Theoretical design of an energy recovering divertor

Derek Baver

Lodestar Research Corporation

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D. A. Baver, Lodestar Research Corporation

An energy recovering divertor (ERD) is a device for converting thermal to electrical energy in the divertor channel of a tokamak. Because ERD's are a type of heat engine operating at plasma temperatures, they have the thermodynamic potential for extremely high efficiencies. An ERD offers several important benefits to a tokamak fusion reactor. First, any energy recovered by the ERD is subtracted from divertor heat load, thus circumventing materials limitations. Second, energy recovered by the ERD is available for auxiliary heating, thus allowing the reactor to break even at a lower Lawson parameter. Third, an ERD can be used to power auxiliary current drive, thus reducing dependence on bootstrap current.
We will present a design for an ERD based on amplification of Alfven waves in a manner analogous to a free-electron laser. While its projected efficiency falls short of the thermodynamic potential for this class of device, it nonetheless demonstrates the theoretical viability of direct power conversion in a tokamak divertor. We will also present potential approaches towards higher efficiency devices of this type.

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Outline

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Introduction

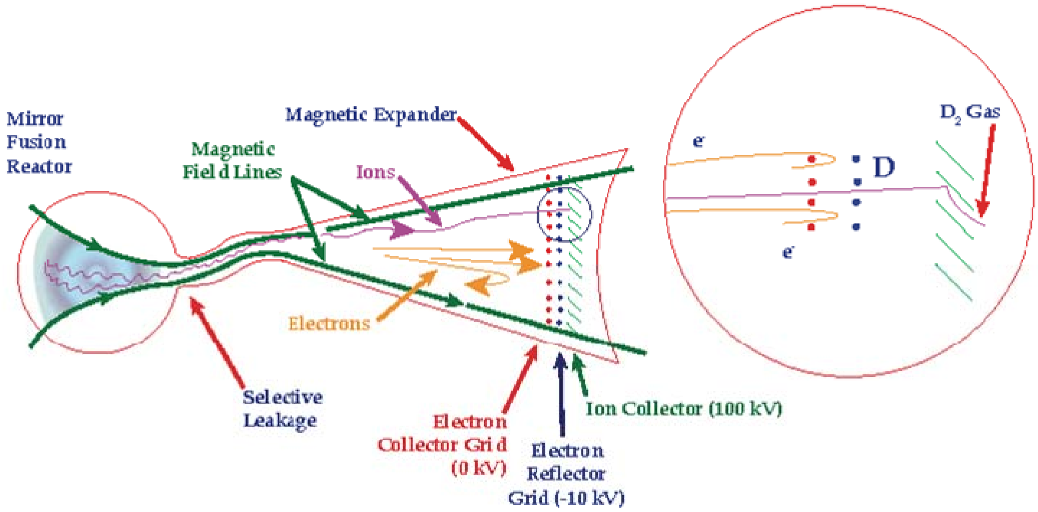
- An energy recovering divertor (ERD) is a type of plasma direct converter (PDC) designed to harness tokamak divertor plasma.
- PDC’s convert plasma thermal energy into electricity.
  - Multi-electrode design is common on mirror machines.
  - Efficiencies over 80% reported in some cases.
- ERD’s require different principles than PDC’s used on mirrors.
  - High density, low magnetic expansion renders multi-electrode design impractical.
  - Strong toroidal field necessitates PDC construction inside reactor vessel rather than as a separate device.
- Design presented here satisfies these conditions.
  - Alfven waves are able to penetrate plasma in high field, high density regime.

Motivation

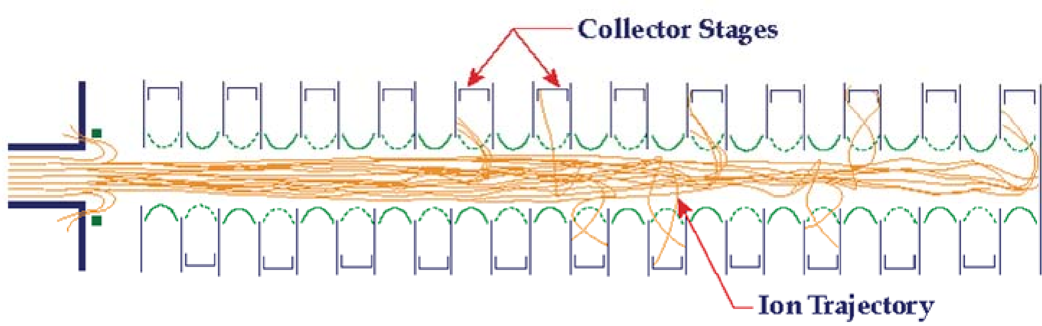
- Divertor heat flux problem:
  - Current calculations suggest challenging divertor heat fluxes for ITER, DEMO.
    - 10-20 MW/m^2 for ITER
      - Careful design pushes against materials constraints.
    - 30-40 MW/m^2 for DEMO
      - Exceeds current materials constraints.
  - Reduced heat flux necessary for viable reactor.
  - Current approaches emphasize spreading out heat.
    - Snowflake divertor
    - Super-X divertor
  - Alternate approach: prevent heat from reaching the divertor plate.
    - Electric power does not count towards thermal flux.
    - Extracted power provides additional benefits.
      - Impoved power plant efficiency.
      - Possibility of high recycled power operation.

Background

- PDC’s are devices to convert plasma heat into electricity.
  - Originally developed for mirror machines.
  - Plasma escaping one end of the mirror passes through a magnetic expander.
    - Converts perpendicular velocity into parallel velocity.
    - Reduces density.
  - A grid separates charged particle species.
  - One species passes a series of charged plates.
    - Electric field around plates focuses particles with sufficient energy to pass.
    - Reflected particles defocus and hit plates.
    - Particles are sorted by energy so that thermal kinetic energy is converted into electrical potential energy.
  - Very high efficiencies reported in experiments.
    - Cuspec: 70%
    - Moir-Barr-Carlson: 86%



A simple one-stage PDC with conical magnetic expander.*



A 22-stage PDC with ion trajectories inside focusing and collecting system.*

*from Direct Energy Conversion in Fusion Reactors, Ralph W. Moir, Energy Technology Handbook.

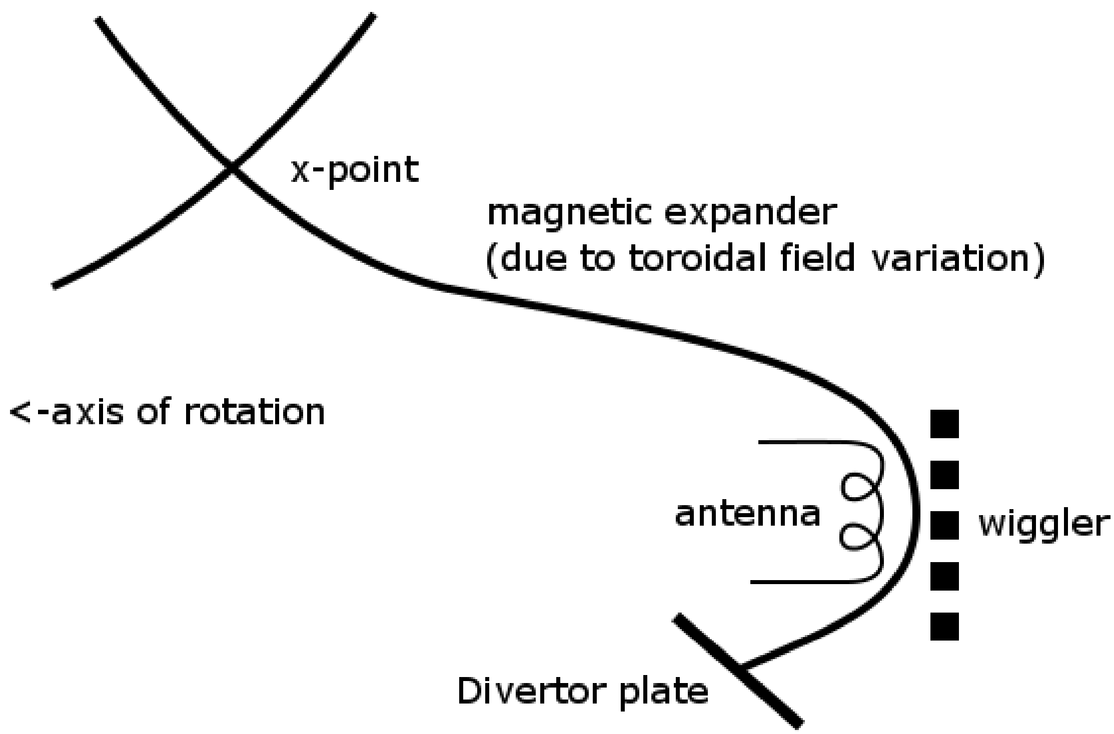
ERD Thermodynamics

- ERD efficiency is constrained by the second law of thermodynamics in two ways:
- General Carnot efficiency.
  - $\varepsilon=1-T_H/T_C$
  - T_H is plasma temperature
  - T_C is wall temperature
  - Efficiency ~99.9% for ERD
  - Not a significant issue given practical engineering constraints
- Carnot efficiency assuming constant phase space density.
  - T_C limited by ability of plasma to expand.
  - Ability of plasma to expand limited by conservation of mass flux.
    - Bulk plasma velocity is proportional to ion thermal speed.
    - Temperature is proportional to density to the 2/3 power.
    - Combining these gives temperature proportional to square root of cross-section area.
  - Combining this with Carnot efficiency formula gives maximum ERD efficiency in terms of area expansion.
    - $\varepsilon=1-(A_C/A_H)^{1/2}$

Main design

- Wiggler-Alfven approach.
- Plasma gains forward velocity due to mirror force from magnetic expander.
- Plasma enters region containing divertor toroidal Alfven eigenmode.
- Plasma passes wiggler magnet while subject to D-TAE.
- Ponderomotive force from beat wave traps plasma.
- Tapering of wiggler results in net deceleration.
  - Absorbed energy amplifies Alfven wave.
- Alfven wave absorbed by antenna and rectified.

Layout of wiggler-Alfven converter:



Ponderomotive plasma deceleration:

- Superposition of wiggler and Alfven wave yields beat wave.
  - Frequency determined by Alfven wave.
  - Wavelength dominated by wiggler.
  - Correct ratio of Alfven to wiggler wavelength yields beat wave resonant with ions.
  - Off-resonant particles also affected if potential wells are deep enough.
  - Reverse beat wave is not resonant with ions.
- Ponderomotive force at Alfven frequencies is attractive.
  - Force on electrons/ions can be attractive or repulsive depending on polarization direction.
  - Forces on different species are coupled by plasma potential.
  - Net force is approximately independent of polarization direction.

$$\frac{1}{m_i\,\omega(\omega+\Omega_{ci})} + \frac{1}{m_e\,\omega(\omega-\Omega_{ce})} \approx -\frac{1}{m_i\,\Omega_{ci}^2}$$

- Tapering wiggler gives net deceleration.
  - Bunched particles slowed as beat wave phase velocity slows.
  - Energy extraction limited by adiabatic heating from parallel compression.

Divertor toroidal Alfven eigenmode:

- Amplification of Alfven wave requires a bounded eigenmode.
  - Wave propagation to divertor plate results in absorption by sheath.
  - Wave propagation to X-point results in absorption by bulk plasma.
- To lowest approximation, shear Alfven waves propagate parallel to magnetic field.
  - Waves eventually collide with divertor plate.
- Taking into account finite thickness of divertor plasma adds correction term to dispersion relation.
  - Waves have component of group velocity in poloidal direction.

$$\frac{v_{gx}}{v_{gz}} \approx \mathrm{h}\, k_x \text{ if } k_x << k_z \;,\; \frac{v_{gx}}{v_{gz}} \approx \frac{h\, k_z}{2} \text{ if } k_z << k_x$$

  - Allows waves to propagate toroidally despite field line pitch angle.
- Toroidally propagating wave confined by variations in radius.
  - Alfven speed decreases with radius.
    - Magnetic field squared falls faster than density.
  - Angular phase speed decreases with radius.
  - Wave with fixed toroidal mode number will be refracted to largest radius.

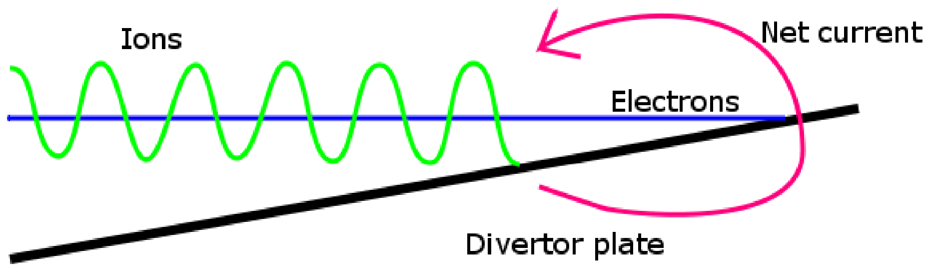
Plasma expansion and efficiency estimates:

- Magnetic expander generates mirror force.
  - Converts perpendicular temperature to parallel temperature and KE.
- Collisions equilibriate parallel and perpendicular temperature.
  - Parallel temperature converted into perpendicular temperature.
  - Thermal energy has multiple opportunities to convert to KE.
- Plasma potential couples ion and electron KE.
  - Density gradient in magnetic expander creates plasma potential gradient.
  - Plasma potential accelerates ions.
- If plasma is collisional, then efficiency can be estimated based on thermodynamic constraints.
  - Expansion ratio ~2-3 yields efficiency ~29-42%.
- If plasma is weakly collisional, ions will be unable to expand efficiently.
  - Residual parallel thermal energy impedes deceleration due to adiabatic compression.
  - Electrons can still equilibriate due to higher collision frequency.
  - Expansion ratio ~2-3 yields efficiency ~15-21%.

Secondary design

- Motivation: size and efficiency
  - Efficiency of wiggler-Alfven converter is limited by magnetic expansion ratio.
    - $\varepsilon=1-(B_o/B_i)^{1/2}$
  - Magnetic expander is awkward.
    - Adds extra volume inside toroidal field coils.
    - Existing tokamaks may not be able to retrofit to allow for this divertor geometry.
  - Much greater expansion ratio possible from pitch angle of divertor plates.
    - Expansion ratio ~100.
    - Yields theoretical efficiency ~90%.
  - Also yields more compact design.
    - Pitch angle used instead of magnetic expander.
    - ERD would be barely larger than existing divertors.
    - Would fit into nearly any existing tokamak.

- Method: lateral ion scrape-off
  - Elliptically polarized wave near sheath.
  - Normal component of wave motion modulates plasma contact with divertor plate.
    - Roving zones of high sheath current.
    - Separated by zones of low sheath current.
  - Ions and electrons exit plasma at different locations due to FLR effects.
    - Electrons follow field lines until they reach divertor.
    - Ions leave when guiding center passes within Larmor radius of divertor.
    - If wave has correct wavelength, ions and electrons leave via different contact points.
    - Results in plasma current tangential to surface.
  - Modulation of tangential plasma current amplifies tangential wave motion.
    - Optimal wave amplitude cancels ion perpendicular motion.
    - Perpendicular ion energy recovered



- Additional electron and parallel energy recovered by other means.
  - Electron parallel energy charges potential of magetized sheath.
    - Converts to ion perpendicular energy.
  - Electron perpendicular energy converts to parallel energy via collisions.
    - Electron collision frequency is high.
  - Ion parallel energy can be harnessed via wiggler-Alfven scheme
    - Limitation on efficiency due to compressional heating during deceleration mitigated by particle losses at sheath.

Issues with secondary scheme:

- Requires plasma waves near sheath.
  - Sheath effects can absorb these waves.
  - Absorption must be less than wave amplification for net power extraction to occur.
  - Absorption can be avoided if divertor is electrically insulating.
    - Charge accumulation on divertor surface counteracts variations in sheath current.
  - Insulating divertor requires exotic materials.
    - Synthetic diamond?
- More complicated construction
  - Requires wiggler for optimum efficiency.
  - Divertor plates must be sculpted to match perturbed magnetic field.
    - Wiggler is next to divertor, unlike in pure wiggler-Alfven approach.
- Not suitable for initial prototype.
  - High failure risk compared with pure wiggler-Alfven converter.

Conclusions

- Energy recovering divertors can significantly alter the energetics of a fusion plasma.
  - Reduced divertor heat flux.
  - More available power for profile control.
  - Reduced Lawson parameter threshold for breakeven.
- The wiggler-Alfven approach provides a promising route to an ERD.
  - Modest efficiency.
  - Simple design and operation.
- Other ERD designs offer potential for future improvements.
  - Extremely high efficiency.
  - More complex construction and operating mechanisms.