Electrical theory of thermodynamics & Particle scale heat engines

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Abstract

In most conventional sources, including nuclear, chemical and photovoltaic, the energy manifests initially in the form of extremely energetic **"hot particles"**, and then rapidly disperses into the surrounding bulk medium as heat. In chemical and photovoltaic scenarios, energy gets released or absorbed, respectively, in units of around **1-5 eV**, less a work function of at most about **1 eV**. Given that $\mathbf{1\ eV \approx 1.16 \times 10^4\ K}$, the nascent chemical reaction products and photoelectrons thus have temperatures of the order of $\mathbf{10,000\text{-}50,000\ K}$. The daughter nuclei in U^{235} decay carry **55-100 MeV** [1], which correspond to $\mathbf{10^{12}\ K}$. The Carnot efficiency for direct conversion of chemical hot particle energies would be **97-99%**, and virtually **indistinguishable from unity** for nascent nuclear fission products. The hot particles are so called because they are indeed this hot against the backdrop of bulk medium temperature, and therefore represent an extremely low entropy energy source. However, all conversion methods have been historically limited by thermal diffusion processes. I explain below the two theoretic challenges to hot particle energy conversion, how both can be solved using electromagnetic fields in the place of mechanical pistons, and the practical challenges to be addressed. The approach would be best employed for "front-end" conversion, as the uncaptured waste heat would be left in the bulk medium for the conventional generators.

Conversion of hot particle energies

FUNDAMENTAL CHALLENGES

Sub-picosecond lifetimes

In solids, the dispersion of hot electron energies to an initial set of phonons occurs on the order of **100 fs**. The initial phonons relax into heat in **1-10 ps** [2][3]. Relaxation processes vary in speed, and are generally slower in gases. A convertor needs to harness the hot particles for work within the corresponding relaxation times.

The Carnot efficiency would be highest for exploiting hot particles directly. The initial phonon temperatures reflect the inertia of the atoms participating in the phonon mode, and are already down to **10-50 meV ∼ 100-500 K** in photovoltaic semiconductors. The temperatures of the secondary and tertiary phonons diminish progressively, blending into the bulk.

Randomness of times, locations and motions

In general, hot particles occur randomly at random locations in a bulk medium, and speed in random directions. The convertor will not know their occurrence times, locations, or directions.

This information cannot be acquired for use in the conversion. An attempt to learn would reduce to the Maxwell demon problem and would be impossible, by the second law of thermodynamics [4].

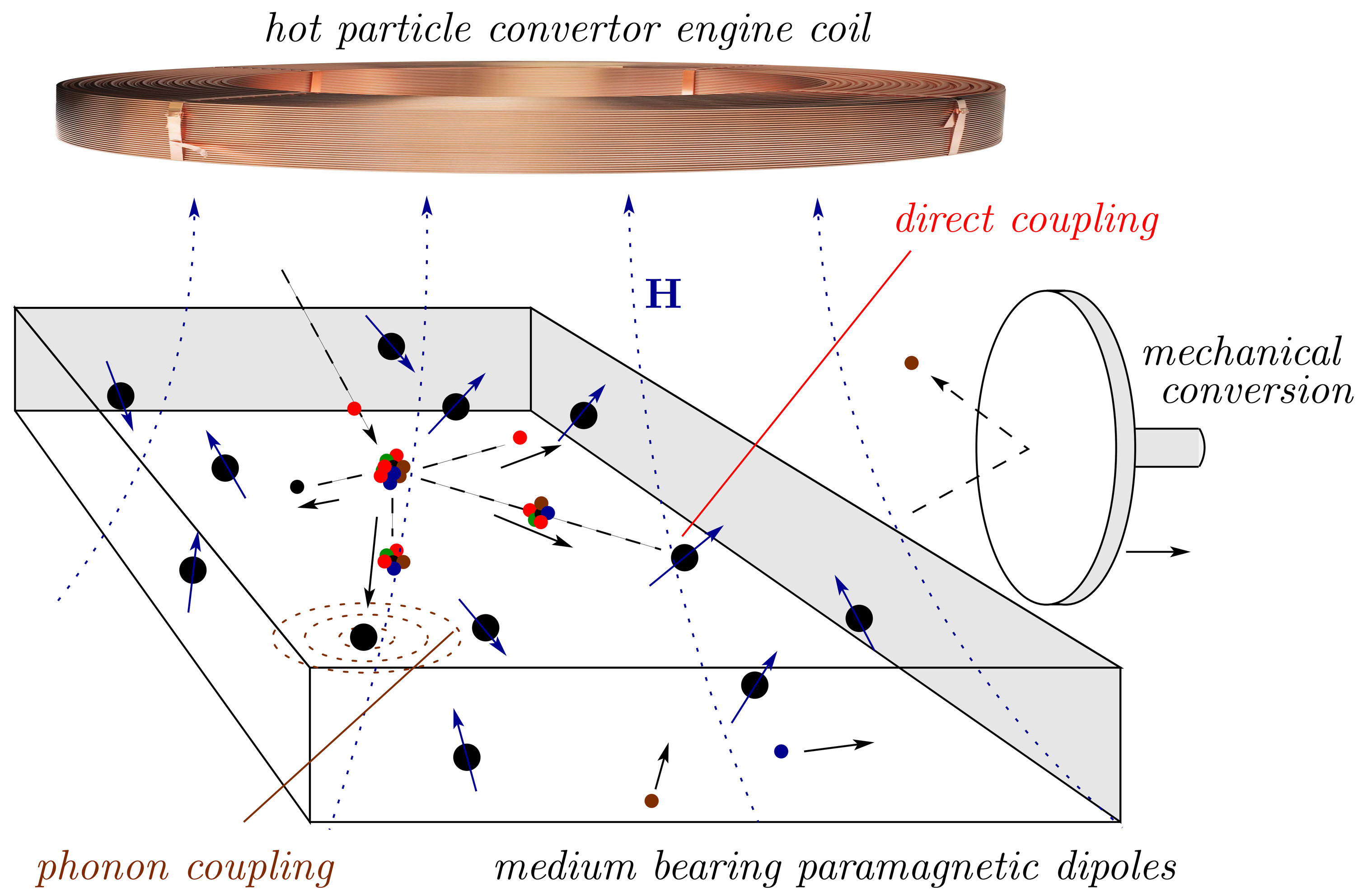

Fig. 1: Hot particle energy conversion

Fig. 1 illustrates the novel concept of intercepting and converting the energies of hot particles before their temperature gets diluted by the bulk medium. Both direct and phonon coupling are shown for completeness. Notice that unconverted hot particle energies would remain available for conventional mechanical conversion, which cannot exploit the hot particles.

TRADITIONAL CONSTRAINTS

Pistons and blades need molecular contact

In a gas engine, work is performed only by the molecules that impact the piston or turbine blade. Some of these may happen to be hot at the moments of impact, but the majority of molecules only reflect the bulk temperature. Hence, the energy gets only utilized *after* dilution into the bulk medium by thermal relaxation processes.

Current methods are diffusion-bound

Even in thermoelectric and photovoltaic technologies, the generated potential gradients and emfs again result from diffusion processes. In fact, quantum dot solar cells research seeks to block Auger processes, because they bypass the *phonon bottlenecks* that would prevent the photoelectrons from turning prematurely into heat (cf. [2, p218]).

Solution

Use induction for instant, uniform contact

An electric or magnetic field can provide instant contact with all parts of the medium, *avoiding need for diffusive transfer.*

Use a heat engine to convert

– without depending on the locations or directions of motions.

Electrical heat engines theory

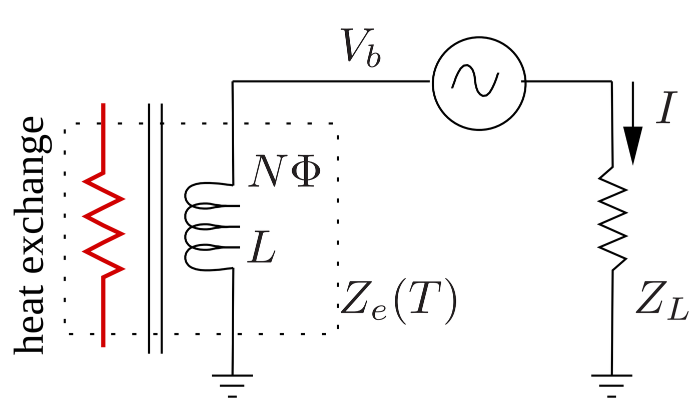

Fig. 2: Inductive heat engine

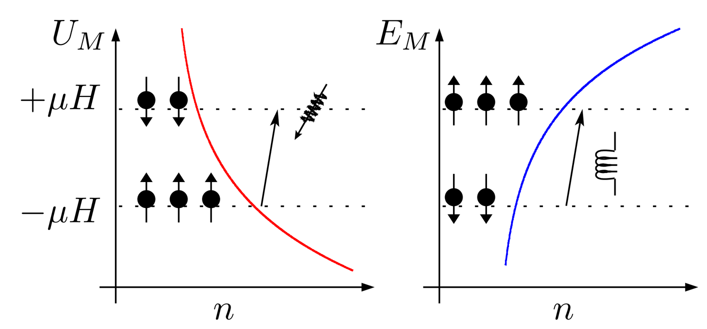

Fig. 3: Energy distributions

Fig. 2 illustrates the basic inductive heat engine circuit. The magnetic medium is the thermodynamic medium. In this context, the heat exchange is conceptual and the medium is preferably superparamagnetic. Fig. 3 illustrates the occupancy of energy levels by the dipoles under magnetization by a nonzero current $\boldsymbol{I}$. In magnetization, the current does work $\mathbf{2\mu_B H}$ on the dipole, which is lost to heat as phonons.

During demagnetization, phonons or hot particles must conversely do work flipping the dipole against the coupled load circuit. Net work is done if the demagnetizing hot particles or phonons are hotter (Fig. 4).

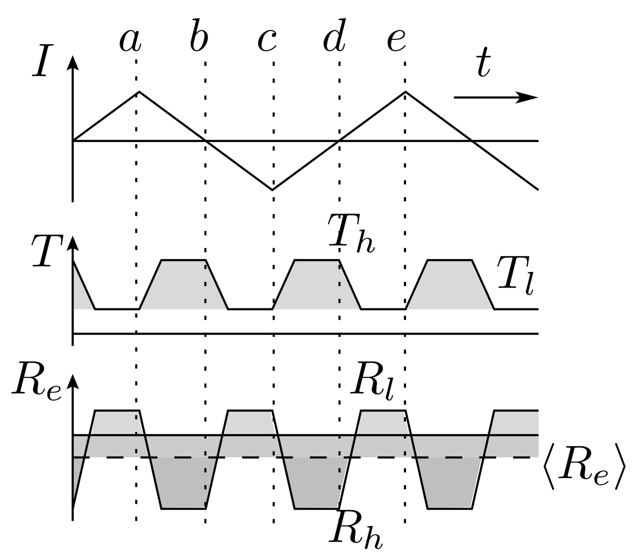

Fig. 4: Timing diagram

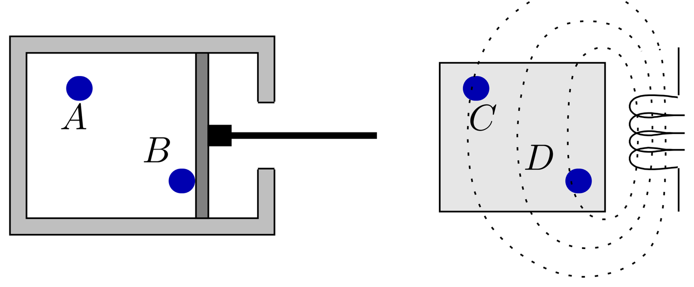

Fig. 5: Additive conversion

The theory of inductive engines is developed in detail in the paper. Fig. 5 illustrates the molecular contact problem in mechanical engines that limits them to the much lower bulk temperature, and how the magnetic field provides simultaneous coupling throughout the medium, so that the hot particles can work directly on the load.

Example: hot carriers in CMOS

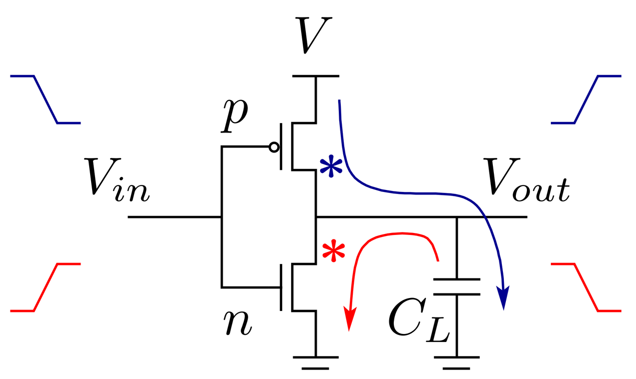

Fig. 6: CMOS dissipation

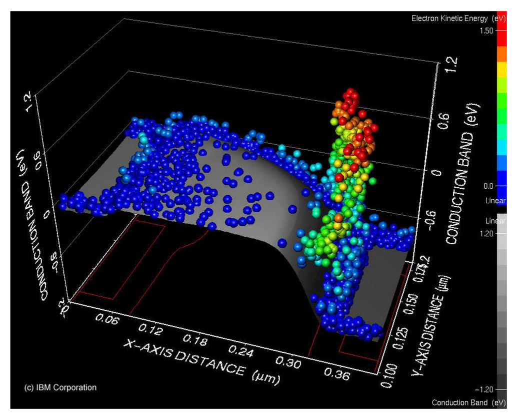

Fig. 7: Hot carriers

Fig. 6 illustrates switching dissipation in CMOS chips. The load $\boldsymbol{C_L}$ refers to the gate capacitance of the next stage. The '*' indicates the drain end of the MOSFET channel where the dissipation occurs.

Fig. 7 is a 3D plot of the carrier energies that occur during a CMOS gate transition. As the plot shows, only about **10%** of the carriers become "hot", and are responsible for most of the dissipation, and most of the lattice damage via impact ionization.

Current chip cooling research is however still focused on removing only the bulk heat using thermoelectric, micro heat pipes and micro fluidics, and lattice damage is being addressed only by reducing the operating voltage. Processor manufacturers have been stuck at a speed barrier of under **5 GHz** for over five years!

With front-end energy removal from hot carriers, it should be possible to raise clock speeds to **100 GHz** using current semiconductor and chip design technologies.

Conclusion

Similarities in photovoltaic work

Efforts to slow the relaxation of photoelectrons are another form of competing with thermal diffusion, and are expected to yield efficiency of the order of **85%** [2].

Where we stand

Both traditional generation and chip cooling technologies are lagging in terms of competing with relaxation processes. The electrical formalism of heat engines provides the link to thermodynamic theory so that relaxation processes can be similarly researched in these scenarios to enable mankind to exploit heat at fundamentally better efficiencies.

References

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[2] A Martí and A Luque, editors. *Next Generation Photovoltaics: High Efficiency through Full Spectrum Utilization (Series in Optics and Optoelectronics).* IOP, 2004.

[3] W M Rohsenow, J P Hartnett, and Y I Cho, editors. *Handbook of Heat Transfer.* McGraw-Hill, 1998.

[4] C H Bennett. Demons, Engines and the Second Law. *Sc Am*, Nov 1987.