Studies of Closed Cycle MHD Electrical Power Generation at Tokyo Institute of Technology

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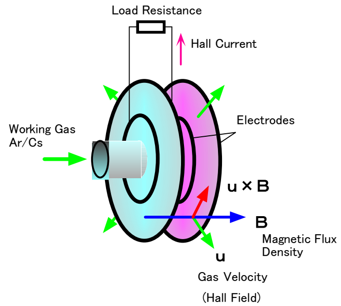

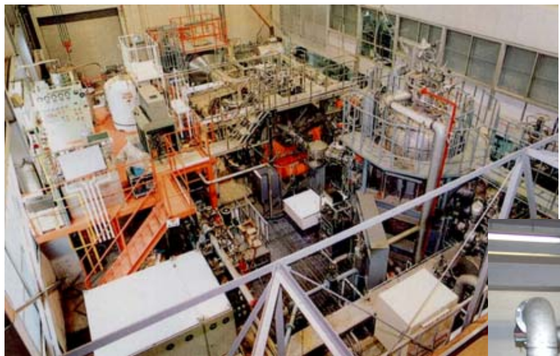

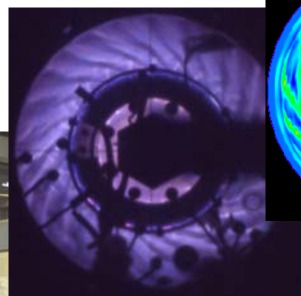

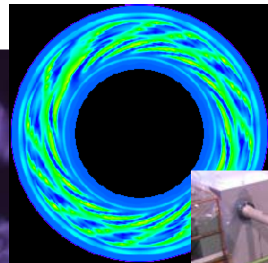

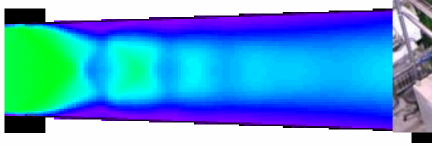

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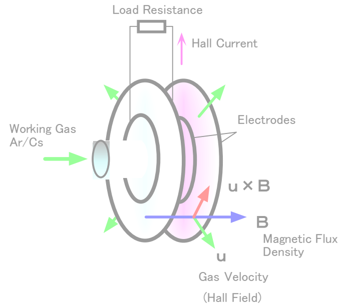
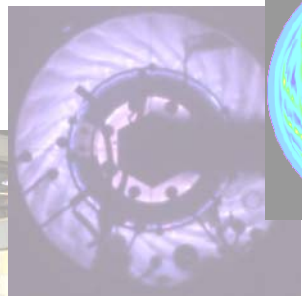
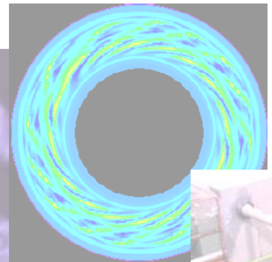
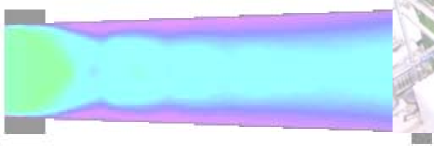
- ***MHD Flow Behavior and Performance of MHD generator***
- ***Improvement by applying RF Electromagnetic Filed***









Numerical Simulation of MHD Nonequilibrium Plasma Flow

- **Basic Equations**
- **Plasma Structure and Behavior**

Plasma & Fluid Flow in MHD Generator

Supersonic (compressible) Flow ー

Development and Separation of Boundary Layer,

Shock wave, Turbulence

Plasma Electrical Conducting Flow –

Nonequilibrium Ionization, (weakly) magnetized Plasma,

Self-excited electromotive force

Plasma Instability => Self-organized Plasma Structure

MHD Interaction-

Lorentz Force – Energy Conversion

Governing Equations of MHD Flow

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$

Momentum Equation:

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = \vec{j} \times \vec{B} - \nabla p - \vec{P}_L$$

Energy Equation:

$$\frac{\partial E_s}{\partial t} + \nabla \cdot \{(E_s + p)\vec{u}\} = \frac{\left|\vec{j}\right|^2}{\sigma} + \vec{u} \cdot (\vec{j} \times \vec{B}) - Q_L$$

Equation of State:

$$E_s = \rho c_v T_g + \frac{1}{2} \rho u^2$$

$$p = \rho R T_g$$

Governing Equation of Electromagnetic field

Generalized Ohm's Law (from Momentum Equation of Electrons)

$$\vec{j} + \frac{\beta}{|B|}(\vec{j} \times \vec{B}) = \sigma \left(\vec{E} + \vec{u} \times \vec{B} + \frac{\nabla p_e}{e n_e} \right)$$

Hall Parameter $\beta = \varpi_e \tau_e = \dfrac{eB}{m_e \nu_e} \quad (rad),$

Electrical Conductivity $\sigma = \dfrac{e^2 n_e}{m_e \nu_e} \quad (S/m)$

Maxwell's Equations

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad \nabla \times \vec{H} - \frac{\partial D}{\partial t} = \vec{j}, \quad \nabla \cdot D = \rho^c, \quad \nabla \cdot B = 0$$

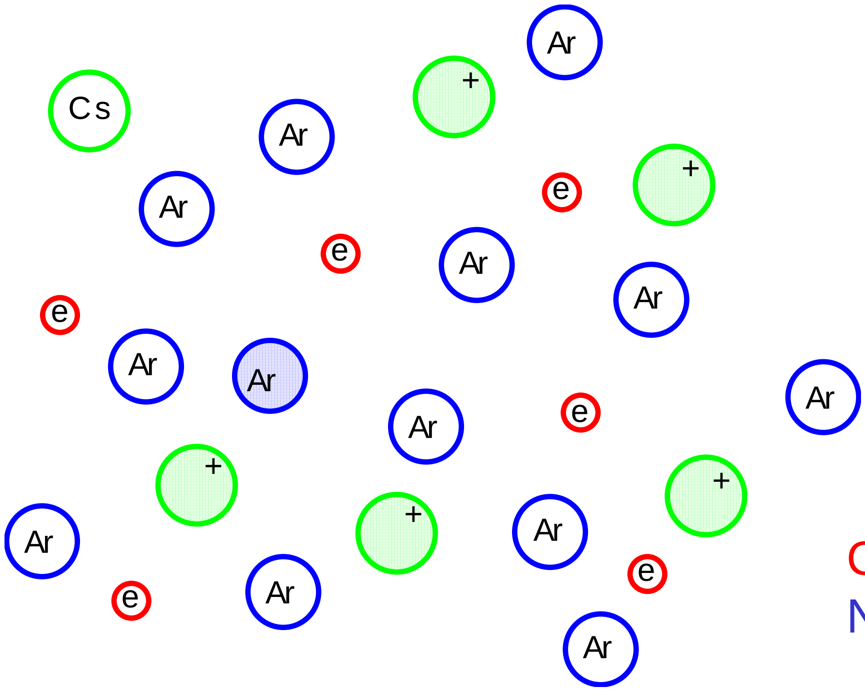
MHD Approximation:

- neglecting displacement current
- charge neutrality
- Low magnetic Reynolds number

$$\nabla \times \vec{E} = 0, \qquad \nabla \cdot \vec{j} = 0$$

Ar/Cs Nonequilibrium Plasma

Ar, Ar^{+}, Cs, Cs^{+}, e



$$Seed \ \ fraction = \frac{n_{Cs}}{n_{Ar}}$$

$10^{-5} \sim 10^{-4}$

$$n_e = n_{Cs}^{+} + n_{Ar}^{+}$$

Collision Dominant
Nonequilibrium plasma（Te>Tg）
=> *Two-Temperature Model*

Two-Temperature model of Nonequilibrium Plasma

Ion Continuity Equation:

$$\frac{\partial n_i^+}{\partial t} + \nabla \cdot (n_i^+ \vec{u}) = k_{f_i} n_e n_i - k_r n_e^2 n_i^+ \qquad i = seed\ ,\ noble\ gas$$

Collisional Ionization
– Three-Body (Collisional) Recombination

Charge Neutrality:

$$n_e = \sum_i n_i^+$$

Electron Energy Equation:

$$\frac{\partial U_e}{\partial t} + \nabla \cdot (U_e \vec{u}_e) = \boxed{\vec{j} \cdot (\vec{E} + \vec{u} \times \vec{B})} - p_e \nabla \cdot \vec{u}_e - \nabla \cdot \vec{q}_e - \boxed{\sum_h \frac{2m_e}{m_h} \nu_{eh} n_e \frac{3}{2} k (T_e - T_g)} - \dot{R}$$

Joule Heating

Collision Loss

$$U_e = \frac{3}{2} n_e k T_e + \sum_i n_i^+ \varepsilon_i$$

Basic Equations of Nonequilibrium Plasma MHD Flow

Nonequilibrium Two-Temperature Plasma Model:

$$\frac{\partial n_i^+}{\partial t} + \nabla \cdot (n_i^+ \vec{u}) = k_{f_i} n_e n_i - k_r n_e^2 n_i^+ \qquad n_e = \sum_i n_i^+$$

$$\vec{j} + \frac{\beta}{B}(\vec{j} \times \vec{B}) = \sigma(\vec{E} + \vec{u} \times \vec{B} + \frac{\nabla p_e}{e n_e})$$

$$\frac{\partial U_e}{\partial t} + \nabla \cdot (U_e \vec{u}_e) = \vec{j} \cdot (\vec{E} + \vec{u} \times \vec{B}) - p_e \nabla \cdot \vec{u}_e - \nabla \cdot \vec{q}_e - \sum_h \frac{2 m_e}{m_h} \nu_{eh} n_e \frac{3}{2} k (T_e - T_g) - \dot{R}$$

MHD Flow Equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \qquad p = \rho R T_g$$

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = \vec{j} \times \vec{B} - \nabla p - \vec{P}_L$$

$$\frac{\partial E_s}{\partial t} + \nabla \cdot \{(E_s + p)\vec{u}\} = \frac{|\vec{j}|^2}{\sigma} + \vec{u} \cdot (\vec{j} \times \vec{B}) - Q_L$$

Maxwell's Equations:

$$\nabla \times \vec{E} = 0, \qquad \nabla \cdot \vec{j} = 0$$

Numerical methods

Fluid Flow Equations（Continuity Equation, etc）

Hyperbolic type Equations:

MacCormack Method,

TVD (Total Variation Diminishing) Method

CIP (Cubic Interpolated Propagation) Method, etc

Electromagnetic Field Equations

Generalized Ohm's Law + Maxwell' Equations

=> Elliptic Equation (for electric potential function)

Finite Differential Method, Final Element Method

+ Bi-CGSTAB method, etc

Characteristic Times

Characteristic Times :

Electron Temperature (～0.1 μ s)

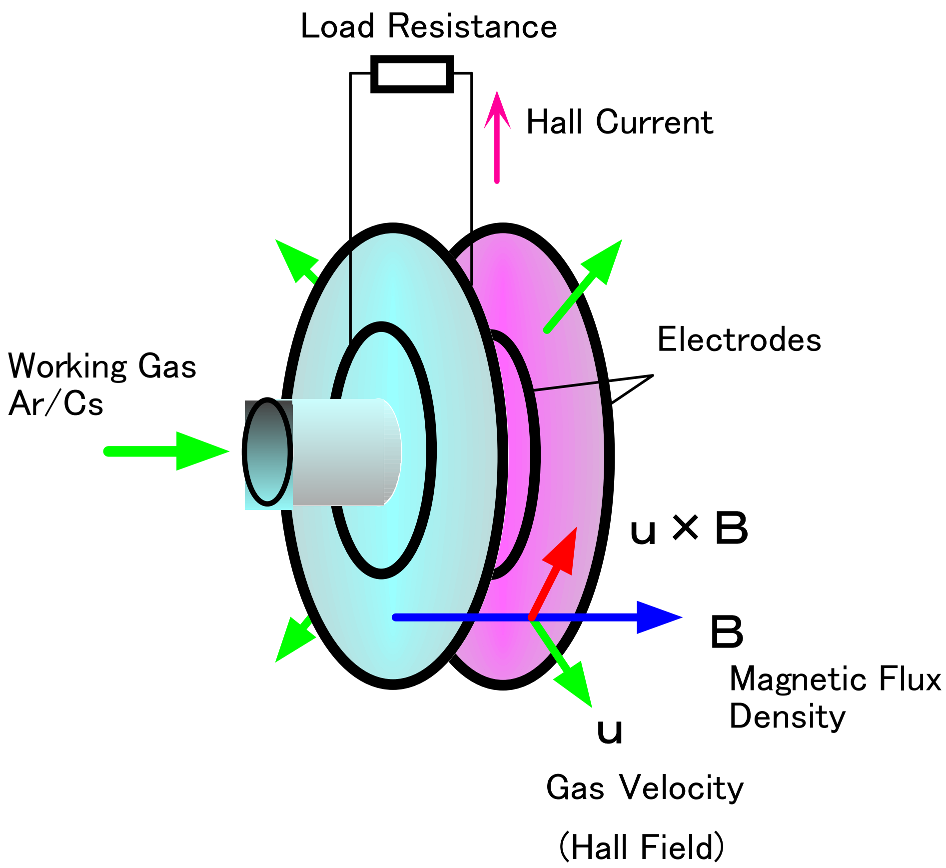
＜ Electron Number Density (～ μ s)

＜ MHD Fluid Flow (～ms)

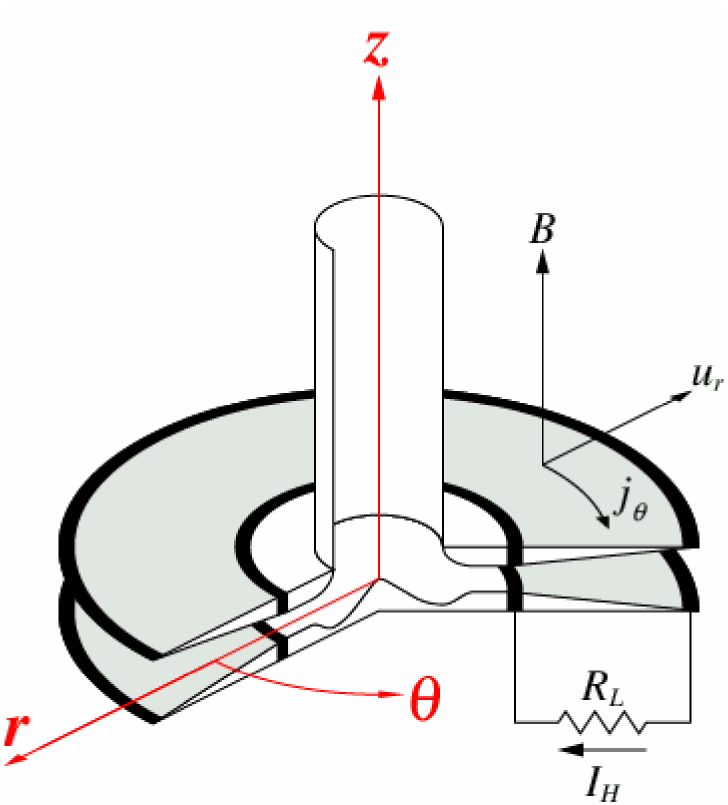
＜ Connection to AC Line (～10ms)

＜ System Start-up & Shut-down (～s, ～hrs.)

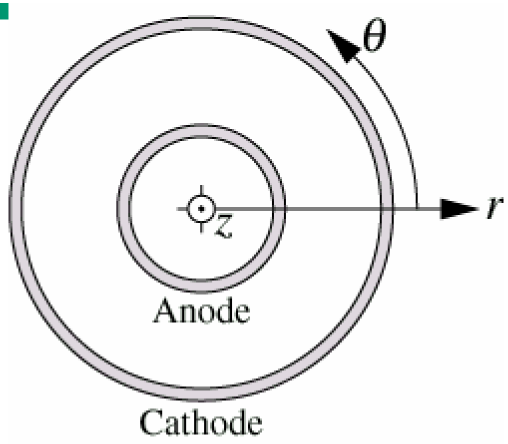
Disk MHD Generator



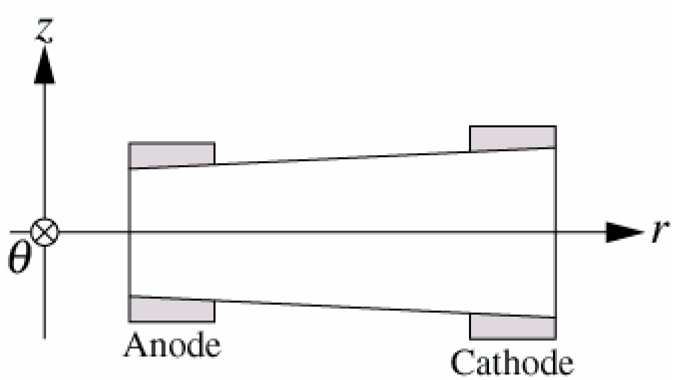
Coordinates System



Coordinates system

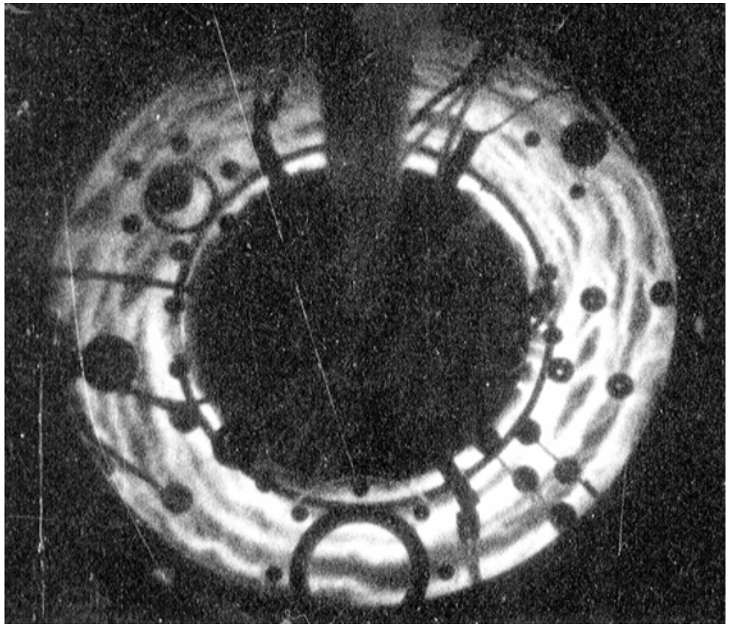


Cross sectional view in r-θ plane

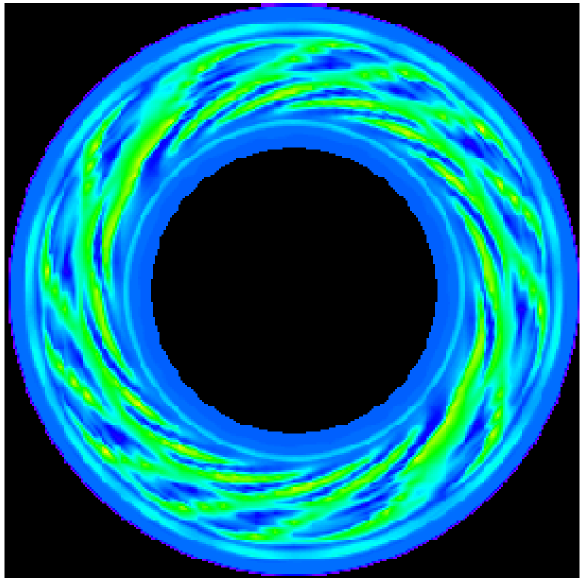


Cross sectional view in r-z plane

Nonuniform Plasma Structure in Disk Generator

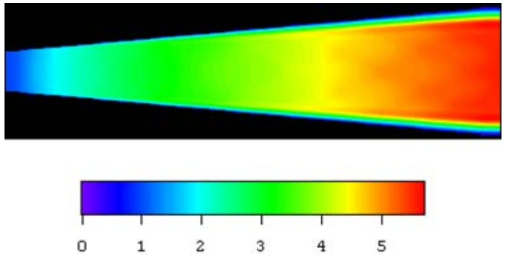


Shock Tube Experiments

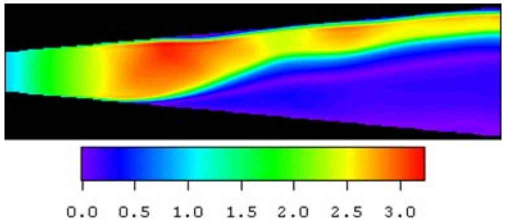


r- θ 2-D Simulation

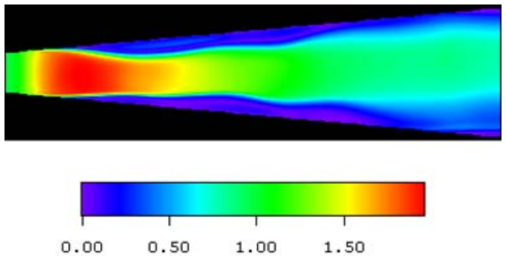
Flow Behavior under Different Back Pressure



B=0
Low back pressure



B=0
High back pressure



MHD Interaction $B \neq 0$
High back pressure

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Flow Behavior in Disk Generator (r-z 2-D Simulation)

non- B => applying B

Back Pressure:10kPa

Distribution of Radial Velocity

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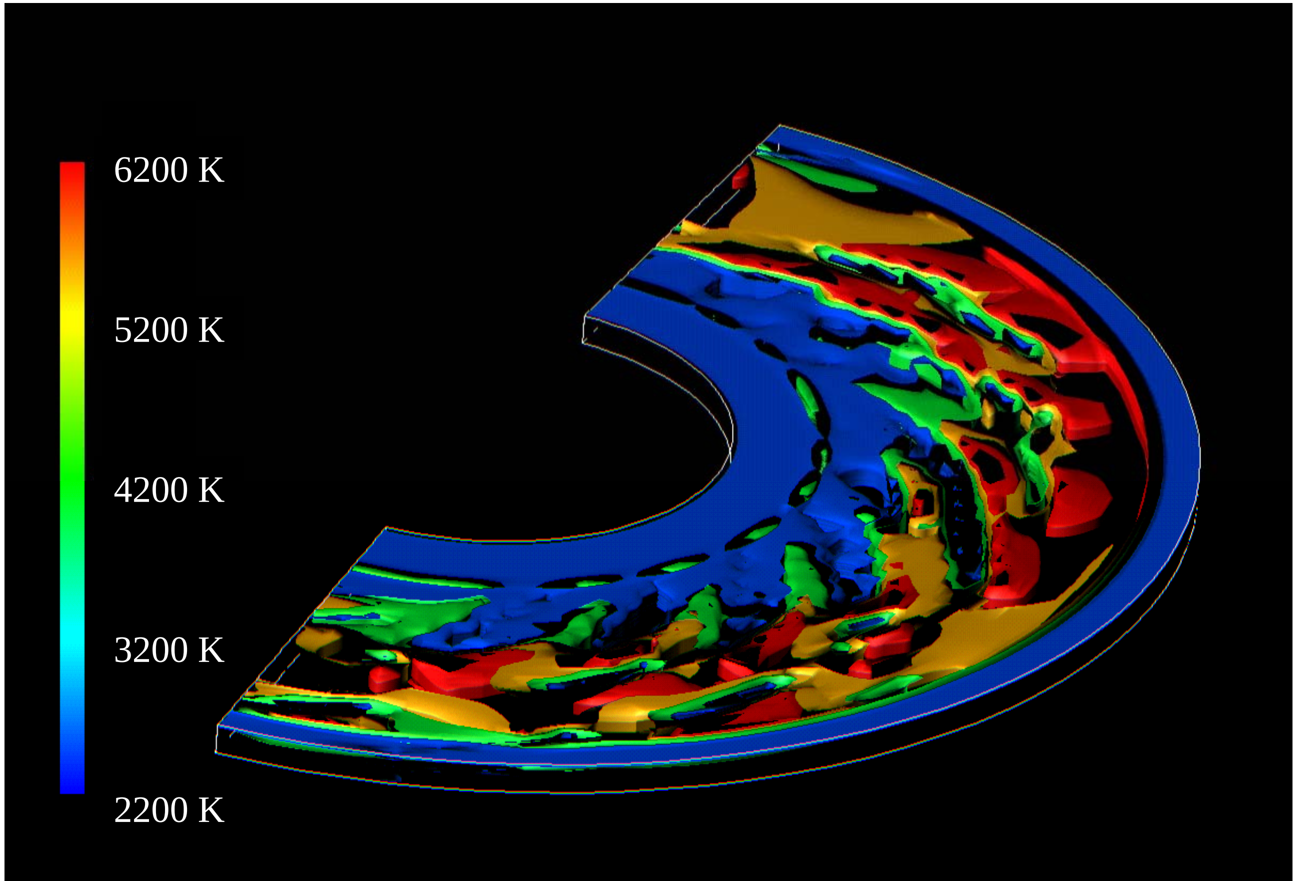
3-D plasma Structure in Disk Generator



Contour surface at electron temperature of 2500, 4000, 5500, 6500 K

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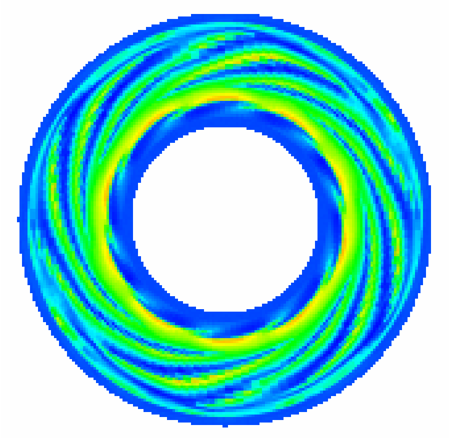
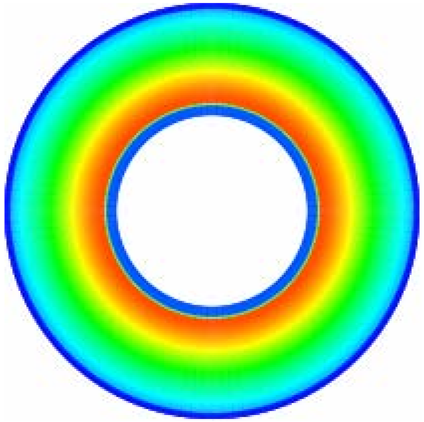
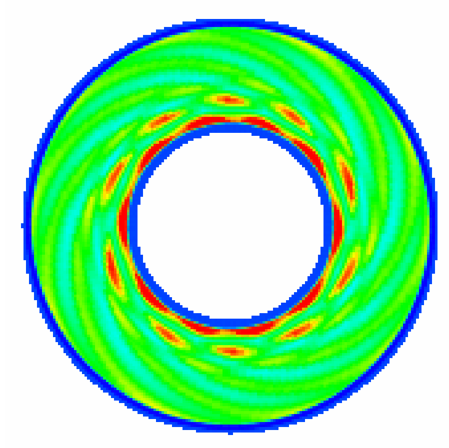
Plasma Behavior in Disk Generator



R_L=2.0 [Ω]



R_L=6.0 [Ω]



R_L=7.0 [Ω]

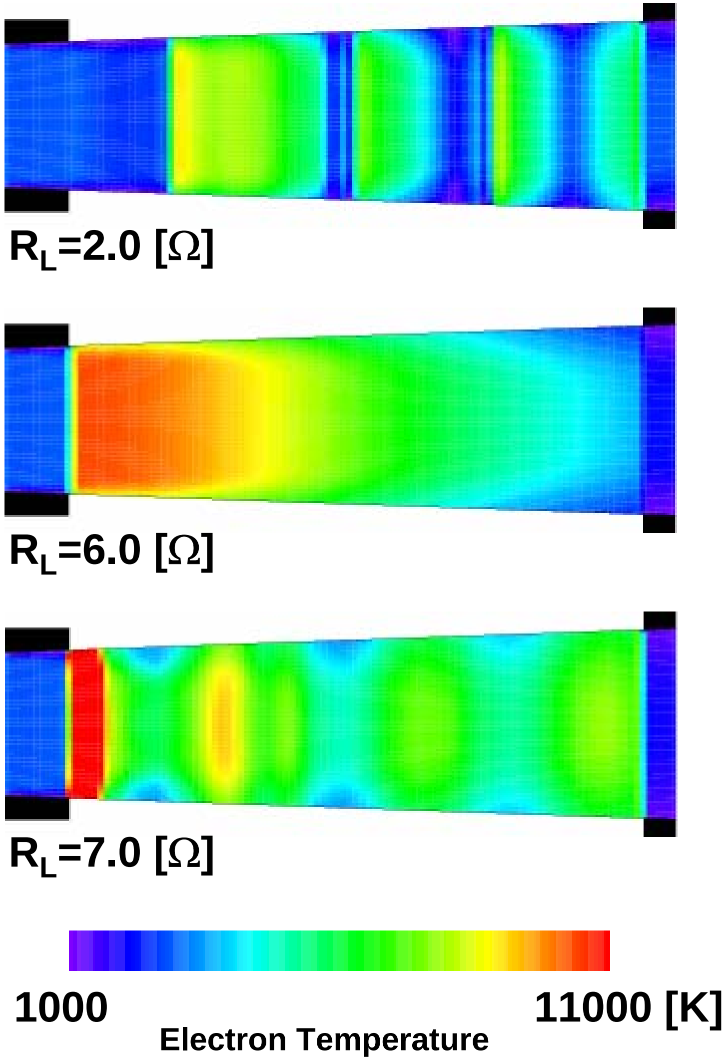
1000 Electron Temperature 11000 [K]

Low load resistance → **Unsteady streamer structure**

Optimum load resistance → **Steady and uniform structure**

High load resistance → **Unsteady domain structure**

Electron temperature Distribution in Disk Generator (r-z plane : 3-D Simulation)



<u>In main flow…</u>

Electron temperature distribution is uniform in *z*-direction which is parallel to the magnetic field.

<u>In boundary layer…</u>

Electron temperature is decreased.

Decrease in the Joule heating
Increase in the collision frequency

Decrease in the gas velocity
Increase in the number density of heavy particles

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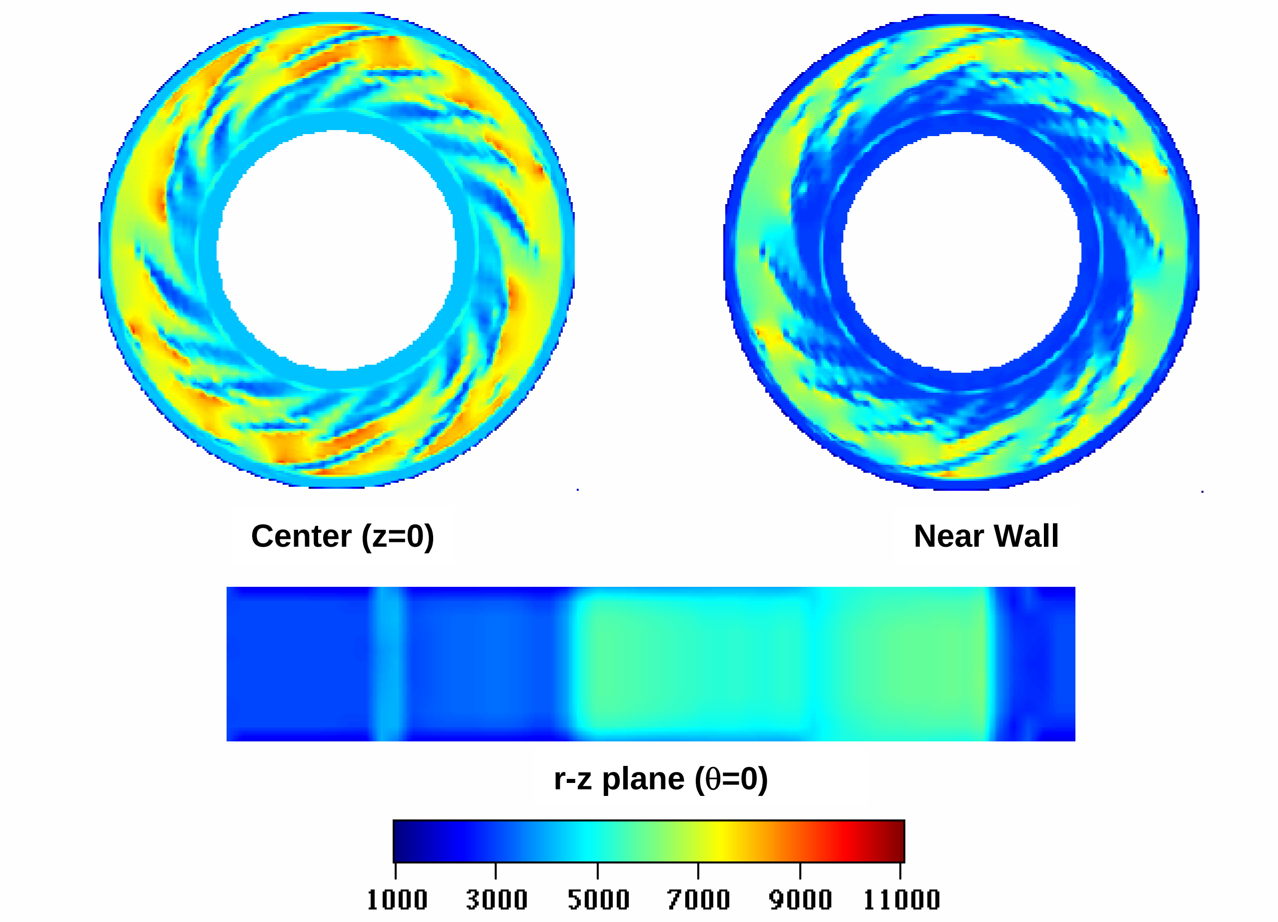
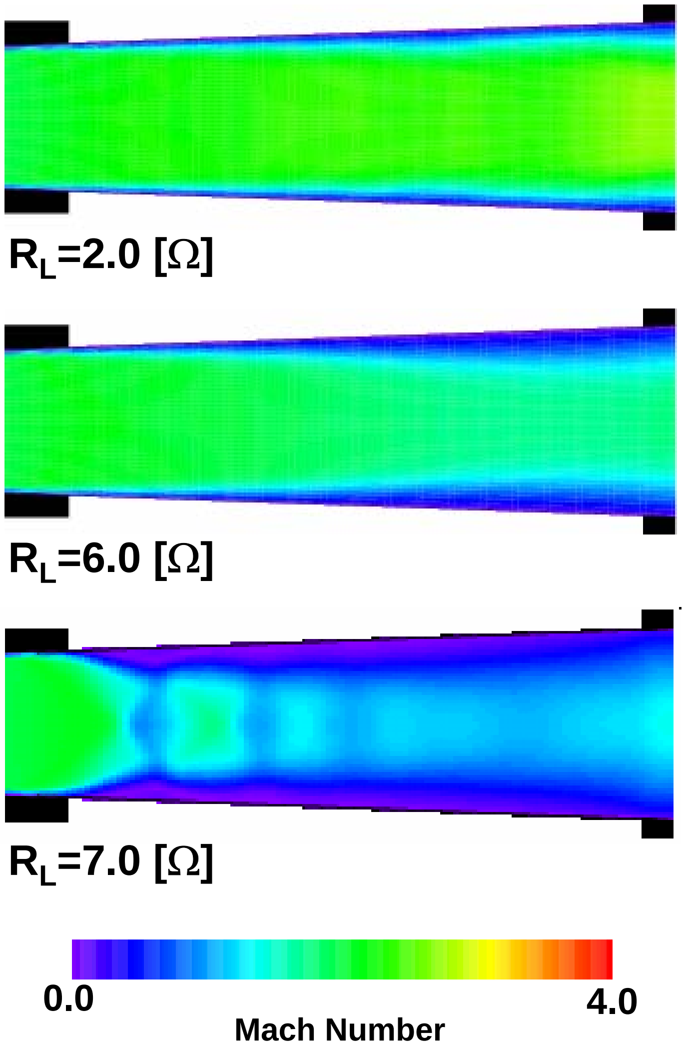
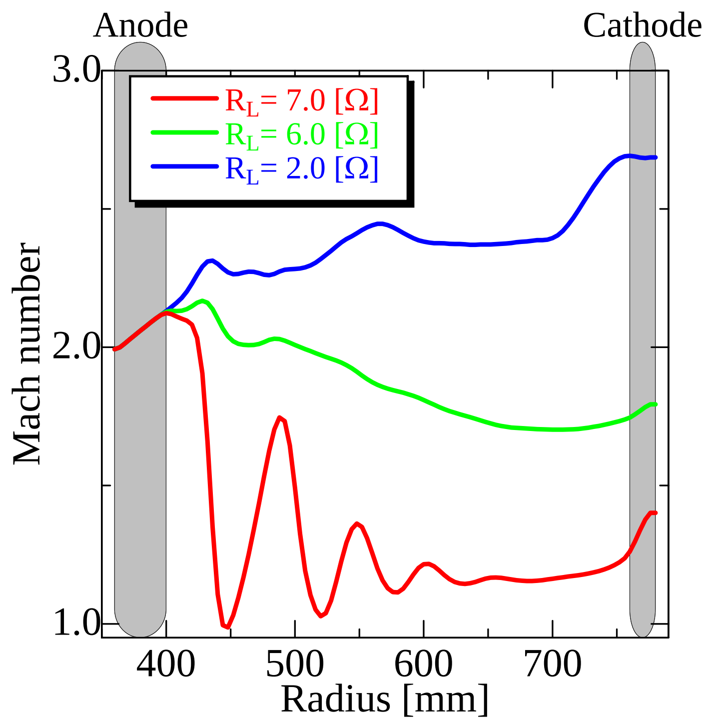
3-D Plasma Behavior in Disk Generator



3-D Distributions of Electron Temperature

Flow Behavior in Disk Generator (r-z plane : 3-D Simulation)



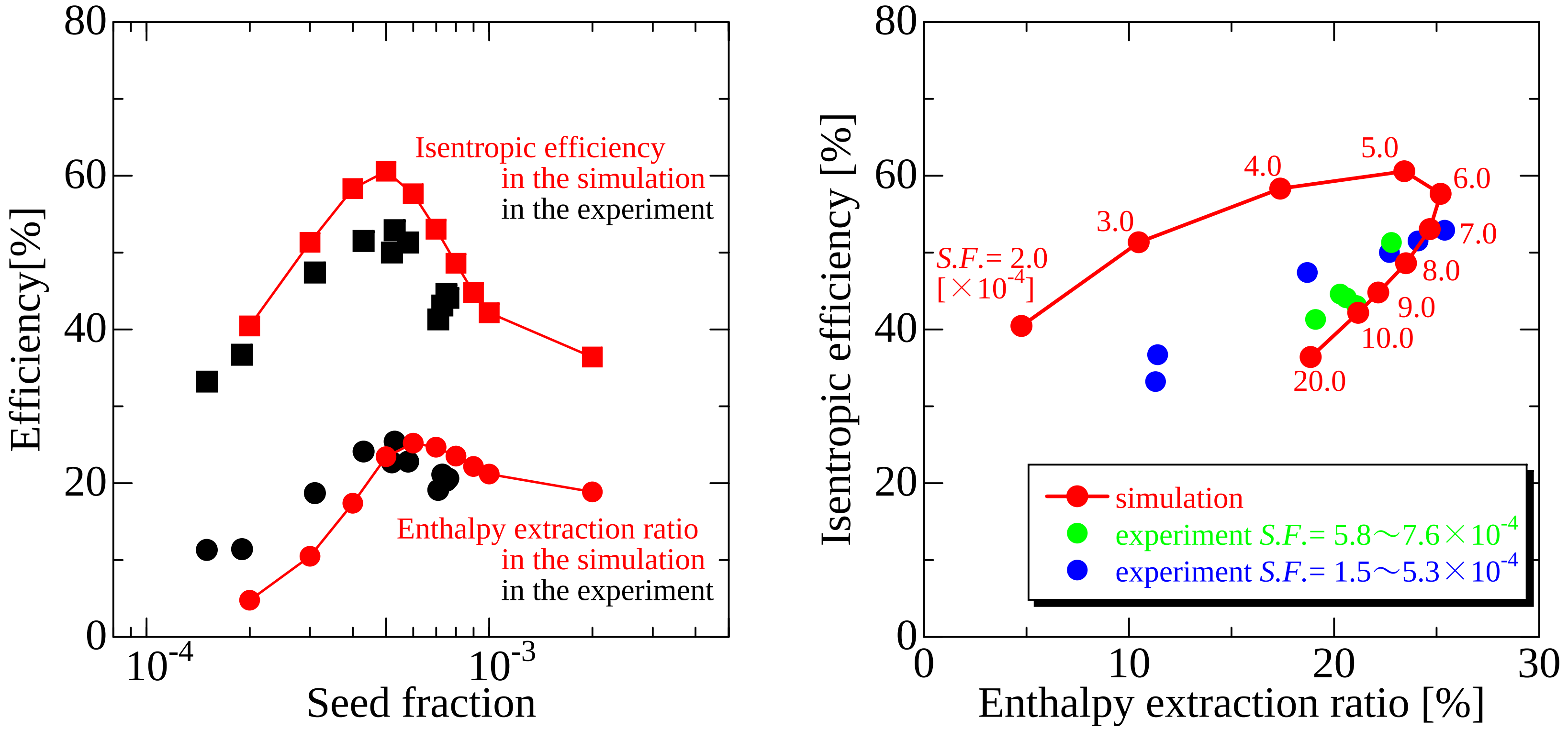


High load resistance

Strong Lorentz force - Development of boundary layer

pseudo-shock-like structure in the upstream region

Efficiencies of in a Shuck-tunnel Driven Disk MHD Generator



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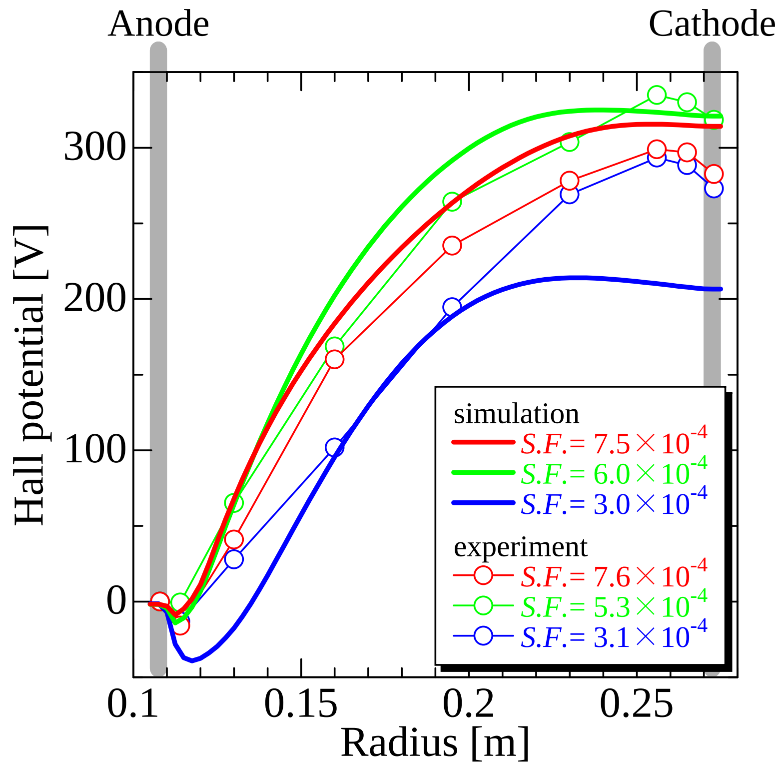
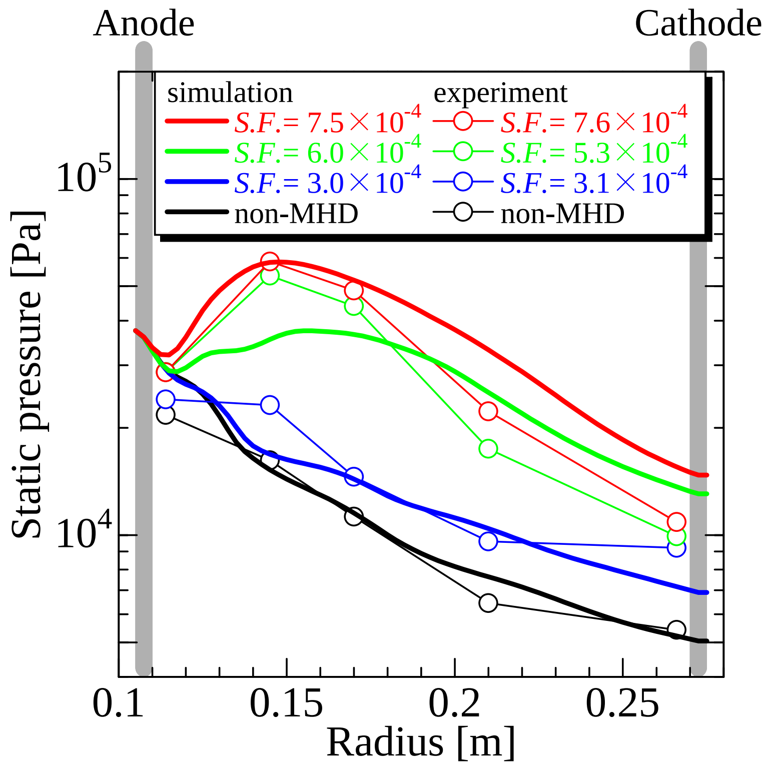
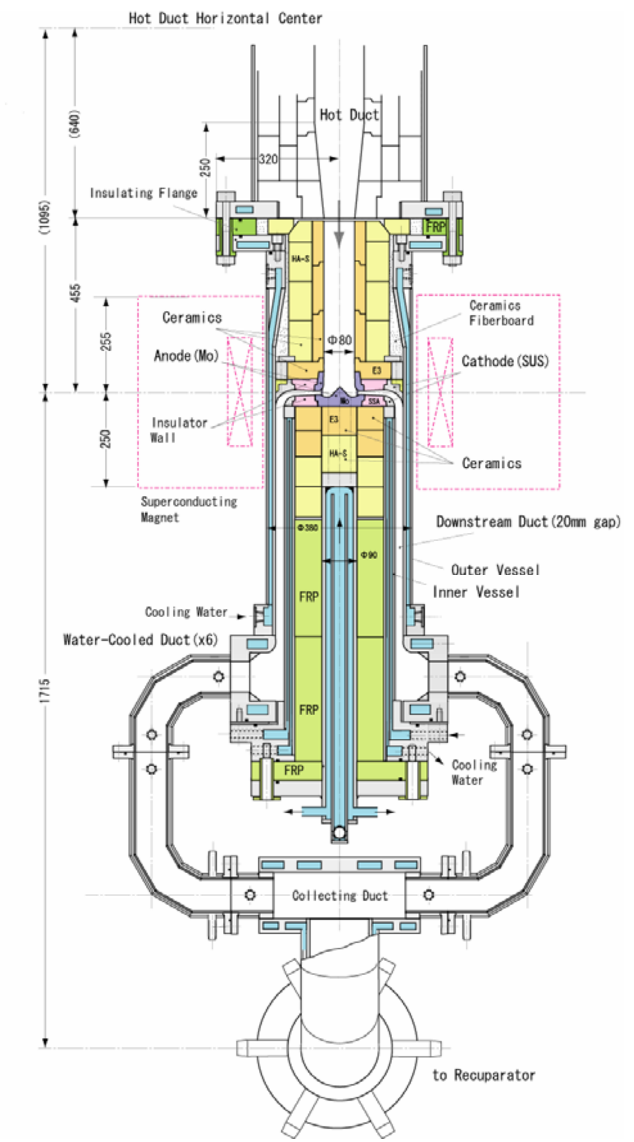
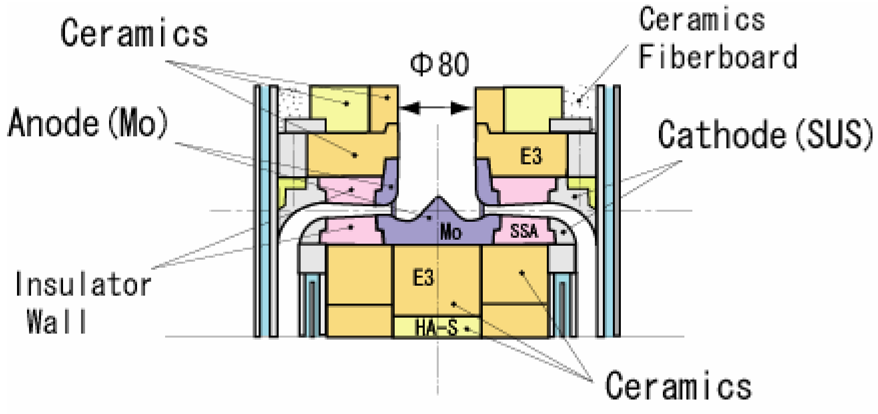
Hall Potential and Static Pressure Distributions in a Shuck-tunnel Driven Disk MHD Generator





Disk MHD Generator in the Closed Loop Experimental Facility (CLEF) for Continuous Operation

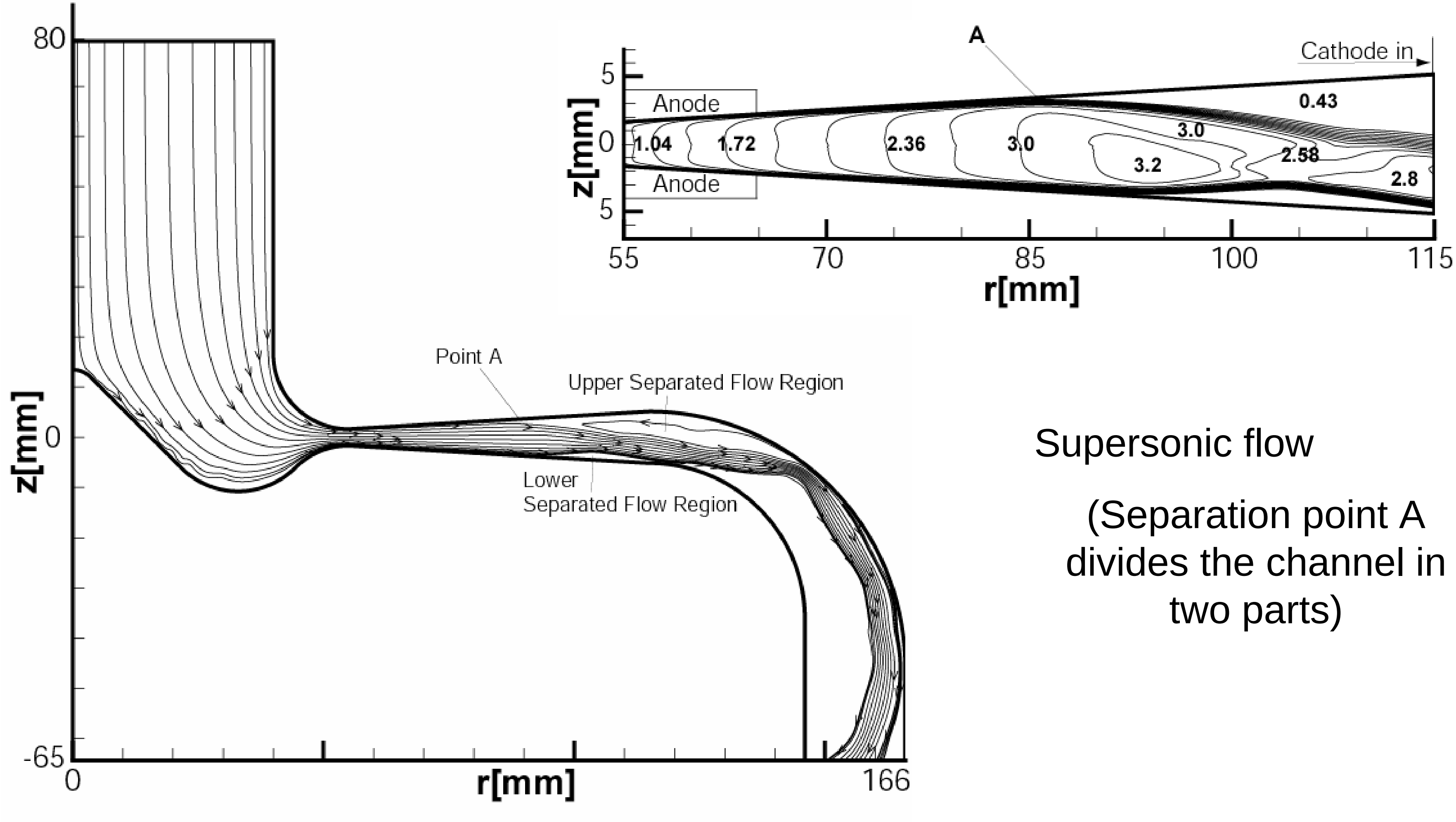




MHD Generator Channel

Radius [mm]	Height [mm]
55 (throat)	3.3
65 (anode)	4.5
115 (cathode)	10.3
A_{exit} / A_{throat}	6.5

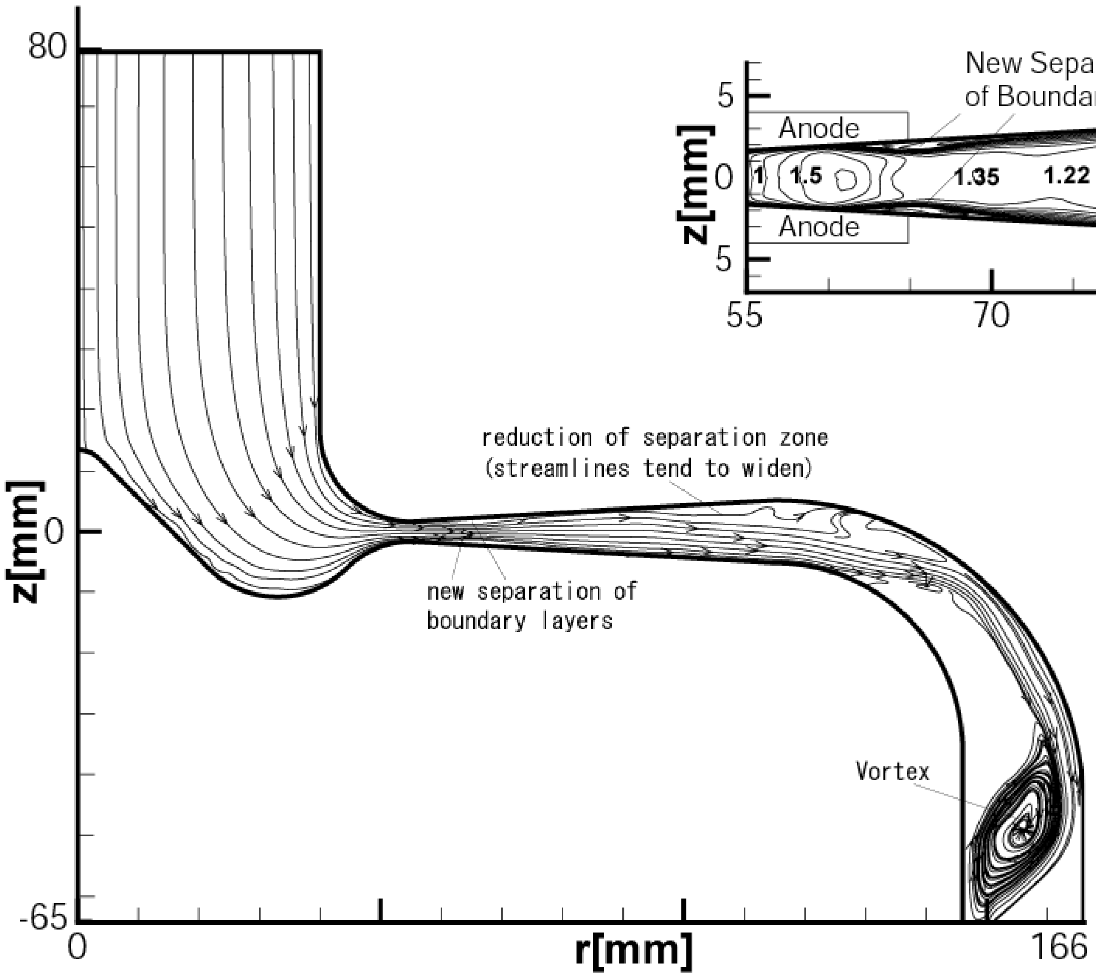
Velocity Streamlines of Non-MHD flow (CLEF)

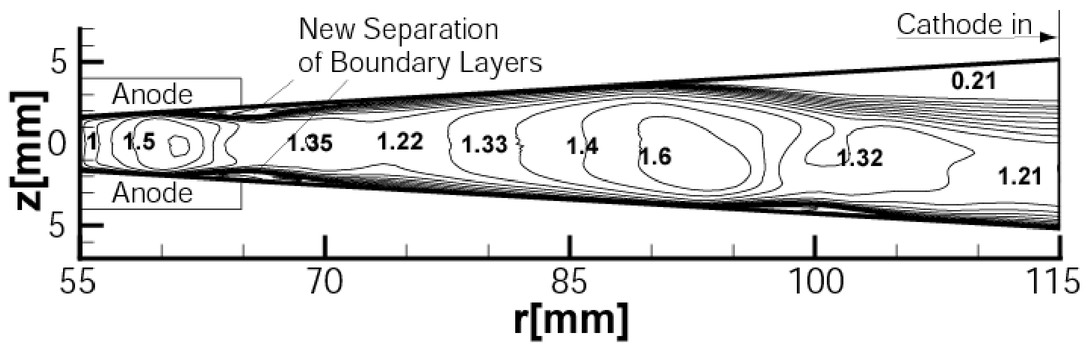


Supersonic flow

(Separation point A divides the channel in two parts)

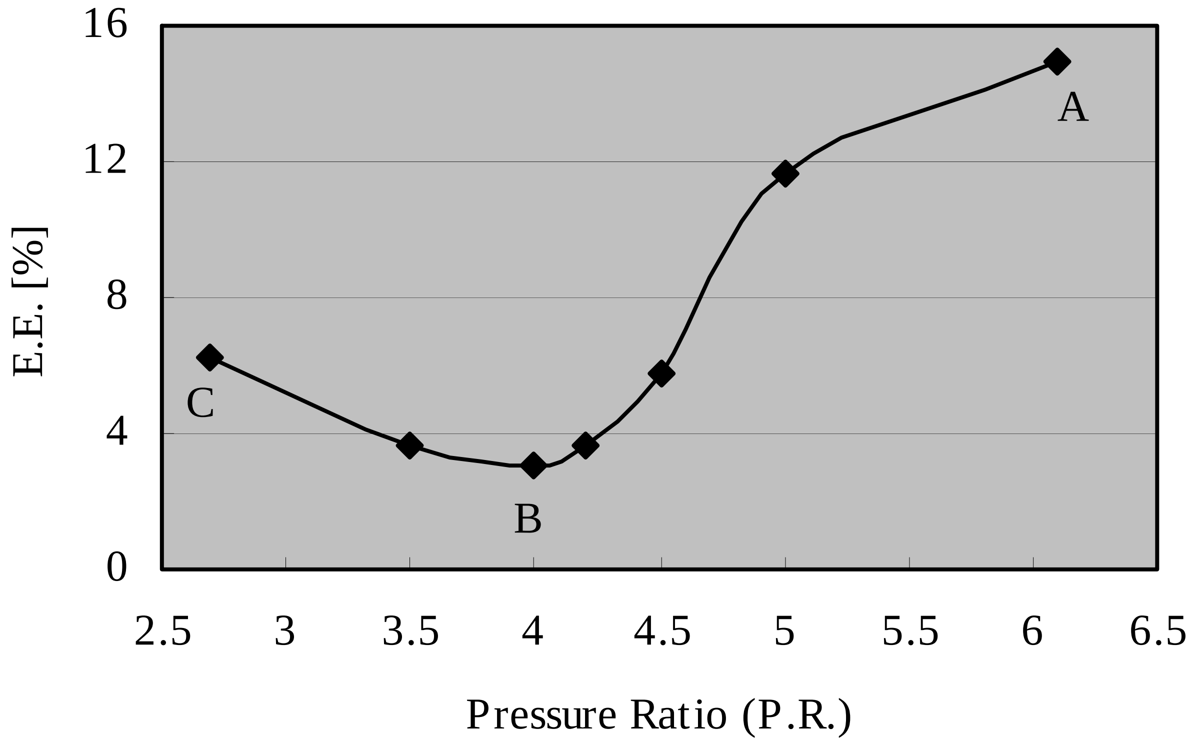
Velocity Streamlines of MHD flow (CLEF)





High MHD Interaction can be obtained in the channel

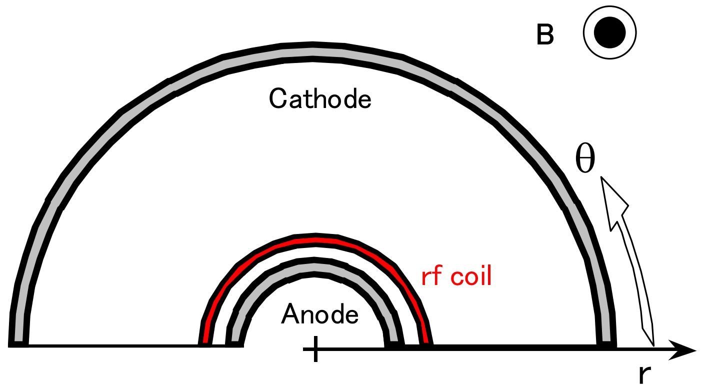
Effect of Pressure Ratio P.R. on Enthalpy Extraction Ratio E.E. (CLEF)

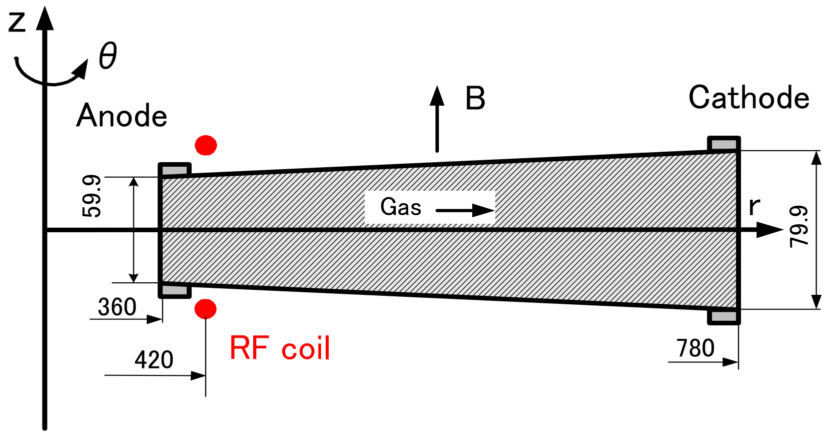


Minimum E.E. is obtained for P.R. = 4.0

Improvement by applying RF Electromagnetic Filed

Working gas	**He-Cs**
Thermal inlet	**117 [MWt]**
Inlet stagnation temperature	**2000 [K]**
Inlet stagnation pressure	**3.0 [atm]**
Magnetic flux density	**6.0 [Tesla]**
Inlet Mach number	**2.2**
Frequency of rf power	**13.56×10^6 [Hz]**





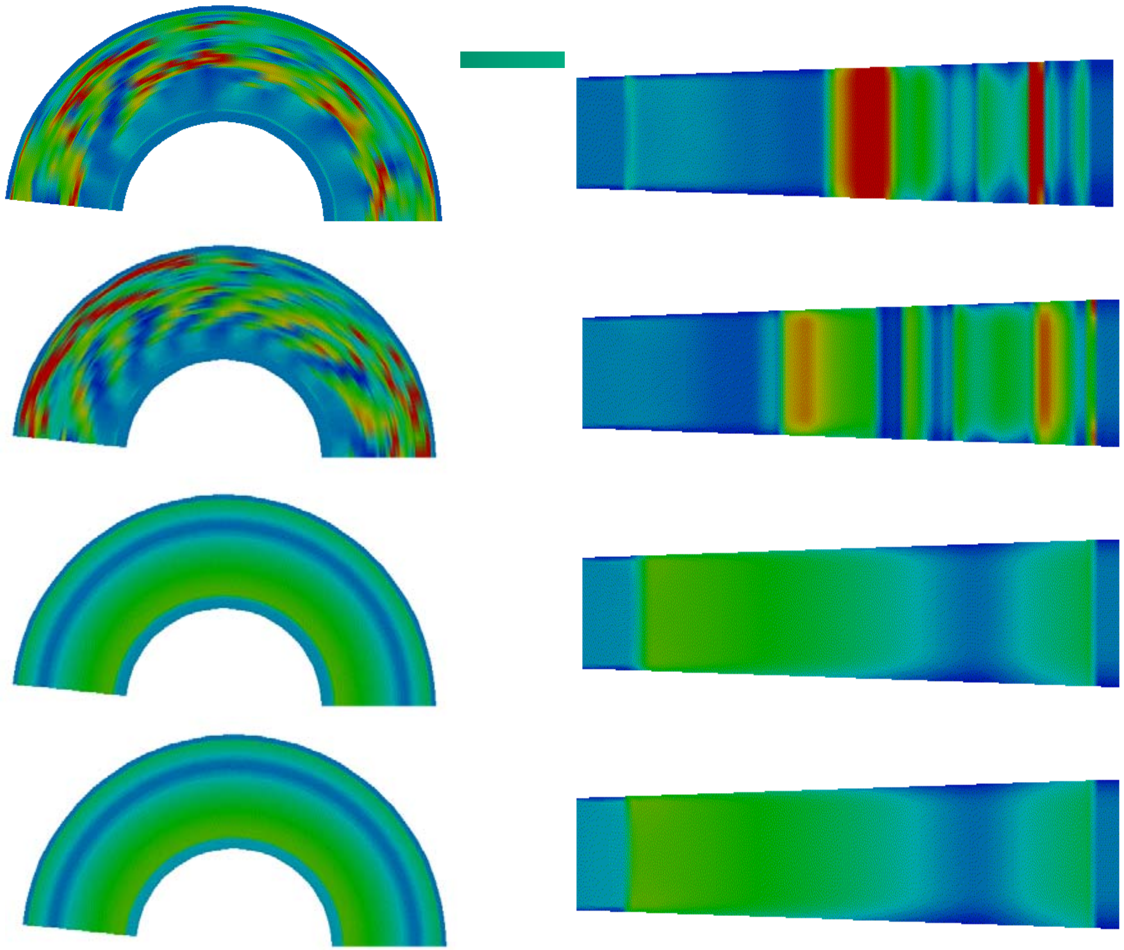
Plasma structure with different rf power for sf = 1.0×10^{-5}

(a) without rf
Tein = 2829 K
Ic = 0 A

(b) with rf
Ic = 100 A

(c) with rf
Ic = 150 A

(d) with rf
Ic = 200 A



RL = 2.0 ohm

1000 Electron temperature (K) 12000

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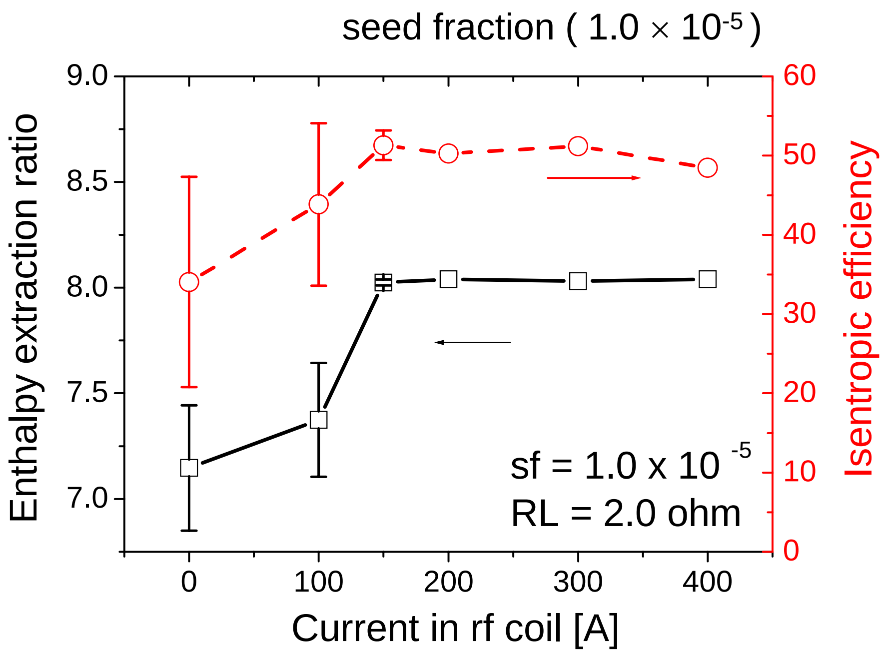
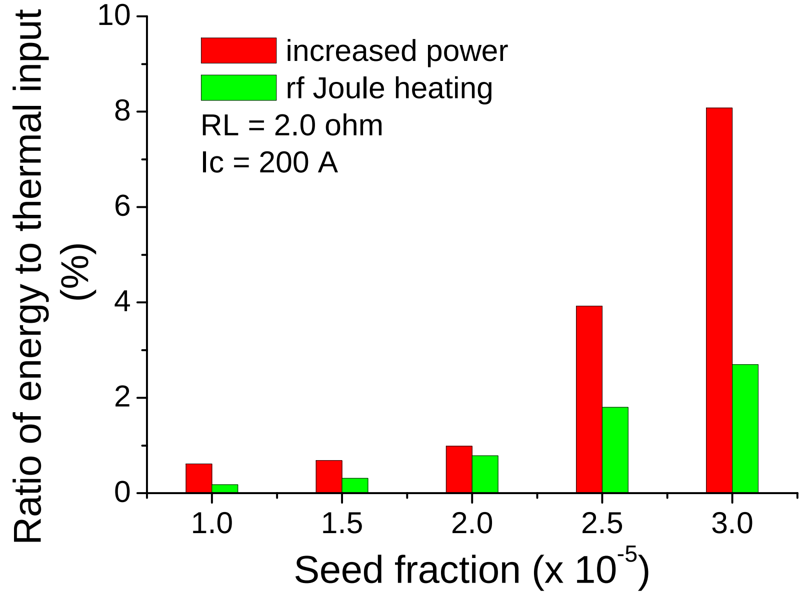
Improvement by applying RF Electromagnetic Filed





Effect of different rf power on performance of MHD generator

Ratio of increased power and rf Joule heating to thermal input versus seed fraction

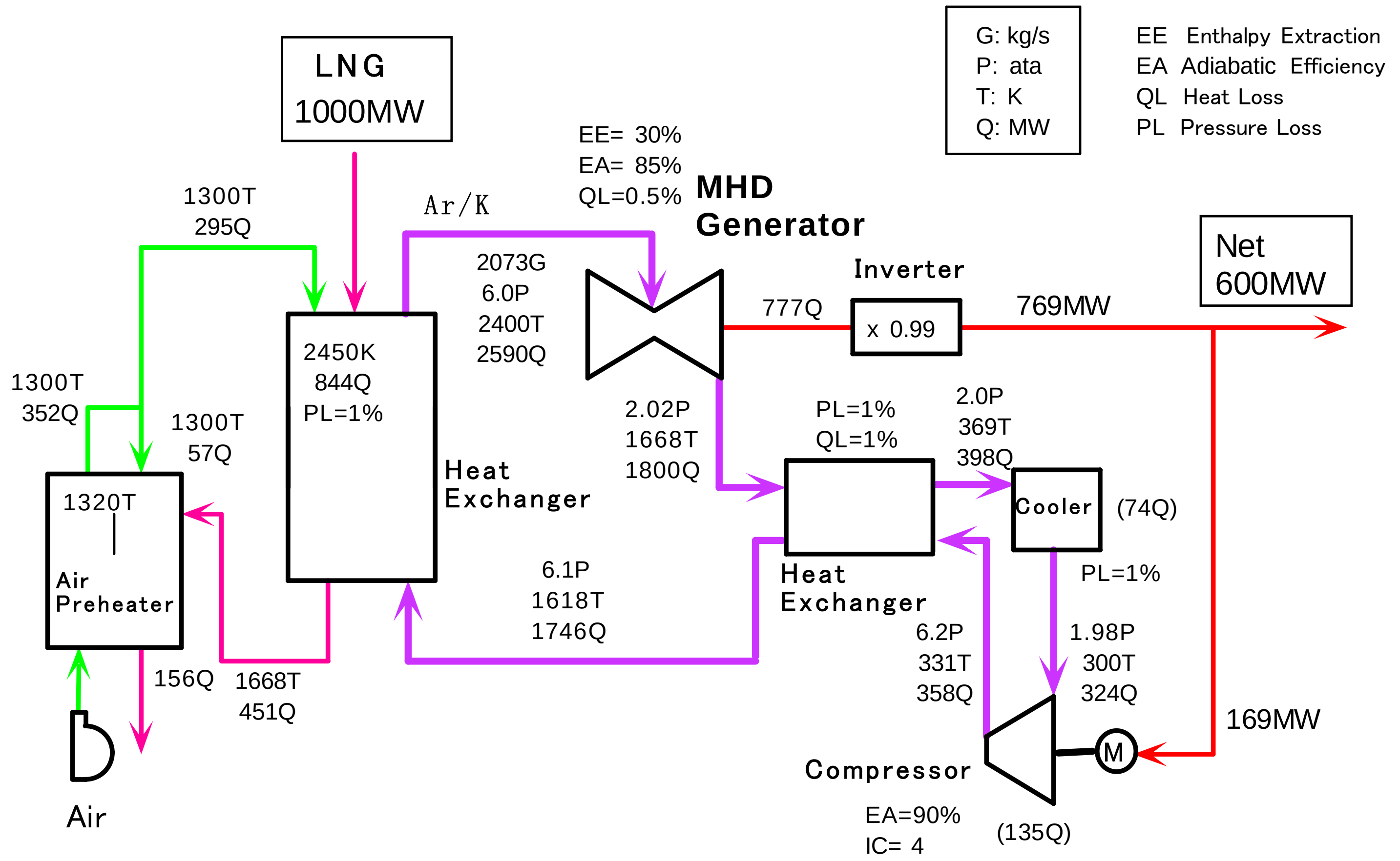
Closed Cycle MHD Power Plant

1) Closed Cycle MHD Single Cycle

2) CCMHD / ST or CCMHD / GT Combined Cycle

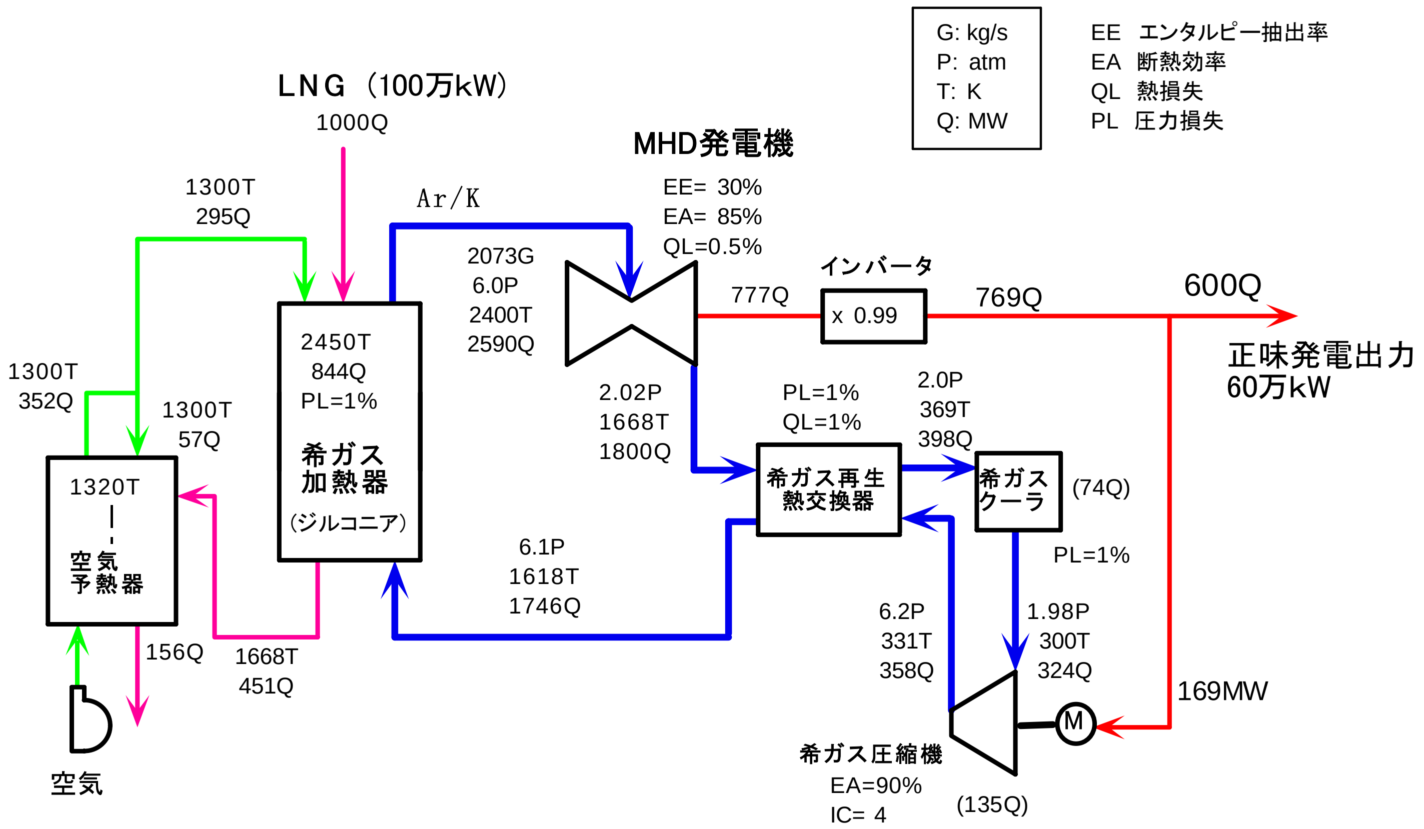
3) CCMHD / GT / ST Triple Combined Cycle

Closed cycle MHD single system



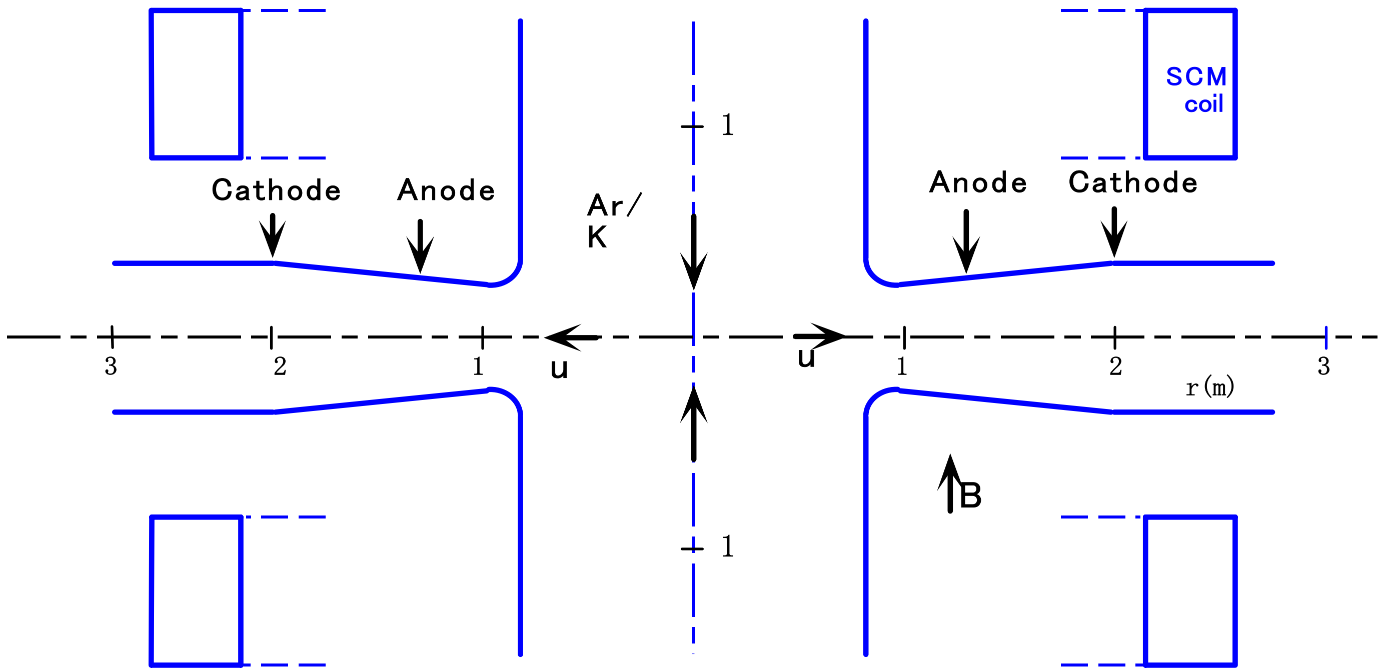
Total Efficiency = 60%

CCMHD単独発電システム



60万kW級 CCMHD単独発電システム（プラント熱効率60%）

ディスク形MHD発電機



Bo = 7.0T
Stored Energy=2490MJ
V ～ 5.8 kV
I ～ 134 kA

熱入力2590MWディスク形CCMHD発電機断面図
(E.E.=30%, E.A.=85%)

MHD/ガスタービン/蒸気タービン トリプルコンバインド発電システム

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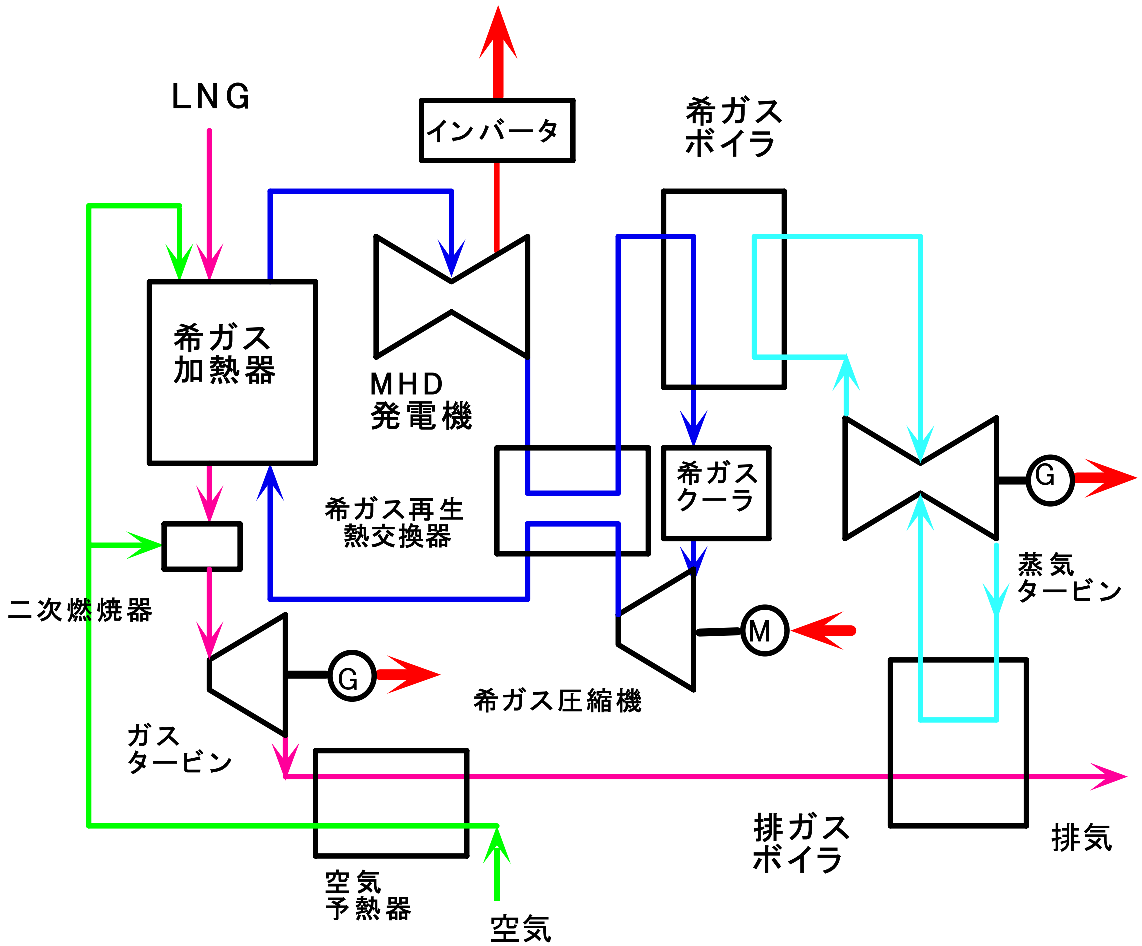

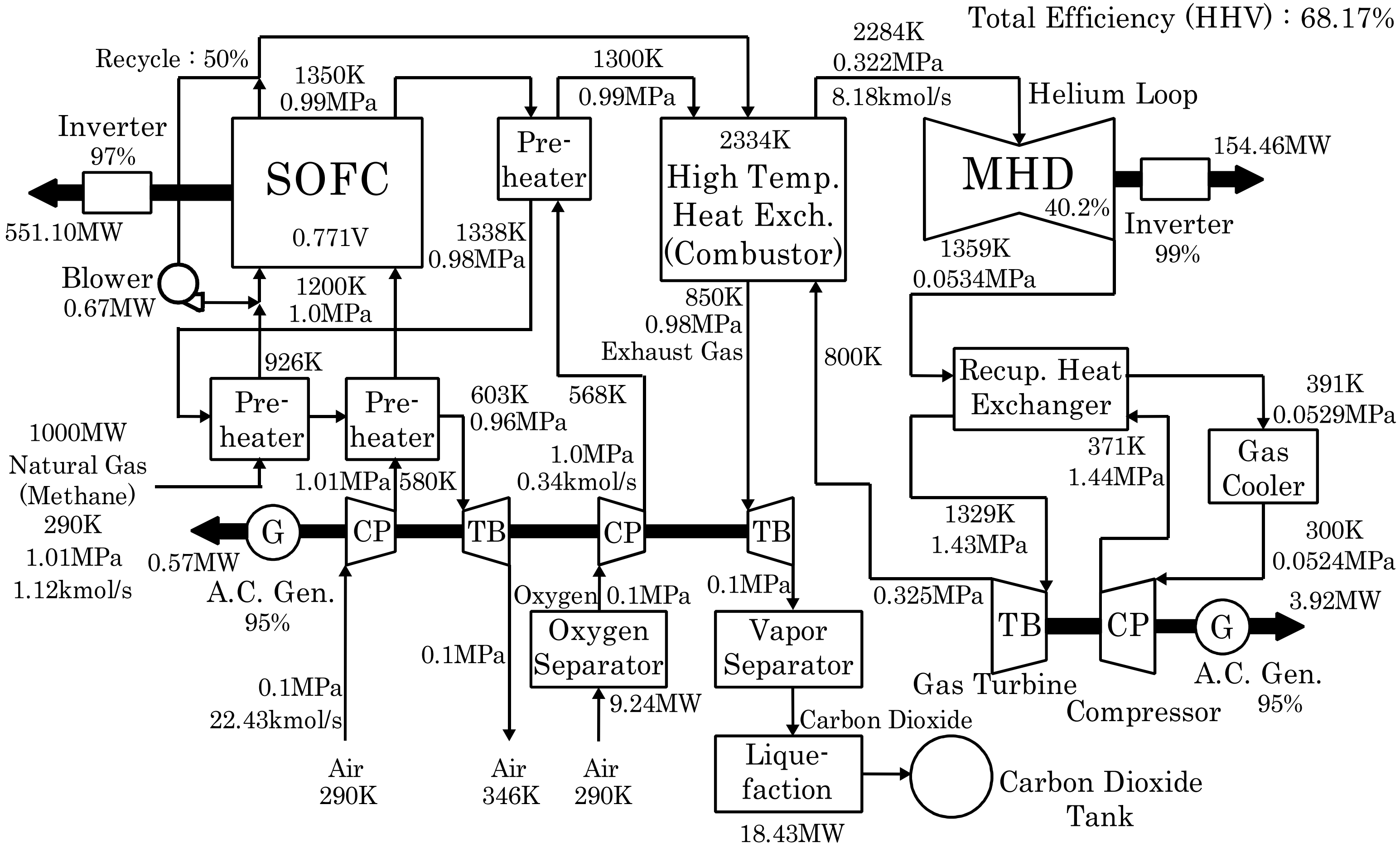

改良型炭酸ガス液化回収式固体酸化物形燃料電池・クローズドサイクルMHD複合発電システムの構成とエネルギーバランス

（出典： 乾 義尚ら，電学論B，**123**，9，1097～1104 (平15-9)）

Numerical Simulation Related to MHD Nonequilibrium Plasma Flow

MHD Plasma Behavior

Plasma Behavior under rf electromagnetic Field,
FIP (Frozen Inert gas Plasma) MHD Concept,
***Pulse Detonation* MHD Power Generation,**
***Laser Driven* MHD Power Generation,**
Air ICP MHD Nonequilibrium Plasma Behavior, etc

Closed Loop Experimental Facility

Operation Procedure, Prediction of Performance,
Transient Phenomena, Heat Transfer, etc

MHD Acceleration

MHD Accelerator, **MPD Thruster,**
MHD Energy bypass Scramjet Engine, etc

Flow Control

Drag Reduction, Thermal Protection, etc