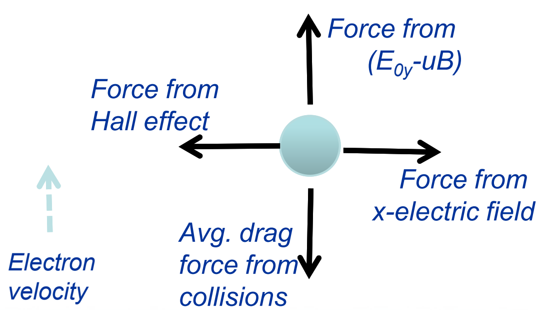
Note that the E_{net} includes –uB in the y-direction.
The electrons move vertically in response to (E_{0y}-uB)





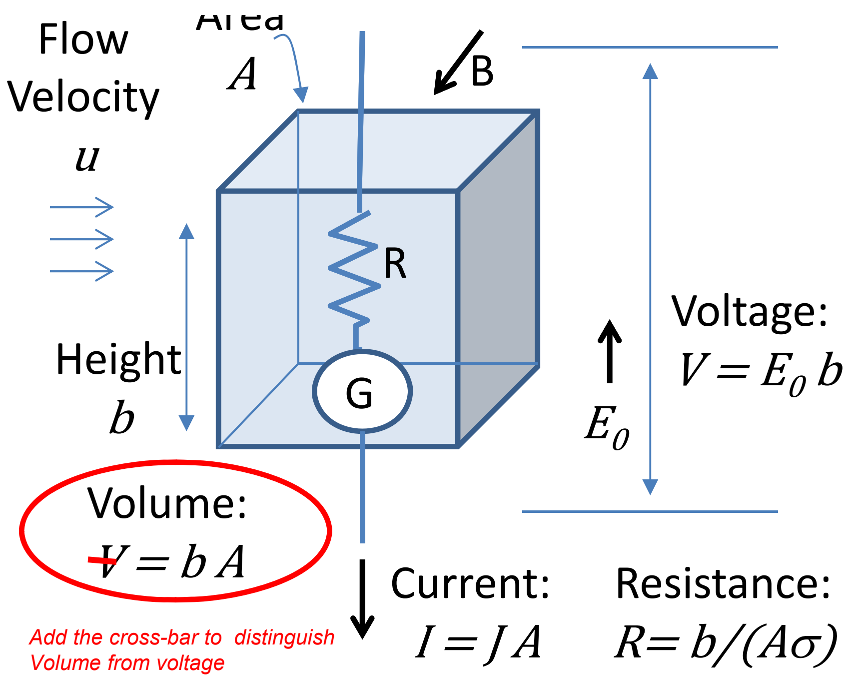
From: Quarterly Technical Progress Report, July 1 – Sept 30, 1985, Component Development and Integration Facility
Work performed under DOE DE-AC07-781D01745; Original Reports currently available only at NETL .

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



Fluid mechanics and thermodynamics

1-D Energy Balance



Ohmic loss:

$$I^2 R = \frac{A^2 J^2 b}{A\,\sigma} = \cancel{V}\,\frac{J^2}{\sigma} \qquad \text{per unit volume:} \quad \frac{J^2}{\sigma}$$

(i)

Electrical power *output from* the volume:

$$I\,V = A\,(-J)\,E_0\,b \qquad \text{per unit volume:} \quad -J\,E_0$$

(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):

x-body force per unit volume:

$$\left(n_e(Q)\{\boldsymbol{u_e} + \boldsymbol{u}\} \times \boldsymbol{B} \cdot \hat{\imath}\right) = \left(n_e(Q)\boldsymbol{u_e} \times \boldsymbol{B} \cdot \hat{\imath}\right) = \boldsymbol{J} \times \boldsymbol{B} \cdot \hat{\imath}$$

Charges per unit volume

Force on a charge Q = (-e)

Note $\boldsymbol{u}$ has only x-component; $\boldsymbol{u} \times \boldsymbol{B} \cdot \hat{\imath} = 0$

The vector product points left

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)*

$$\boxed{K = {}^{E_0}\!/_{(u\,B)} \;\; ; \;\; J = \sigma\, u\, B\, (K-1)}$$

$$(1)\, ohmic\ loss = \sigma\, u^2 B^2 (K-1)^2$$
$$(2)\, electrical\ power\ out = -\sigma\, u^2 B^2 K (K-1)$$
$$(3)\, mech\ power\ input = -\sigma\, u^2 B^2 (K-1)$$

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

$$\frac{d(\rho\, u)}{dx} = 0$$

Continuity: *Familiar*

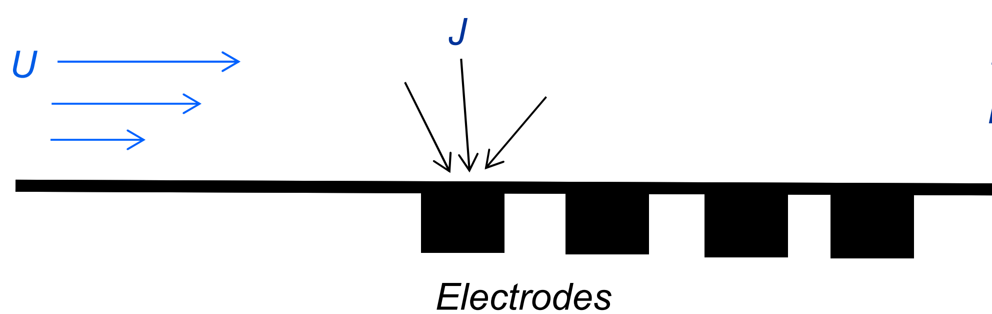
$$\frac{dP}{dx} + \rho u \frac{du}{dx} = J\, B$$

Momentum eqn: *Note JB 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 <u>output</u> 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**

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

Copper σ ~ = 6 x 10^7 Siemen/m

Seeded MHD σ ~ = 10 Siemen/m

Siemen = 1/ohm

Gas Conductivity: Seeding

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

Simple generator: Power density

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

The power density is maximum at

$$K = ½ \quad \therefore \quad P_{max} = \sigma U^2 B^2/4$$

Reasonable Design:

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

$\sigma \approx 10$ S/m (S=Siemen = 1/ohm)

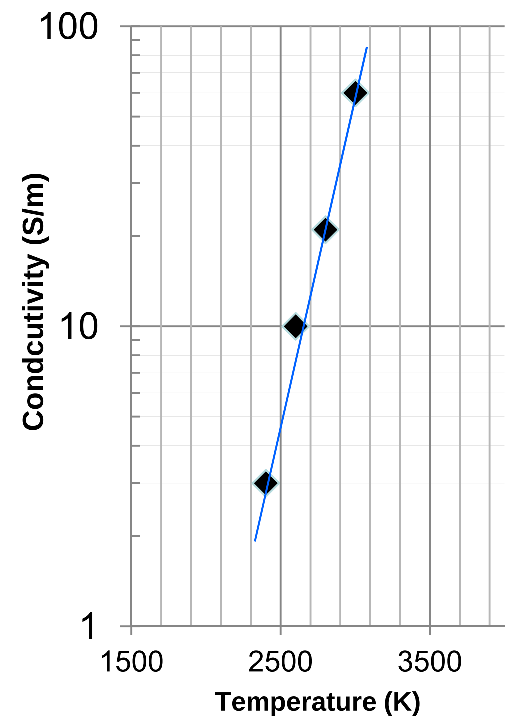
Two points:

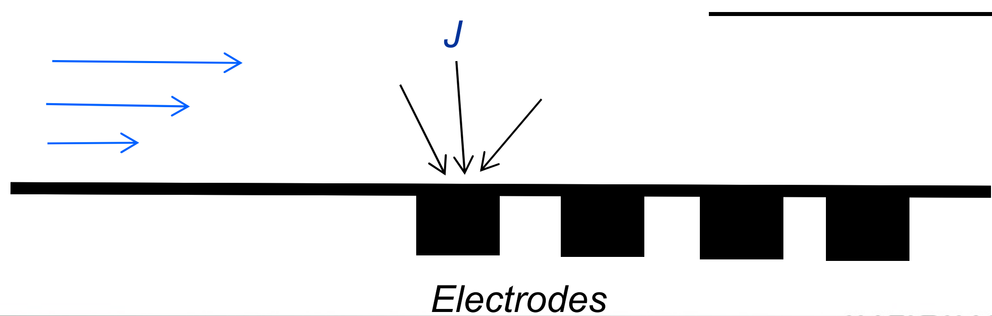
1. The <u>magnitude</u> of the conductivity with temperature: operating temp ~ > 2600K
2. The slope versus temperature: very sensitive

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_2O	*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.





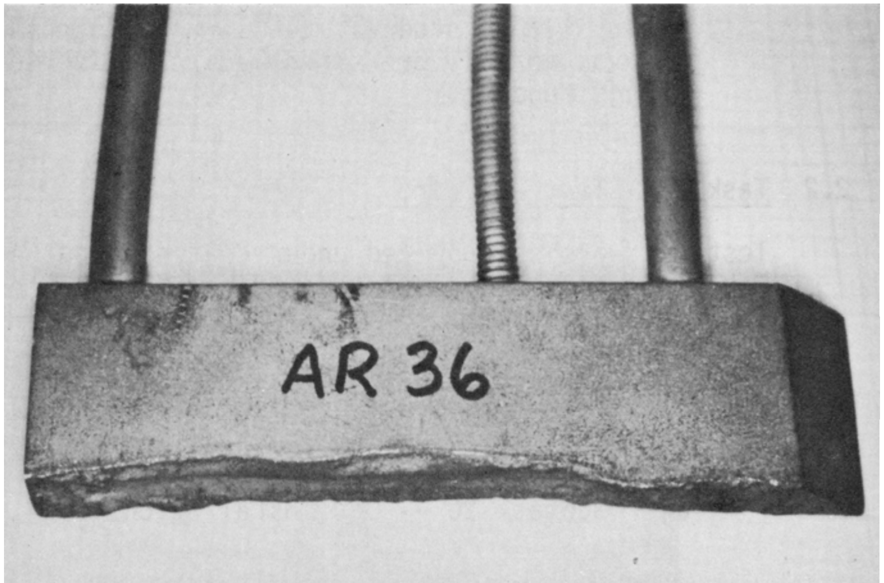
The real situation:
Describe the conductivity near the electrodes?

Seeding

- **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?**

Electrodes

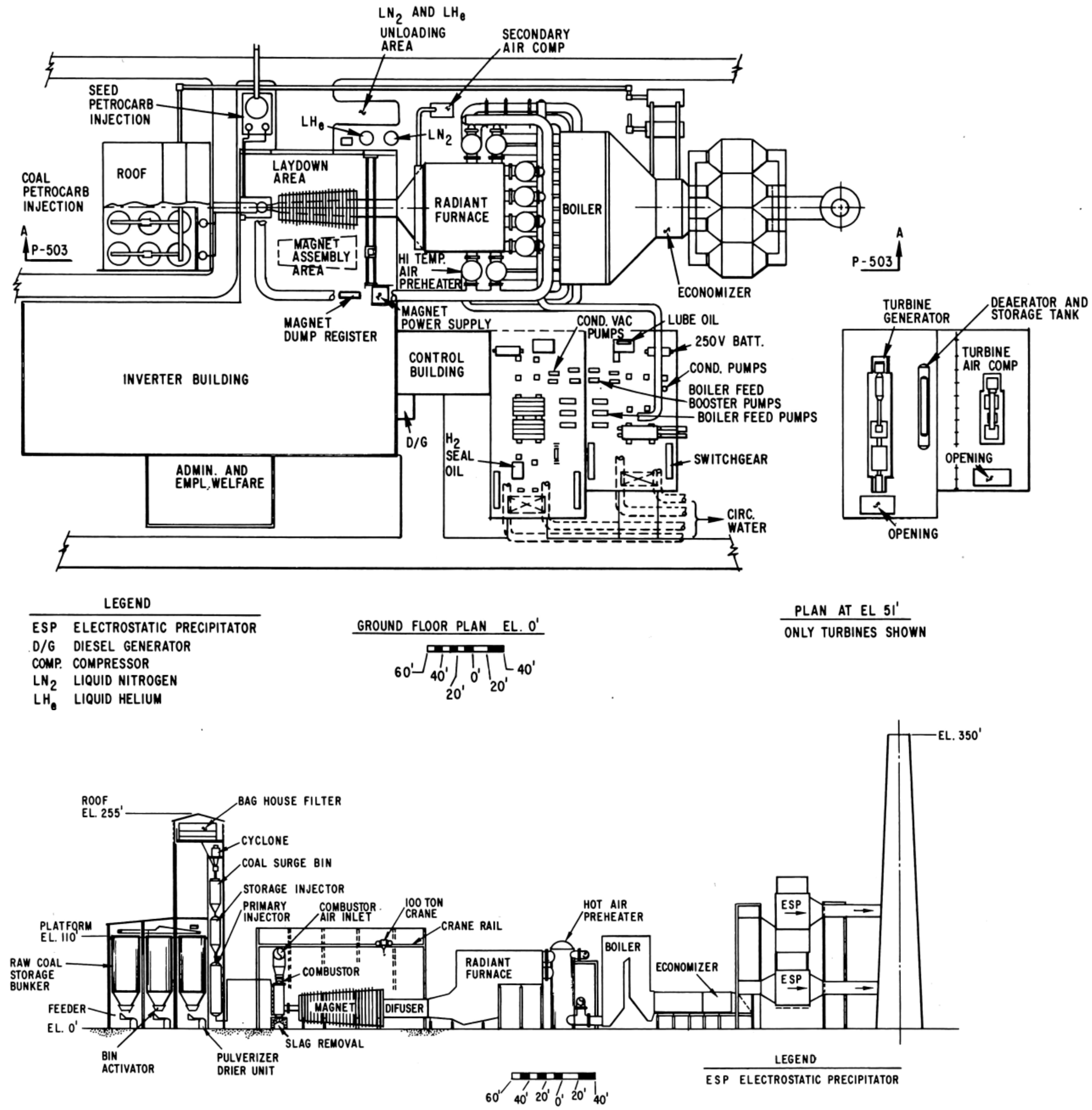
- **Cooled electrodes must operate with high surface temperature to reduce quenching conductivity and heat loss near the walls.**
- **Complicated by thermal, chemical, and electrical attack.**
- **Some tests suggest reasonable life is possible in slag free (gas fuel operation) or with better slag removal.**
- **Current instability can lead to arcing – concentrated current flows – burning the surface.**
  - State of the art electronics may reduce this problem



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

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

A few comments

- **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? Next slide.
- **Can we develop a different approach for *Direct Power Extraction*?**
  - Unsteady flow (e.g. – periodic)?
  - Non-equilibrium plasmas – how about behind a detonation?

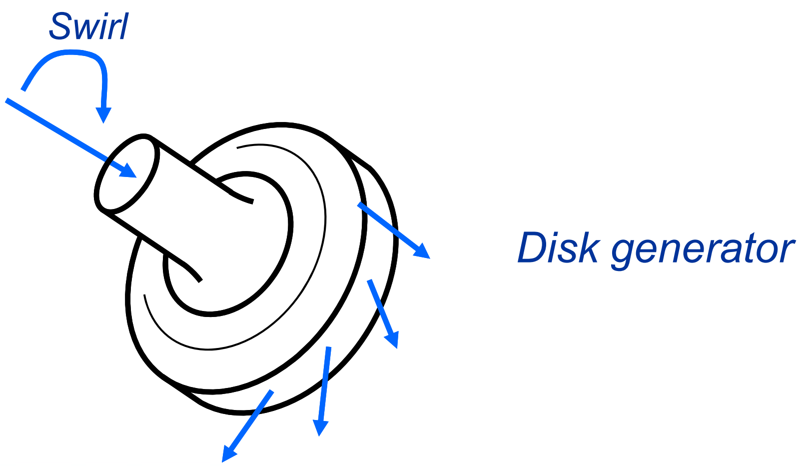
Kayukawa, N. (2004). Open-Cycle magnetohydrodynamic power generation: a review and future perspectives. Progress in Energy and Combustion Science , Vol 30, pp. 33-60.

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"
    - That information is still in more than 90 boxes at NETL
    - Currently being read and selectively scanned at NETL
    - This may be the largest set of information on MHD (for power) anywhere!
  - Contact NETL if you'd like to hear more about this.

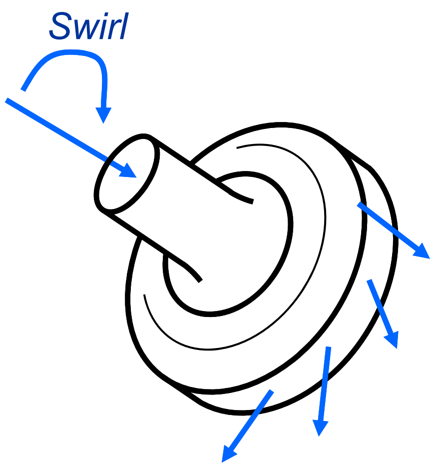
Discussion/thinking/homework

1. **Show using a simple drawing what can happen to the Hall current in a Disk Generator what you add swirl to the inlet flow?**



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

Discussion/thinking/homework

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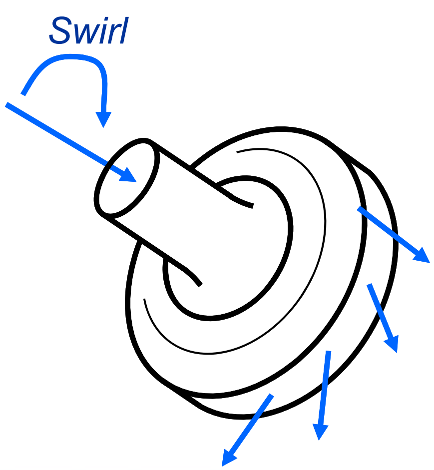

Disk generator

Summary

- ***Direct Power Extraction*** **from high-temperature oxy-fuel flames is possible using magnetohydrodyanmics.**
- **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: Review of old data for simulation validation cases and exploration of innovative/new approaches.**