

A new opportunity for MHD energy conversion?

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Brief MHD Generator Review

- A device that converts kinetic energy of a gas to electricity

- Pros:

Direct conversion

No Carnot – limitation

High conversion efficiency

No moving mechanical parts

Cons:

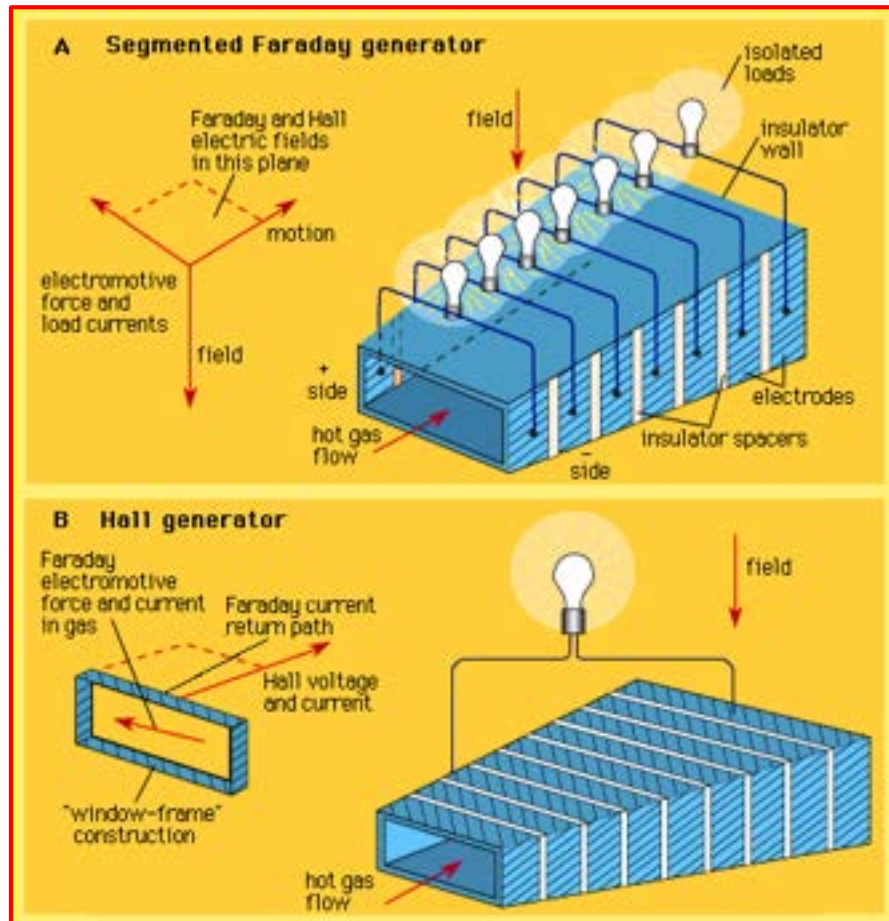
Requires high field magnets

Requires “good” plasma behavior

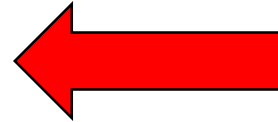
Hard to make an MHD plasma

Research stopped in 1990's

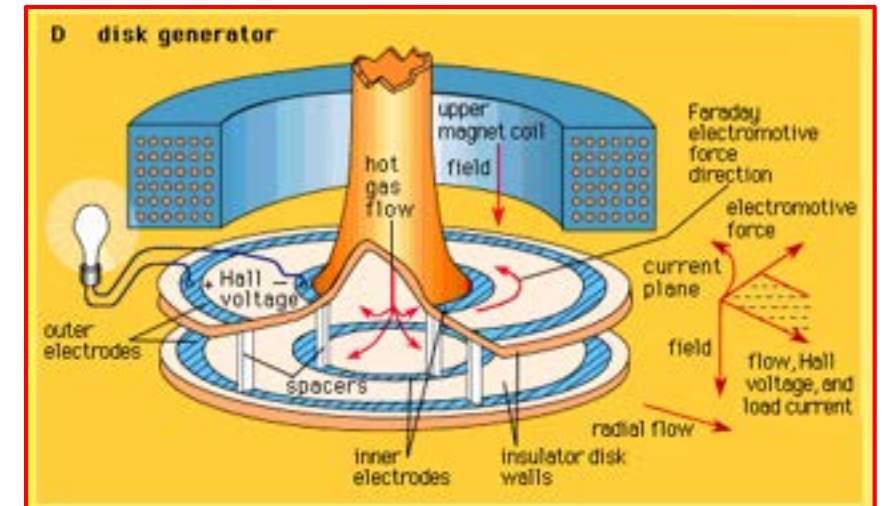
Types of MHD Generators



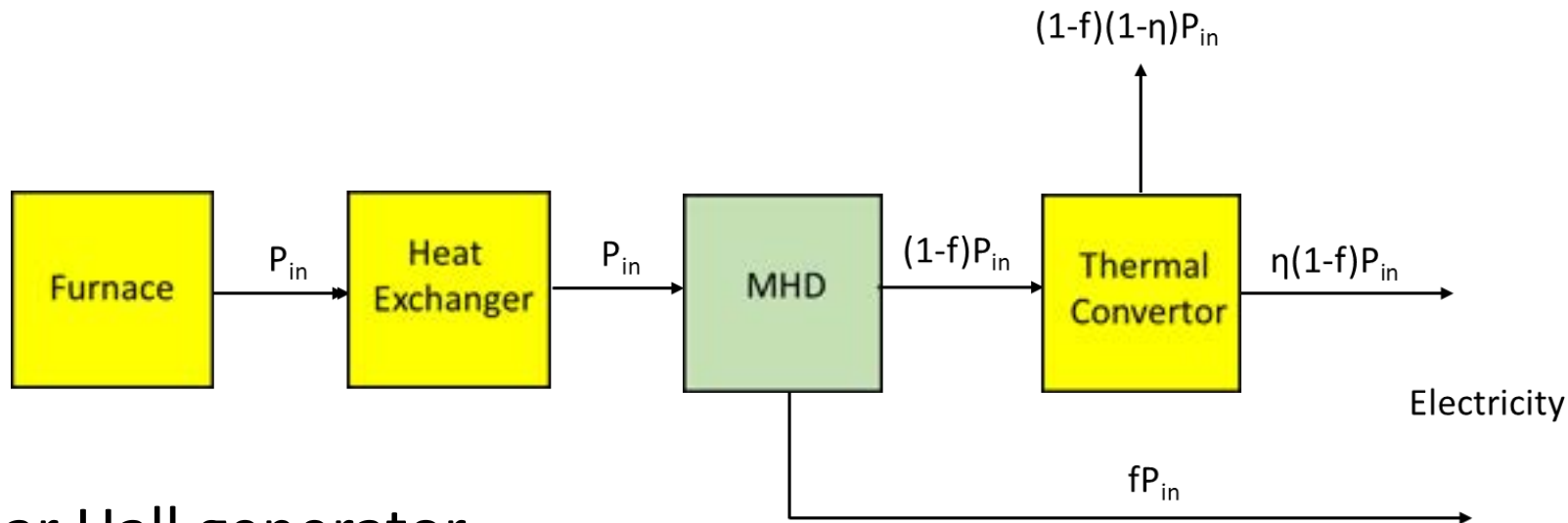
Linear



Disk



The Big Picture – MHD Topping Cycle



- The linear Hall generator
- Easier to build than Faraday – Hall only requires 1 load
- Still, may require 1000 electrodes
- Disk is a cylindrical Hall generator – requires only 2 electrodes
- Disk is a more attractive long term option but we focus on linear Hall
- Goal: Raise the efficiency from **0.35 – 0.4** to **0.55 – 0.6**

Nuclear MHD Topping Cycle

- No CO₂ emissions
- Works for fission and fusion
- Need furnace coolant temperature $T = 1000 \text{ K}$ (tough but doable)
- Strategy: Use an MHD generator with Argon as the primary gas and a small amount (10^{-6}) of Potassium as a seed gas to make the plasma
- Potassium is good – low ionization potential 4.34 eV
- Argon is good – slow energy exchange rate between K-electrons and A-neutrals
- Need high input Mach number for good energy conversion: Laval nozzle

MHD-Nuclear

- Good news
 - Ohmic heating preferentially heats electrons
 - Slow Argon energy equilibration allows large temperature difference
 - Generator input: $T(\text{A-neutrals}) = 500 \text{ K}$, $T(\text{K-electrons}) = 5000 \text{ K}$, $M = 2$
 - Ohmic heating not wasted heating the Argon
- Bad news
 - Finite ΔT generates the ionization instability (Velikov 1962)
 - Plasma breaks up into filaments – performance seriously degraded
 - Believed to be a show stopper for MHD-nuclear

Why revisit MHD-nuclear now?

- **Societal reason**

- **Climate change** more important now than in the 1990's
 - MHD worked but lost out to combined cycle gas for fossil fuels
 - Ionization instability caused very poor performance for nuclear
 - MHD research largely terminated in 1990's
- **Good societal reason** but what about the disastrous ionization instability

Why revisit MHD-nuclear now? (cont)

- **Science and Technology improvements**

- Some experiments showed fully ionized seed could produce stability

No transparent explanation – need a first principles theory

- Development of high T, high B, superconductors

Early experiments had $B = 3 \text{ T}$, now we have $B = 15 - 20 \text{ T}$

- Is high field a path to improved performance?

Progress at Last Meeting

- Assume plausible input parameters from furnace (say an HTGR)
- Focus on a linear MHD Hall generator
- Develop a first principle local theory of the ionization instability
- Showed explicitly how full seed ionization stabilizes the instability
- Not obvious whether high field helps or hurts obtaining high efficiency
- Need a global analysis to see if we can achieve high efficiency

Ionization stability criterion – early reference

- For reference, old stability criterion (approx.) (Rosa 1987)

$$\beta \leq 2 \frac{kT_e}{E_i} \ll 1$$

$$\beta = \frac{eB_0 / m_e}{v_{ep}} \propto B_0$$

$$E_i = 4.34 \text{ eV} = 50,360 \text{ K}$$

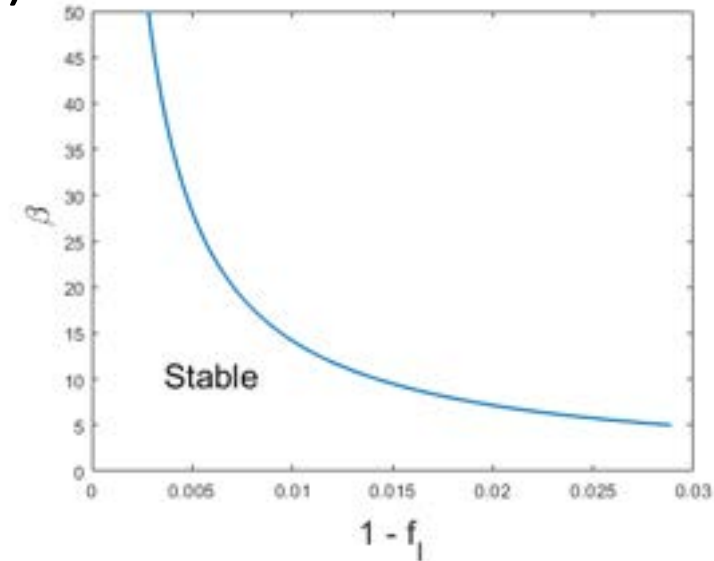
- Not related to the degree of ionization
- Assumes a weakly ionized plasma
- Low β stability limit – high field does not appear to help

New first principles theory completed

- Lots and lots of math
- New criterion (approximate high field limit)

$$\beta < 2^{1/2} \left(\frac{kT_e}{E_i} \right) \left(\frac{1}{1 - f_i} \right)$$

$f_i = \frac{n_e}{n_s}$ seed fractional ionization



- Direct connection between stability and nearly full ionization
- β limit increases as $f_i \rightarrow 1$ - not obvious if high field helps or hurts

The next step – recent progress

- The ionization stability criterion is a local (in space) criterion
- Global analysis needed to determine overall optimized performance
- **High level strategy:** (OK but not great)
 - Specify the furnace – HTGR (p, T, n, v of Argon given as MHD input)
 - Solve the MHD equations subject to engineering constraints
 - Optimize over B, M, n_s
 - Goal: Maximize enthalpy conversion (power to load): $f = 1 - H_{out}/H_{in}$
- **Problem:** Engineering constraints only semi-quantitative without detailed engineering design

A better strategy

- Specify the furnace – HTGR (p , T , n , v of Argon given as input)
- Specify a desired enthalpy conversion: $f = 1 - H_{\text{out}}/H_{\text{in}}$
- Define two figures of merit related to cost
- Solve the MHD equations and optimize over B , M , n_s to minimize cost
- Evaluate the engineering constraints to see if they are reasonable

New global model

- New, self-consistent quasi 1-D model fully developed
- Describes detailed performance of linear MHD Hall generators
- Primary gas: Conservation of mass, momentum, and energy
- Seed gas: Saha equation, generalized Ohm's law, energy balance
- Marginal ionization stability along entire length

Capital cost figure of merit

- Straightforward: $C_{\text{tot}} = \Sigma \text{ everything}$ - too complicated
- Simpler: $C_{\text{tot}} = \text{Magnetic energy cost} + \text{Everything else}$
$$= c_M W_M + c_V \text{Vol}$$
- Problem: We don't know c_M or c_V
- Avoid the problem: $C_{\text{tot}} = (c_M c_V)^{1/2} [(c_M/c_V)^{1/2} W_M + (c_V/c_M)^{1/2} \text{Vol}]$
- Assume both costs are comparable
- Then a simple approximation is the geometric mean
- Figure of merit: $C = C_{\text{tot}} / (c_M c_V)^{1/2} = 2(W_M \text{Vol})^{1/2}$ as small as possible

Availability figure of merit

- MHD generator should operate as long as possible (e.g. before shutting down for repairs, part replacement, maintenance)
- One main problem is component replacement because of seed gas (potassium) corrosion
- To minimize corrosion we need to minimize the amount of potassium seed gas in the generator
- Figure of merit = n_s as small as possible

Engineering Constraints

Primary Engineering Constraints:

- Thermal losses small: requires $l / h < (l / h)_{\max} \sim 20$
- Avoid electrical breakdown: requires $E < (E)_{\max} \sim 15 \text{ kV/m}$

Secondary engineering constraints:

- Large power dissipation in the electrodes: poor power balance
- Wall loading power limit: long channel and electrode lifetime
- Output to input height ratio: prevent flow separation

A Reference Example

Example: HTGR

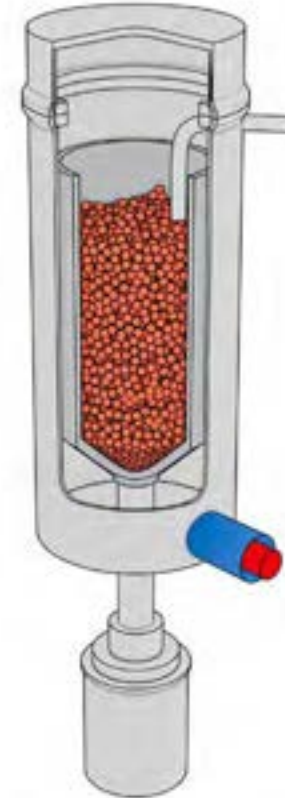
- Argon coolant pressure in = 50 atm
- Argon coolant temperature in = 1000 K
- Argon coolant velocity in = highly subsonic
- MHD power to the load $P_L = 100 \text{ MW}$

Desired enthalpy conversion:

- $f = 1 - H_{\text{out}}/H_{\text{in}} = 0.35 \rightarrow \eta_{\text{tot}} \sim 0.55$

Scan assuming a potassium seed:

- B, M, n_s



Key Reference Results (after iteration)

- Design inputs:

$$(B)_R = 10 \text{ T}$$

$$(n_s)_R = 10^{20} \text{ m}^{-3}$$

$$(M)_R = 2$$

- Engineering outputs:

$$(I / h)_R = 19.9$$

$$(E)_R = -15.0 \text{ kV/m}$$

$$(C)_R = 1270 \text{ (J m}^3\text{)}^{1/2}$$

Run many, many, cases

- Vary B , n_s , M
- Normalize all quantities to their reference values [e.g. $B / (B)_R \rightarrow B$]
- Simple empirical fit

$$\frac{I}{h} \approx \frac{1}{B^{1.3} n_s M^{2.6}} \leq \left(\frac{I}{h} \right)_{\max}$$

$$E \approx B \leq (E)_{\max}$$

$$C \approx \frac{1}{B^{0.5} n_s M^{3.1}}$$

Some Consequences

- High M makes it easier to satisfy the l / h loss constraint
- High M is good to lower the capital cost
- Electric field constraint is independent of M
- Conclusion: Optimum M is the maximum achievable M in a Laval nozzle. Typical engineering constraints lead to $M_{\max} \sim 2$

$$\text{Set } M = M_{\max} = 2$$

Some More Consequences

- High n_s makes it easier to satisfy the I / h loss constraint
- High n_s is good to lower the capital cost
- Electric field constraint is independent of n_s
- **But** high n_s is bad for high availability corrosion requirement
- Which dominates: low capital cost vs. high availability?
- We suggest high availability is more critical
- Conclusion

Set $n_s = (n_s)_{\min}$

Even More Consequences

- High B makes it easier to satisfy the I / h loss constraint
- High B is good to lower the capital cost
- But high B is bad for the electrical breakdown constraint
- Conclusion: Since both engineering constraints must be satisfied, it is not clear what is the optimum choice for B

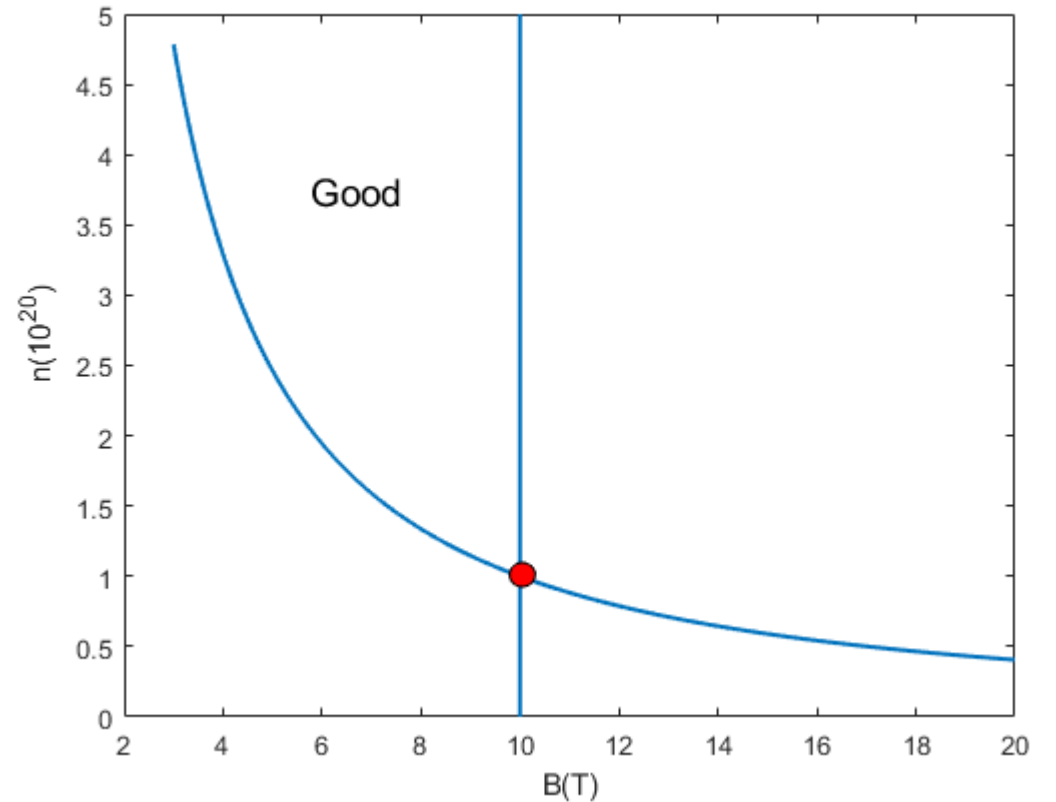
Set B = ?

The Optimum B

- Set $M = 2$
- Invert the constraint relations

$$n_s \approx \left[\frac{1}{M^{2.6} (I / h)} \right] \frac{1}{B^{1.3}} \quad \text{Loss}$$

$$B \approx E \quad \text{Breakdown}$$



The Design

- Choose **B** as large as possible as determined by E breakdown
- Choose **n_s** as small as possible as determined by I / h losses
- Choose **M** as large as possible for realistic Laval nozzle design
- Design: 100 MW MHD generator driven by 1000 K, 50 atm HTGR

$$f = 0.35$$

$$T_A(0) = 430 \text{ K}$$

$$l = 6.4 \text{ m}$$

$$M=2$$

$$p_A(0) = 6 \text{ atm}$$

$$h(0) = 0.32 \text{ m}$$

$$B = 10 \text{ T}$$

$$v_A(0) = 770 \text{ m/s}$$

$$h(l) = 0.52 \text{ m}$$

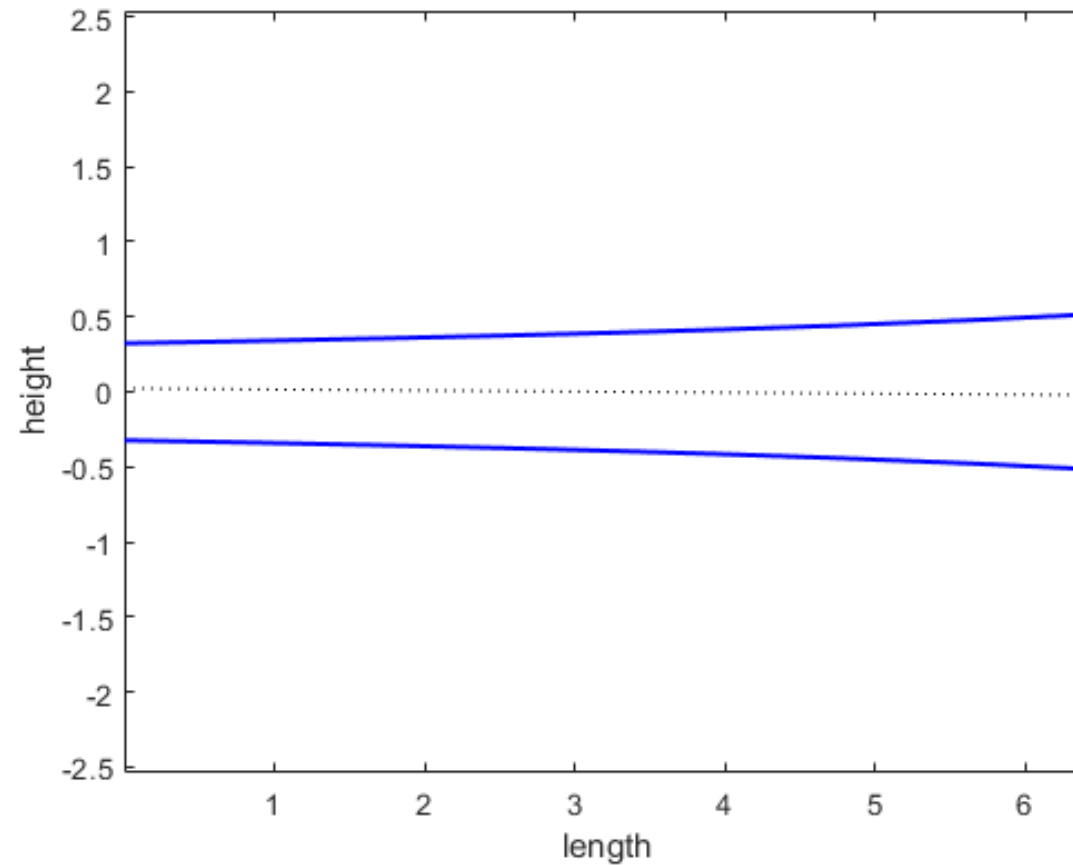
$$n_s = 10^{20} \text{ m}^{-3}$$

$$T_e(0) = 4400 \text{ K}$$

$$VI = 93000 \times 1100 = 10^8 \text{ W}$$

MHD Generator Geometry

- Long and thin



Future Plans

- Redo entire analysis for disk geometry
- Develop a design for an MHD experiment to be built at the PSFC:
Major goal is to stabilize ionization instability at large ΔT
- Probably on the order of 1 M\$ facility