

Revisiting MHD Energy Conversion: Is High Field a Potential Game Changer for Improved Efficiency?

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What is an MHD Generator

- 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:

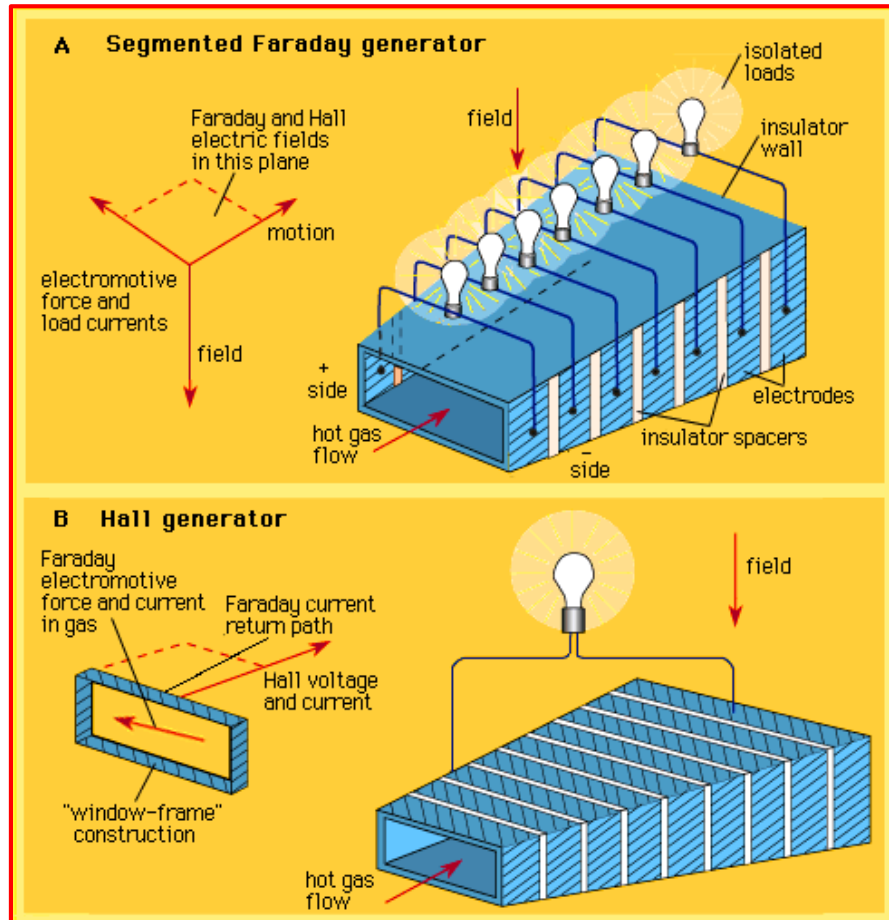
Requires high field magnets

Requires “good” plasma behavior

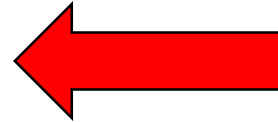
Hard to make an MHD plasma

Research stopped in 1990's

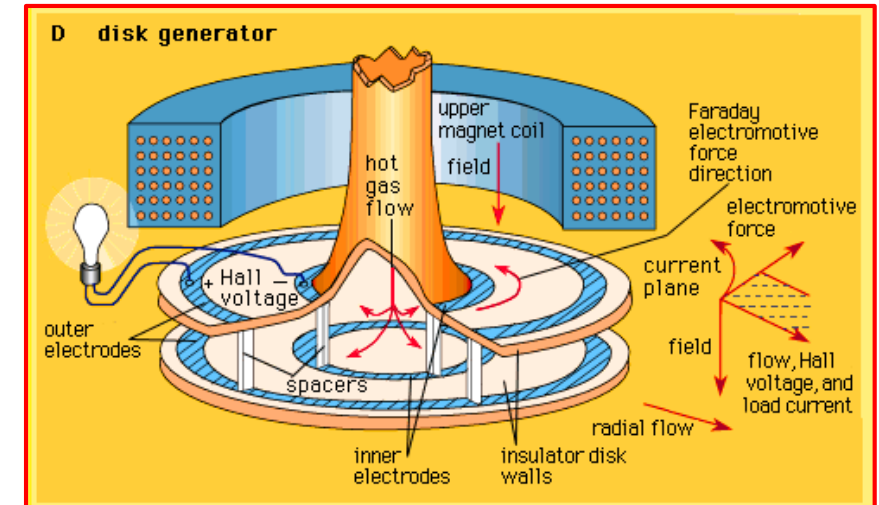
Types of MHD Generators



Linear



Disk



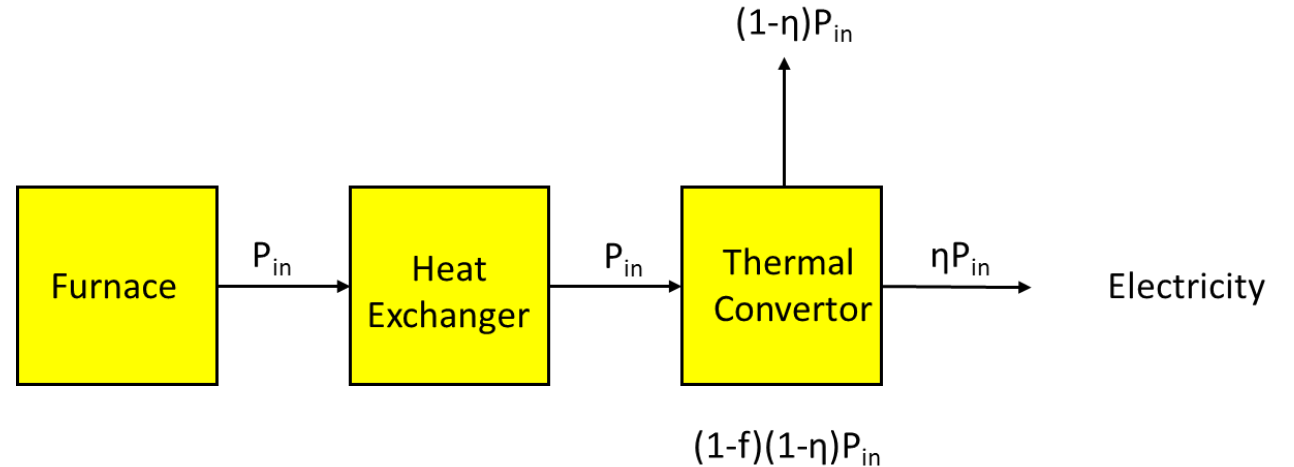
Our focus so far

- The linear Hall generator
- Easier to build than Faraday – Hall only requires 1 load
- Still, may require 100's of electrodes
- Disk is a cylindrical Hall generator – requires only 2 electrodes
- Disk is a more attractive long term option
- Still, our focus so far is the linear Hall generator
- Why? Simpler geometry $\longrightarrow$ simpler mathematics

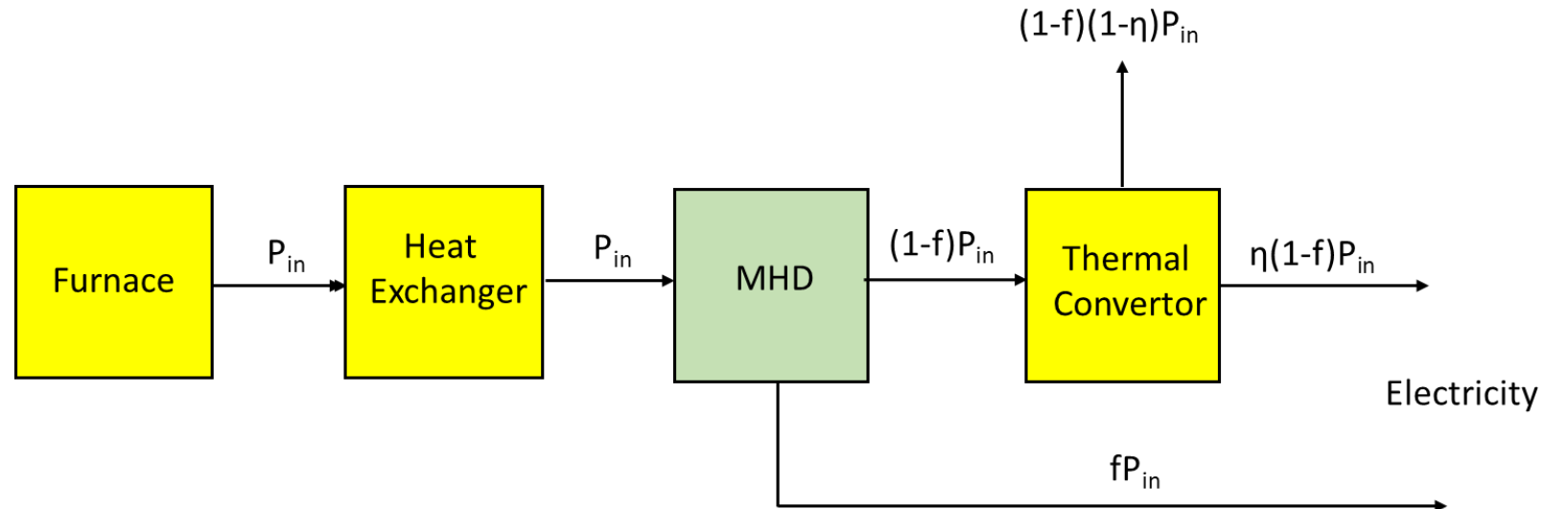
The Big Picture – Setting Our Goal

- Power plants for dummies

- Thermal plant



- Add MHD topping cycle



Typical power plant efficiencies

- Combined cycle gas: 0.55-0.6
- Coal: 0.35
- Nuclear (fission or fusion): 0.35

Desired enthalpy conversion fraction f

- Efficiency of a thermal plant

$$\frac{P_{out}}{P_{in}} = \eta = \eta_T = 0.35$$

- Add an MHD topping cycle

$$\frac{P_{out}}{P_{in}} = \eta = f + (1 - f)\eta_T$$

- Choose $f = 0.31$
- Then η increases from 0.35 to 0.55 – game changing improvement
- Achieving $f = 0.31$ is our goal

Impact on Coal

- MHD is easier for coal – open cycle, higher $T = 2000$ K
- Not too much world excitement for improving coal
- Actually might be **very good for retro-fitting** existing plants
- But, it should not be so good that we build new coal plants
- Retro-fitting would **add substantial capital** costs
- We have studied coal-MHD but this is not our main interest

Impact on Nuclear

- MHD is tougher for nuclear than coal – hard to achieve high T
- For a high T gas cooled reactor (HTGR) $T = 1000\text{ K}$
- Possible solution: closed cycle using Argon as the primary gas and a small amount 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
- Note: From the Saha equation $\frac{n_e(2000)}{n_e(1000)} = 2.4 \times 10^{11}$

Impact on Nuclear (cont.)

- Good news
 - Ohmic heating preferentially heats electrons
 - Slow Argon energy equilibration allows large temperature difference
 - $T(\text{A-neutrals}) = 500 \text{ K}$, $T(\text{K-electrons}) = 5000 \text{ K}$ – easy to make plasma
 - Ohmic heating not wasted heating the Argon

Impact on Nuclear (cont.)

- 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

- Mixed news

- High capital cost of nuclear an advantage(?)
- Extra cost of MHD relatively small – large payoff because of higher efficiency

Plasmas are not your friends



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
- MHD research largely terminated in 1990's
- OK but what about the technology problems

- Science and Technology improvements

- Development of high T, high B, superconductors
- Early experiments had $B = 3 \text{ T}$, now we have $B = 15 - 20 \text{ T}$
- Development of improved ionization stability theory
- Good clues how to improve performance

New Large Scale HTS Magnet (20 T)



Our research strategy

- Assume plausible input parameters from furnace (HTGR)
- Focus on the MHD generator
- Integrated power plant analysis not yet carried out
- Can MHD achieve $f = 0.31$ using
 - High B
 - Improved ionization stability operation

Improved ionization stability analysis

- Experimentally observed that ionization instability suppressed when seed gas is nearly fully ionized
- No clear derivation of this in the literature
- No early pioneers around to provide guidance and theoretical information
- In fact early derivations contradict full ionization hypothesis
- We have carried out a **new first principle derivation** of the ionization instability

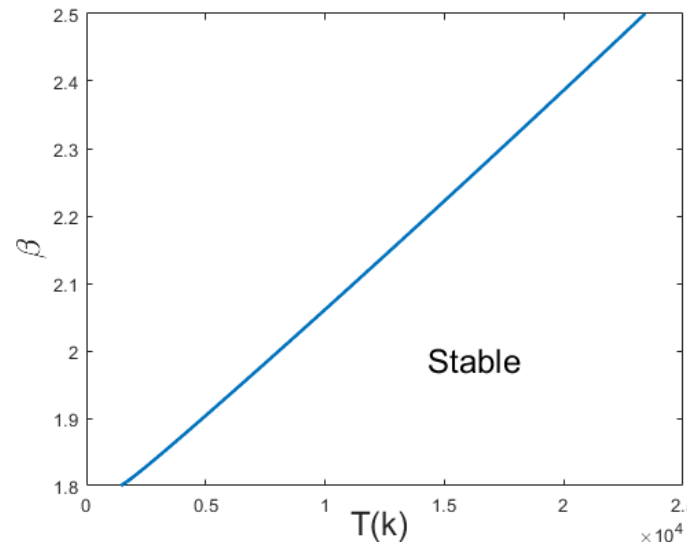
Ionization stability criterion – early reference

- For reference, old instability criterion (Rosa 1987)

$$\beta < 4 \frac{T_e}{T_i} \quad (\text{approx})$$

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

$$T_i = 50,360 \text{ K}$$



- Not related to the degree of ionization

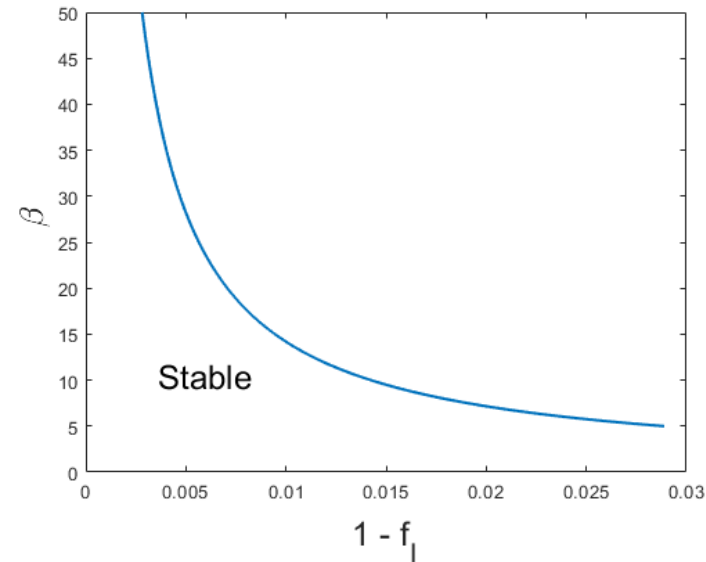
New first principles criterion

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

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

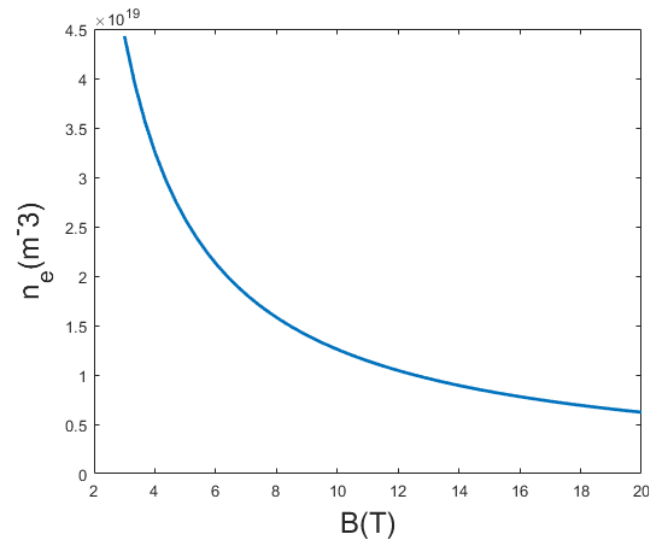
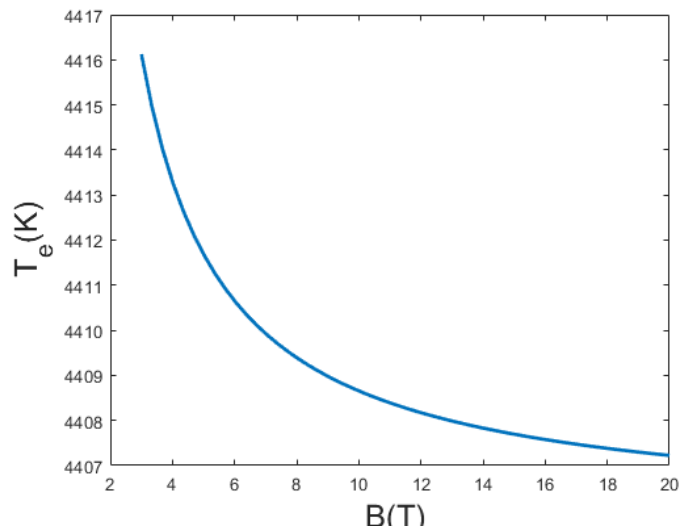
$$f_i = \frac{n_e}{n_s} \text{ seed fractional ionization}$$

- Stability for nearly full ionization



Practical Consequences

- Combine stability with electron power balance (typical HTGR reactor)



- Temperature is almost independent of B : $T_e \approx 4400$ K
- Temperature ratio: $T_e / T_A \approx 10$
- Lower the density as B increases

New model developed

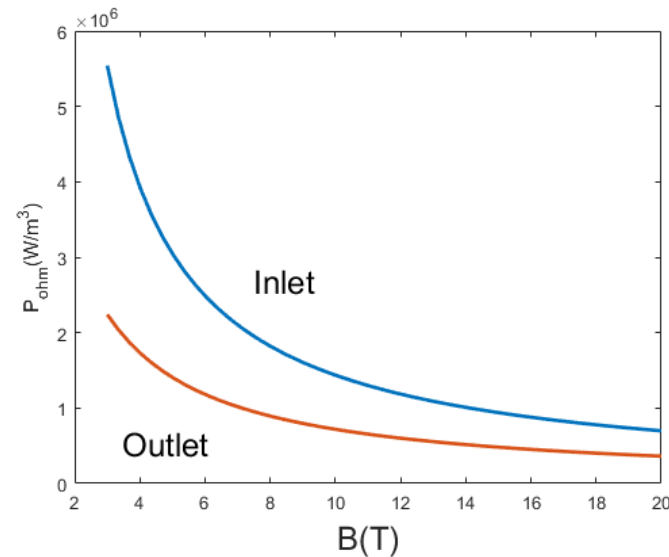
- New, self-consistent quasi 1-D model fully developed
- Describes detailed performance of MHD generators (linear and disk)
- Primary gas: Conservation of mass, momentum, and energy
- Seed gas: Saha equation, generalized Ohm's law, energy balance
- Open cycle (coal): set $T_e = T_p$
- Closed cycle: marginal ionization stability along entire length $T_e > T_A$
- Clever formulation allows simple closed cycle numerical solution

Some results

- Open cycle (coal): high B is a big win – high conversion efficiency, small size. Not our main interest
- Closed cycle (nuclear): code just developed. Preliminary results show high field can achieve $f = 0.31$ for reasonable size generators.
- For fixed electric power out, ohmic power density is reduced as B increases
- This implies better electrode lifetime: less heat load, less surface damage, smaller voltage drop across electrode, easier cooling
- High B implies a larger Hall parameter. MHD generator evolves to a higher voltage, lower current power output as B increases

A closed cycle example (Ohmic power density)

- Solution from our quasi 1-D code



- Observe that Ohmic power decreases by a factor of about 8 from $B = 3 T$ to $B = 20 T$

Future Plans

- Complete linear MHD analysis – does high B help or hurt the overall MHD reactor
- Assume a positive answer
- Examine Saha equation for electron creation near full ionization
- Redo entire analysis for disk geometry
- Develop an integrated power plant pre-conceptual design
- 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 – 10 MW power to the load