Single-Volume Magnetic Reconnection Converter (MRC) with Variable β of Plasmas

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The Aim

In the work, we consider the justification of the magnetic reconnection converter (MRC) based on single-volume plasma (spheromak) with variable β of plasmas at turbulent pumping/discharge phases of the operating cycle. For obtaining the useful energy output in the proposed MRC using the cyclic combination of two physical processes:

1) controlled turbulence using super-linear Richardson diffusion and/or self-generated/self-sustaining physical processes increases the stochasticity of the magnetic field (MF) in a limited volume of plasma and, accordingly, the global helicity H through the processes of twisting, writhing, and linking of the MF flow tubes to the level of a local maximum (optimally global), which is determined by the plasma parameters, boundary conditions, magnetic tension of the field lines, etc. At this stage of the MF turbulent pumping, the β of plasma will decrease to the minimum possible value with a corresponding increase in the accumulated "topological" MF energy;

2) upon reaching the local (if possible global) maximum of MF stochasticity, turbulent magnetic reconnection (TMR) occurs in the plasma, which reduces the state of the local (if possible global) maximum of MF stochasticity and increases the kinetic stochasticity of plasma particles, accelerating and heating them, which is used in direct converters of electrical power and external magnetic coils due induced inner currents in plasmas. At this stage of turbulent discharge, the β of plasma will be increasing to the maximum possible value with a corresponding increase in its kinetic and thermal energy;

3) when the kinetic stochasticity of plasma particles subsequently decreases and reaches a local minimum, the control system repeats the MF turbulent pumping in the plasma, and the cycles are repeated.

The Mathematical Model: applied notations

- H: Global magnetic helicity within the single volume, **B**: Magnetic field,
- β: Plasma beta, E_{kin}: Kinetic energy of particles,
- T: Turbulence intensity, R_i: Richardson number,
- Γ: Turbulence generation rate, η: Magnetic diffusivity,
- **J**: Current density, **E**: Electric field,
- V: Plasma volume, S: the surface area enclosing the plasma volume,
- **A**: Vector potential, p: Plasma pressure
- pm: Magnetic pressure (magnetic energy density), n: Plasma number density,
- kB: Boltzmann constant, T: Plasma temperature,
- μ0: the permeability of free space $4\pi \cdot 10^{-7}$ N/A^2

The Mathematical Model: equations

Stage 1: Conditions for Turbulent Pumping and Plasma Expansion:

- **Helicity evolution:** $\frac{dH}{dt} = 2\int_V \boldsymbol{E}\cdot\boldsymbol{B}dV - 2\eta\int_V (\boldsymbol{J}\cdot\boldsymbol{B})dV + \alpha R_i^{\,m} I + f(\Gamma)$, (1)
where m > 1 represents the super-linear dependence on the Richardson number and f(Γ) represents the self-driven turbulence.

- **Energy evolution:** $\frac{dW}{dt} = -\int_S \boldsymbol{S}\cdot d\boldsymbol{A} - \eta\int_V J^2 dV + \beta\frac{dH}{dt}$, (2)
where β is the ratio of plasma pressure to magnetic pressure: $\beta = \frac{p}{p_m} = \frac{nk_BT}{B^2/2\mu_0}$, (3)

- **Plasma Beta decrease and Volume Expansion**: $\frac{d\beta}{dt} < 0,\ \frac{dV}{dt} > 0$, (4)

- **Termination Condition**: $H \geq H_{target}$ or $W \geq W_{target}$, (5)

The Mathematical Model: equations

Stage 2a: Conditions for Turbulent Magnetic Reconnection (TMR) and Plasma Compression:

- **Magnetic Reconnection Rate:** $\frac{dR}{dt} \approx V_A\left(\frac{1}{L}\right)^{\frac{\alpha}{2}} f(R_i)(\Gamma)$, (6)
where V_A is Alfven velocity in plasma, L – is magnetic reconnection scale, α is gain of turbulence pumping.

- **Energy Conversion:** $\frac{dW}{dt} = -\frac{dW_{kin}}{dt} - \frac{dW_{th}}{dt} - \frac{dW_{rad}}{dt} - \frac{dW_{loss}}{dt} - P_{coil}$, (7)
where the first four terms are changes of kinetic, thermal, radiation, and loss energy, and P_{coil} is the power extracted by the outer coils due to electromagnetic induction at changing plasma currents.

- **Helicity Evolution during Reconnection:** $\frac{dH}{dt} = \frac{dH}{dt} - \frac{dH_{loss}}{dt}$ (8)
this equation highlights that helicity is not perfectly conserved during reconnection, and there might be losses.

- **Plasma Beta increase and Volume Compression:** $\frac{d\beta}{dt} > 0,\ \frac{dV}{dt} < 0$, (9)

- **Termination Condition**: $R \geq R_{target}$, (10)

The Mathematical Model: equations

Stage 2b: Conditions for Energy Extraction and Plasma Relaxation:

- **Energy Extraction:** $\frac{dW_{kin}}{dt} = -P_{outtws} - P_{outpd} - P_{coil} - \frac{dW_{th}}{dt} - \frac{dW_{loss}}{dt}$, (11)
where first three terms are power of direct energy conversion by using traveling wave structure (TWS), plasma dynamic converter (PDC), and plasma varied volume induction method (PVVIM) in outer coils, and next two terms are thermal and loss power.

- **Plasma Relaxation:** $\frac{dT}{dt} < 0,\ \frac{d\beta}{dt} < 0,\ \frac{dH}{dt} < 0$, (12)

- **Termination Condition:** $W_{kin} \leq W_{kinmin}$, (13)

Cycle Repetition:

- The control system monitors W_{kin}.
- When condition (13) holds, the system initiates Stage 1 again.

The Mathematical Model: Overall Efficiency

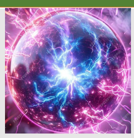
Overall Efficiency of 1-V MRC var β using direct energy conversion by traveling wave structure (TWS), plasma dynamic converter (PDC), and plasma varied volume induction method (PVVIM) in outer coils is:

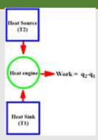
$\eta_{overall} = \frac{P_{outtws}+P_{outpds}+P_{coil}}{P_{in}}$, (14).

The overall efficiency and output power of the 1-volume MRC at increasing the work cycle frequency by 10% are shown in Table 1 (calculation made in PYTHON):

Cycle Frequency (Hz)	Output Power (MW)	Overall Efficiency
1.1	0.22	0.13
2.2	0.27	0.16
3.3	0.32	0.19
4.4	0.37	0.22
5.5	0.42	0.25
6.6	0.46	0.28
7.7	0.51	0.31
8.8	0.56	0.34
9.9	0.61	0.37
11.0	0.66	0.40

An Analogy with the Carnot Cycle

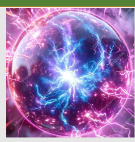


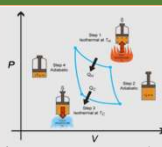


We may consider magneto-thermodynamic processes in 1-V MRC var β as the next interacting "systems":

1. **The local electromagnetic fields** which periodically turbulent magnetic reconnect (TMR) in various scales (a cascade of plasma turbulence eddies) as a heat source due to releasing magnetic energy at changing magnetic topology.
2. **The working body – plasma** under external turbulence control (pumping – discharge or magnetic reconnections of inner local fields) as a heat engine at working cycle compression-expansion of plasma.
3. **The surroundings** as a heat sink. Also, it included external direct energy converters and magnetic coils.

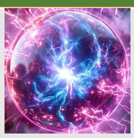
An Analogy with the Carnot Cycle

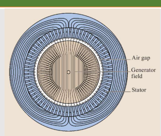




Step 1, Qusiisothermal Expansion: heat, Q_H, is absorbed from the hot reservoir at temperature T_H (TMR at multi-scales). The heat goes into pushing the piston up (direct energy converter) as the gas (plasma) expands.
Step 2, Qusiadiabatic Expansion: the heat sources are remove (multi-scale TMR finished), and allow the gas (plasma) to expand adiabatically with no heat added to the system, and the temperature of the gas (plasma) drops to the temperature of the cold reservoir, T_C (the surroundings plasmas).
Step 3, Qusiisothermal Compression: turbulence do work on the gas (plasma) to compress it at the same (about constant) the temperature. Instead, the heat, Q_c is transferred to the cold reservoir (the surroundings plasmas).
Step 4, Quasiadiabatic Compression: turbulence do work on the gas (plasma), but no longer allow the heat to be transferred to the cold reservoir (the surroundings plasmas) as for start of TMR need to rise back to T_H.

An Analogy with the rotating Electrical Machine





The proposed 1-volume MRC with its cyclic plasma compression and expansion, accompanied by changes in plasma beta, indeed bears a resemblance to the rotor-stator interaction in an electrical machine:

1. **Rotor Analogy:** The plasma volume can be likened to the rotor, undergoing periodic compression and expansion. The changing magnetic field configuration and plasma beta during these phases mimic the rotating magnetic field in a rotor.
2. **Stator Analogy:** The external magnetic field coils surrounding the plasma chamber can be seen as analogous to the stator in an electrical machine. They provide the confining magnetic field and interact with the changing plasma configuration to induce currents and potentially generate additional electrical power.

Single-Volume Magnetic Reconnection Converter (MRC) with Variable β of Plasmas (1-V MRC var β)

Thank you very much for your attention!

For questions and propositions:

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