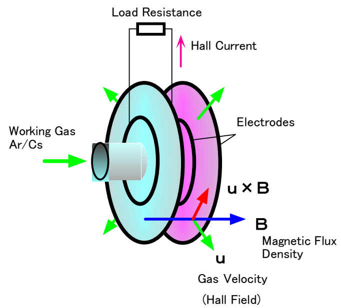
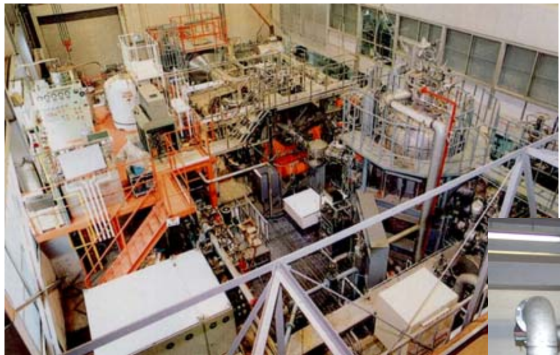
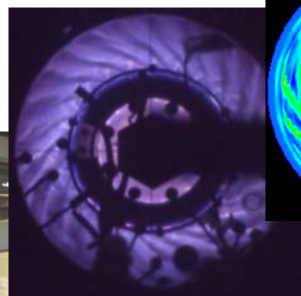
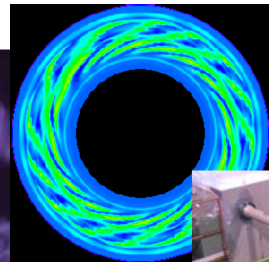
Studies of Closed Cycle MHD Electrical Power Generation at Tokyo Institute of Technology

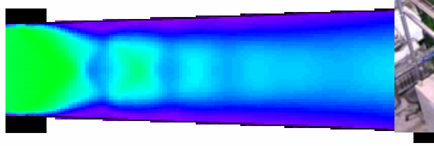
Yoshihiro OKUNO
Department of Energy Sciences
Tokyo Institute of Technology











Contents

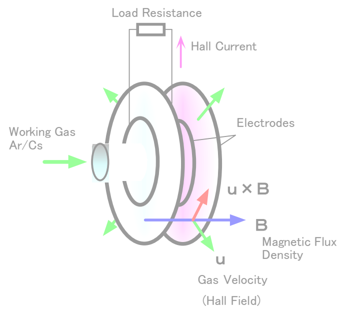
1. Introduction

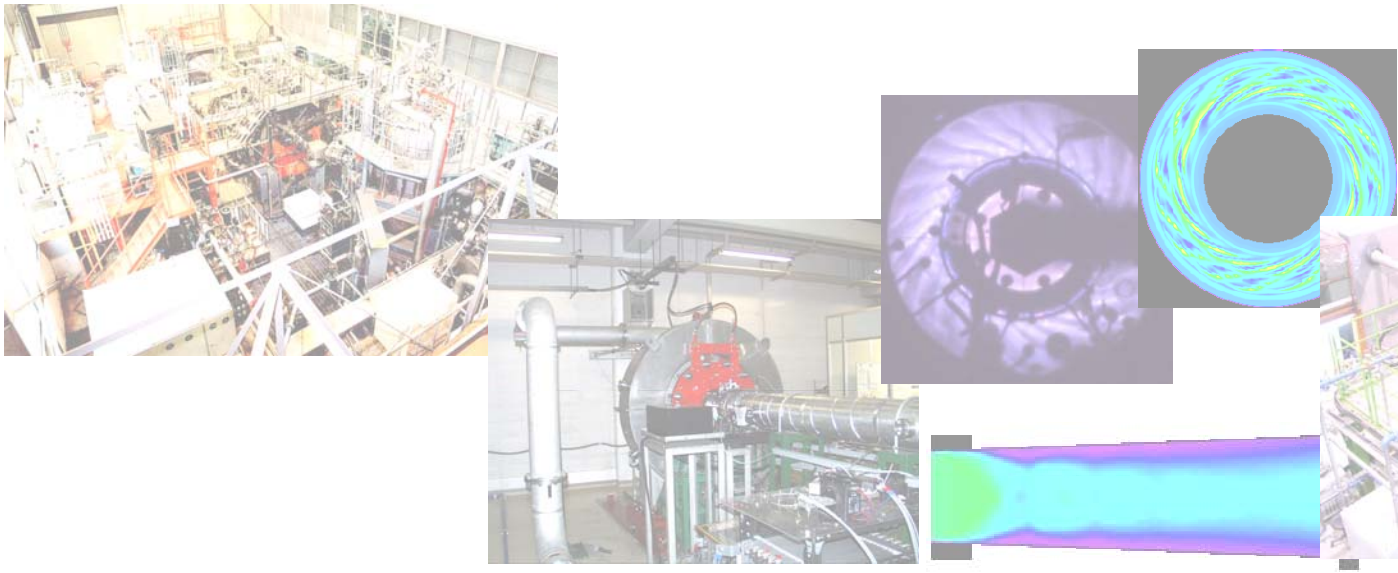
2. Experimental Studies of Closed Cycle MHD Electrical Power Generation

- *Shock-Tunnel Facility (1970? -)*
- *Blow-Down Facility "Fuji-1" (1981 – 1999)*
- *Closed Loop Experimental Facility (2002 -)*

3. Numerical Simulation of MHD Nonequilibrium plasma flow

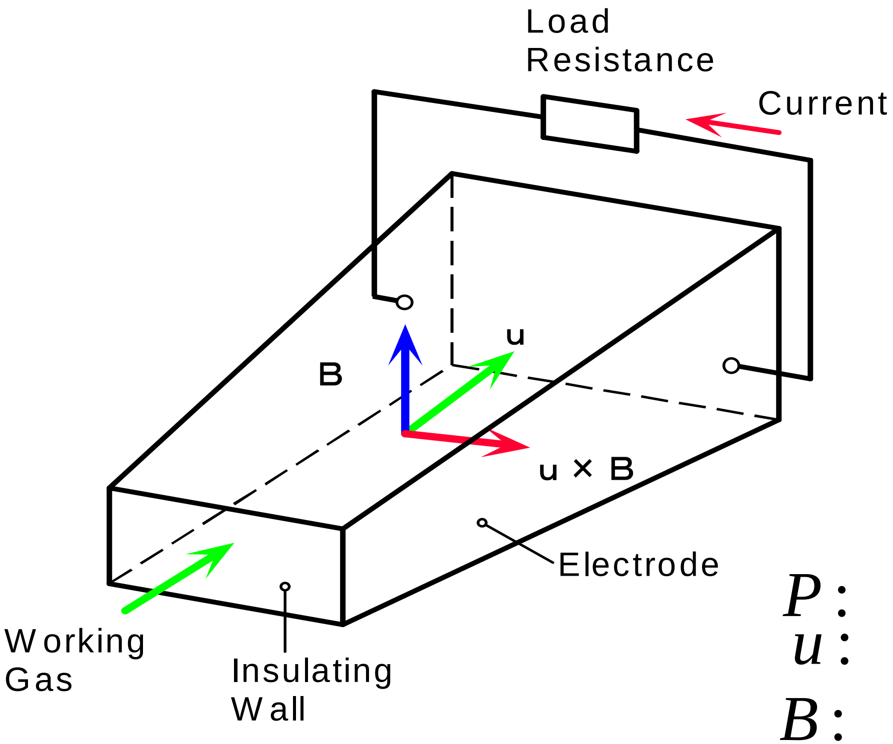
- *MHD Flow Behavior and Performance of MHD generator*
- *Improvement by applying RF Electromagnetic Filed*





Tokyo Institute of Technology
Energy Sciences

Principle of MHD Electrical Power Generator
(Energy converter to the electricity)



Power Density (= Power / Volume)

$$\boxed{P \propto uB \cdot j \propto \sigma u^2 B^2}$$

$$\because \; j \propto \sigma u B$$

P : Power density (W/m³)

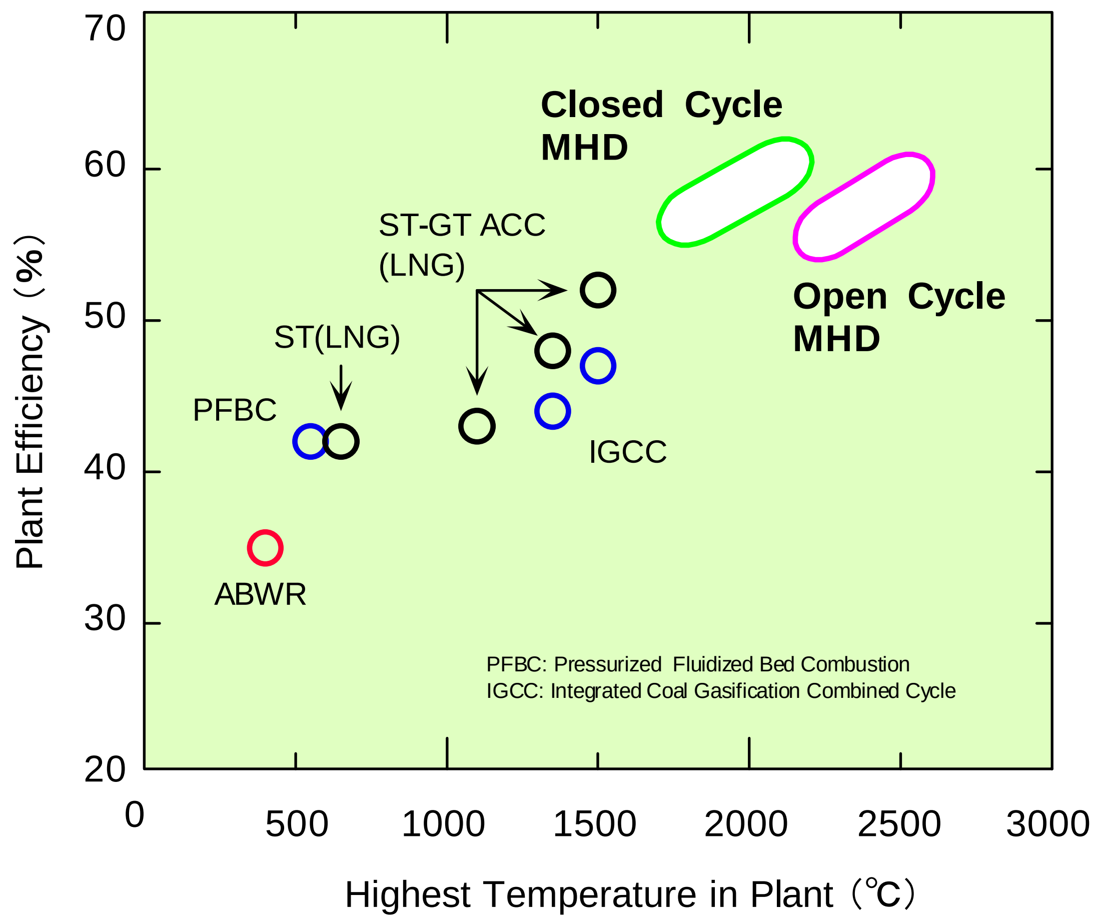
u : Velocity of fluid (m/s) ⇒ Supersonic Flow

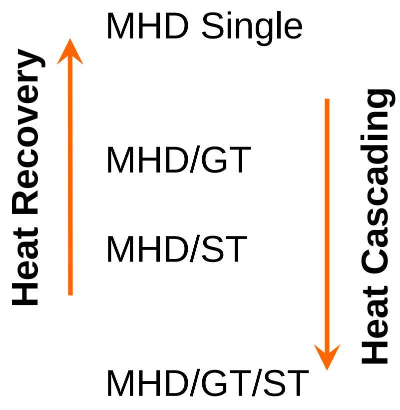
B : Magnetic flux density (T) ⇒ Superconducting

j : Current density (A/m²)

σ : Electrical conductivity (S/m) ⇒ Plasma

Why MHD ? - Plant Efficiency -





MHD System & Working Fluid

Open Cycle MHD Power Generation

Combustion Gas (～3000K) ＋ Seed（K_2CO_3 ～1%）

Thermal Equilibrium Plasma（Te ～ Tg） σ < 1～10 S/m

- ***Efficient Coal Utilization***

Closed Cycle MHD Power Generation

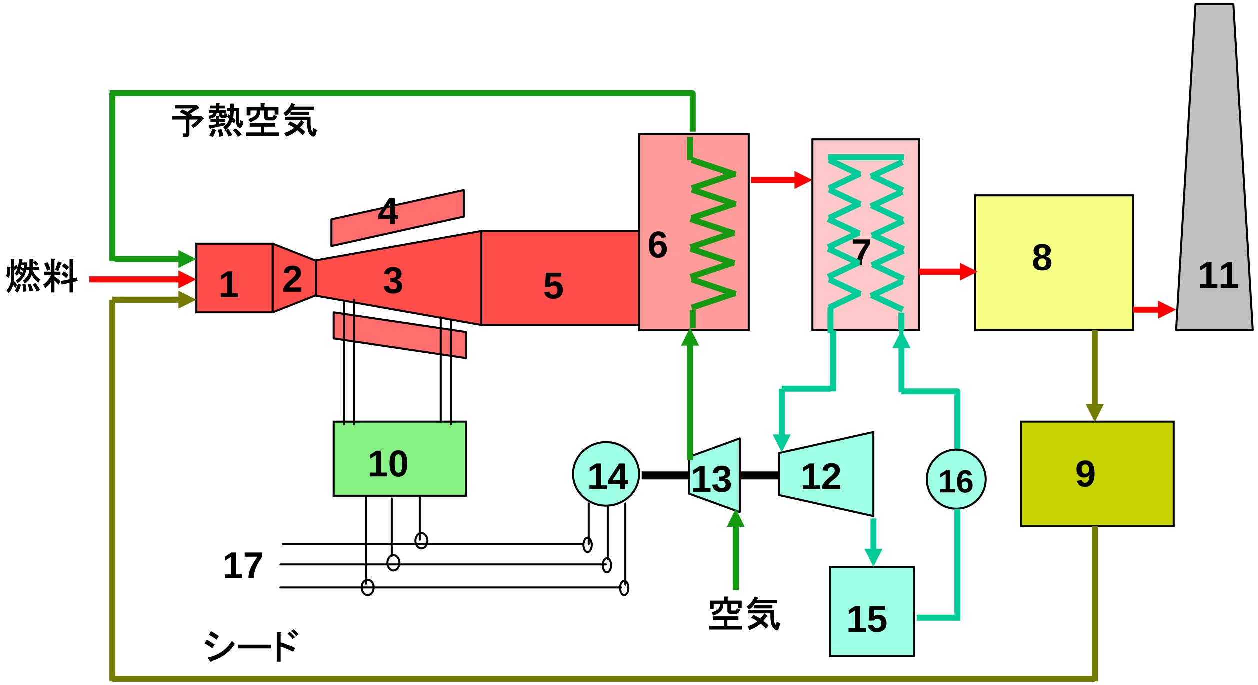
Inert Gas (～2000K) ＋ Seed（K, Cs 0.1-0.01%）

Non-Equilibrium Plasma (Te > Tg) σ ～ 100 S/m

- ***Various Energy Source Utilization***

Highly Efficient Energy Converter to produce the Electricity

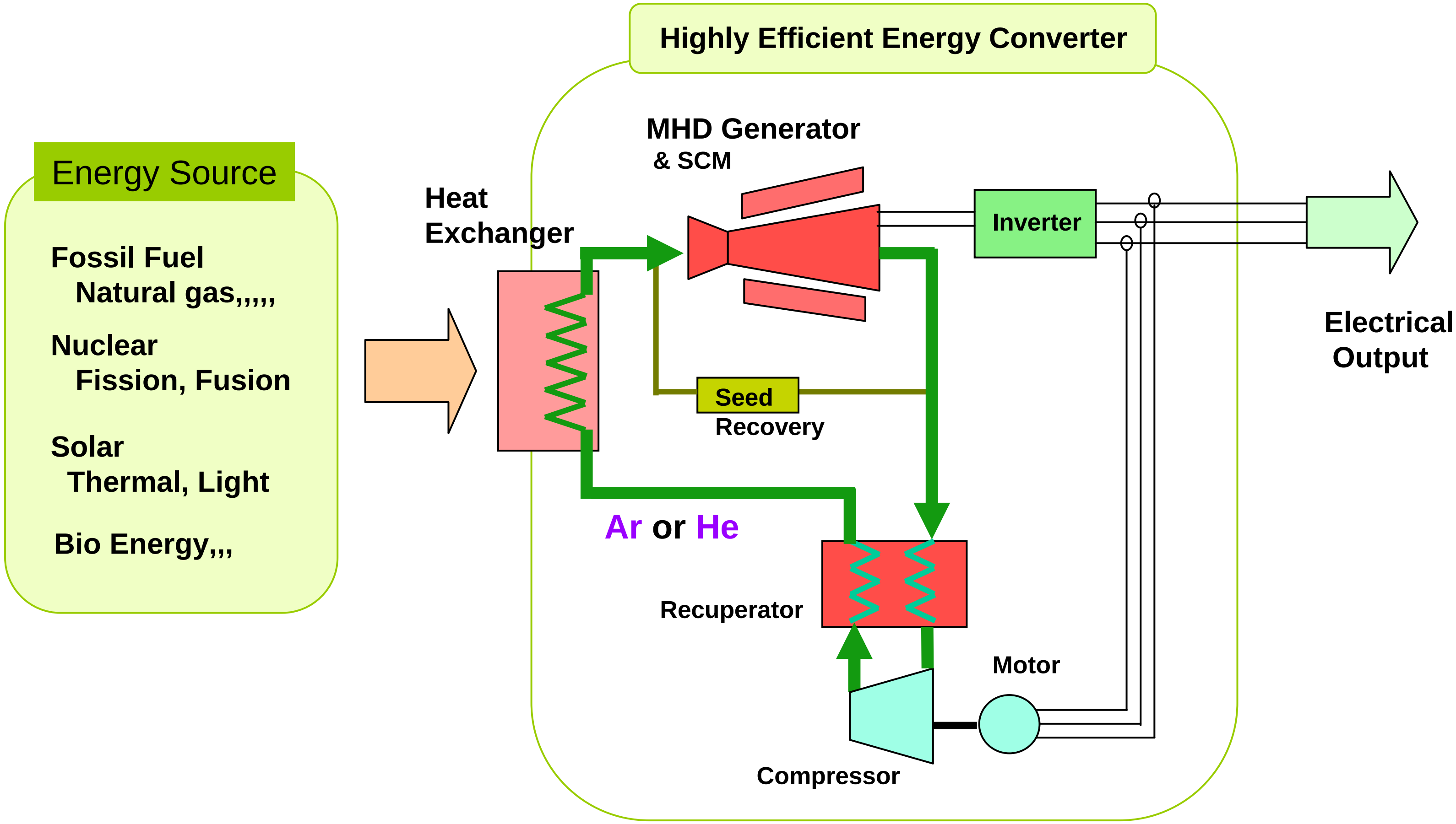
Open Cycle MHD Power Generation System



1 燃焼器，2 ノズル，3 MHD発電機，4 超電導磁石，5 ディフューザ，
6 空気予熱器（再生），7 ボイラ，8 脱硝器,シード回収装置，9 シード再生装置，
10 インバータ，11 煙突，12 蒸気タービン，13 空気圧縮機，14 発電機，15 復水器，
16 ポンプ, 17 電気出力

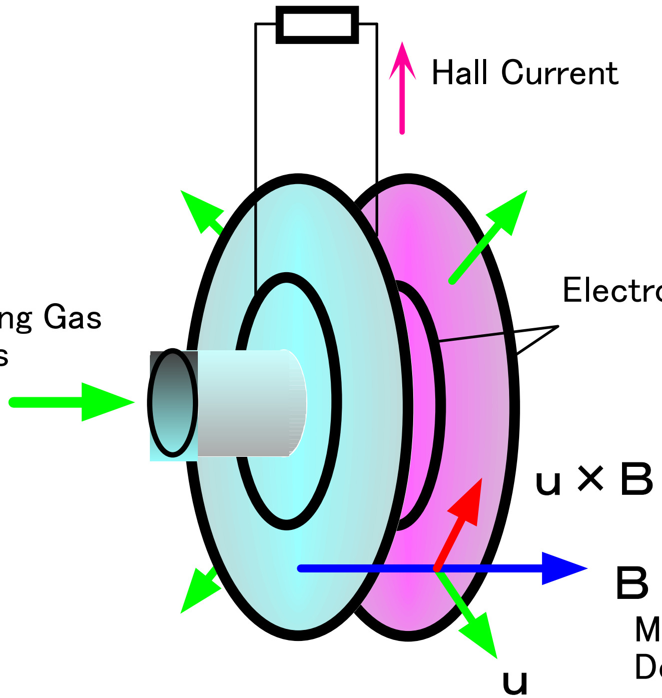
Targeted efficiency : 58-60 %

Closed Cycle MHD Power Generation System



Targeted total plant efficiency :
≧ 60 % (natural gas)

Disk Shaped MHD Generator



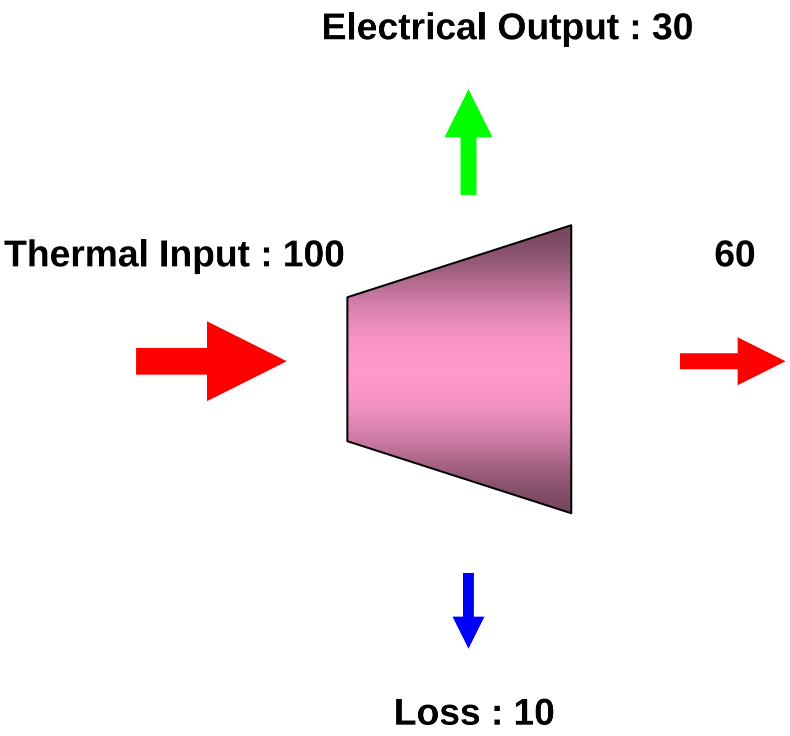
Azimuthal Faraday (uxB) Current
- ✓ ***Uniform nonequilibrium plasma***
  - ***=> High performance***

High Power Density
- ✓***Compact generator***
- ✓***Compact SCM***

Simple Ring shaped electrode
- ✓ ***small voltage drop***
- ✓ ***rotating plasma (no arc spot)***
  - ***=> durability***
- ✓ ***simple DC-AC converter system***

Disk MHD Generator is required to have a high Hall parameter.

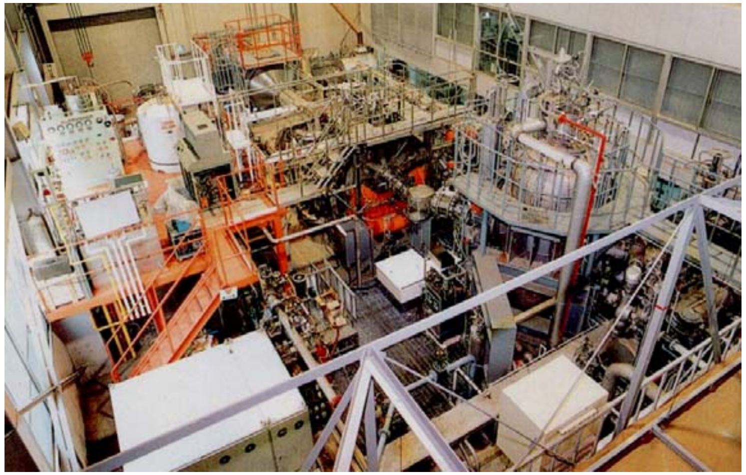
Enthalpy Extraction Ratio & Isentropic Efficiency



$$\text{Enthalpy Extraction Ratio} = \frac{30}{100} = 30\%$$

$$\text{Isentropic Efficiency} = \frac{30}{100-60} = 75\%$$

Experimental Facilities



- **"Fuji1-1" Blow- down facility**
  Magnetic flux density ～4.6 T (SCM)
  Ar / Cs
  Time Duration ～1minute,

- **Shock- tunnel facility**
  Magnetic flux density ～3T
  He / Cs or Ar / Cs
  Time duration ～10 msec,

Improvement in Enthalpy Extraction Ratio and Isentropic Efficiency

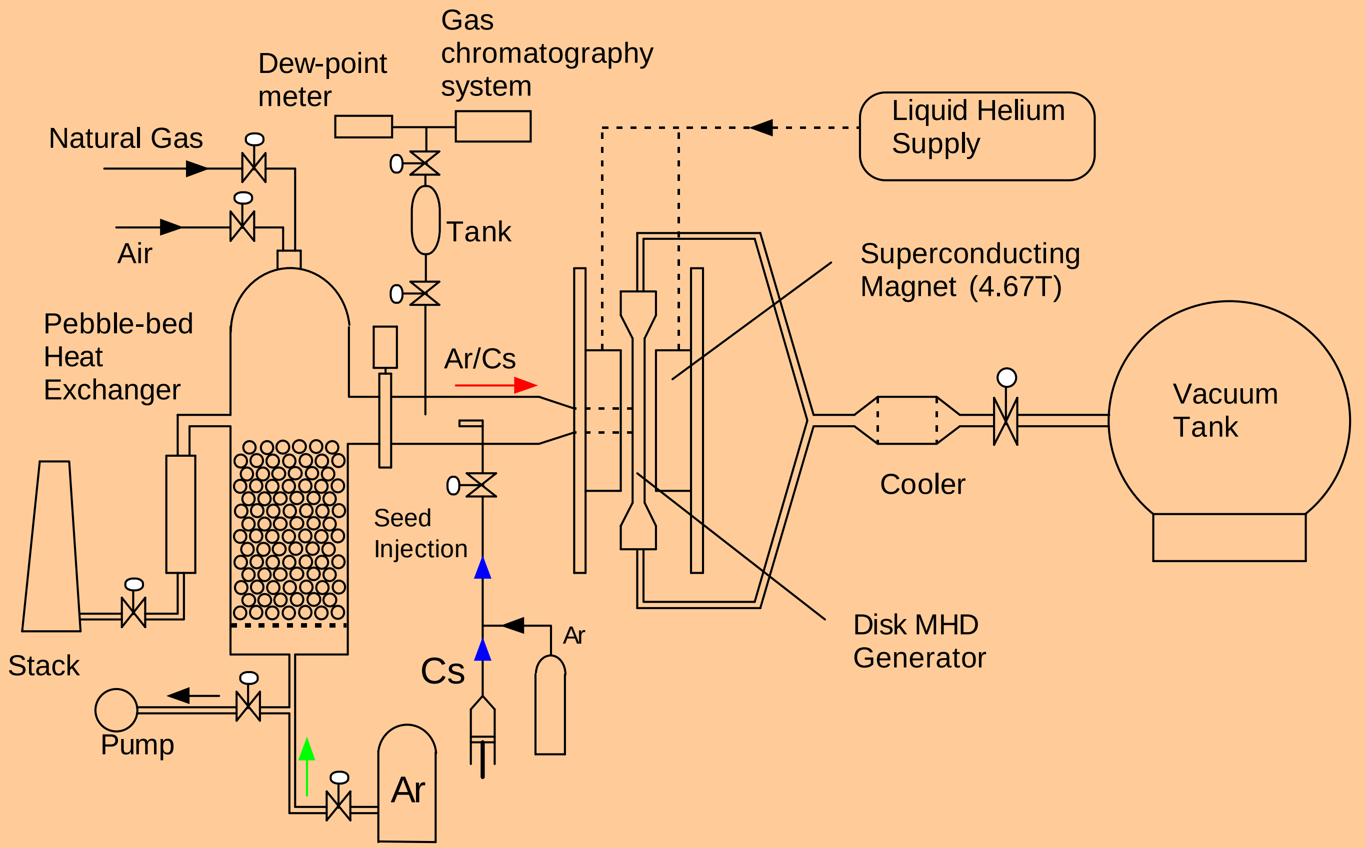
Power Generation Experiments
In Fuji-1 Blow-Down Facility

Main objective in the Fuji-1 MHD power generation experiments was

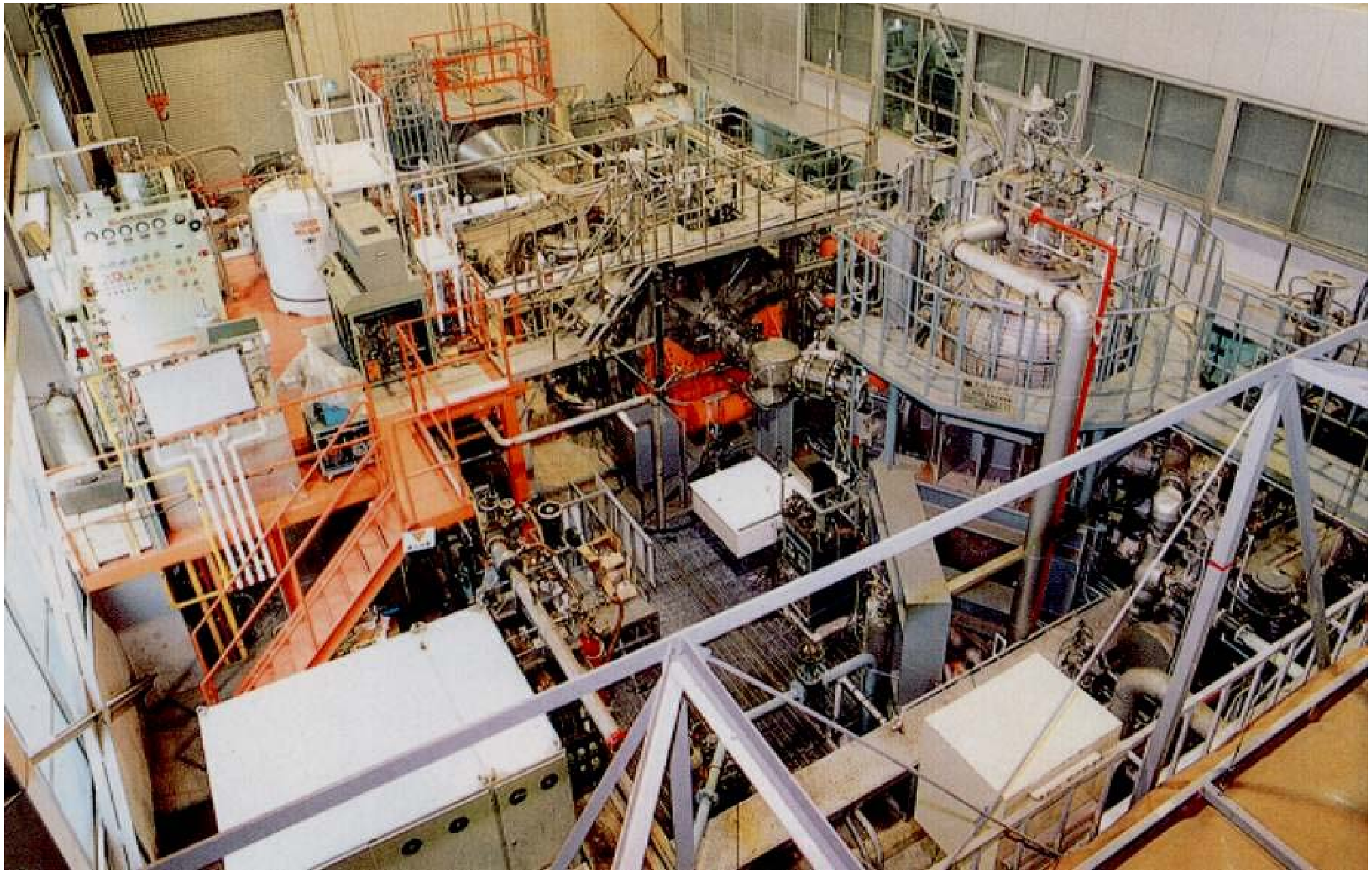
to demonstrate the high enthalpy extraction ratio
(electrical output / thermal input)

with well reproducibility
for a period of several tens of seconds
using a disk shaped generator.

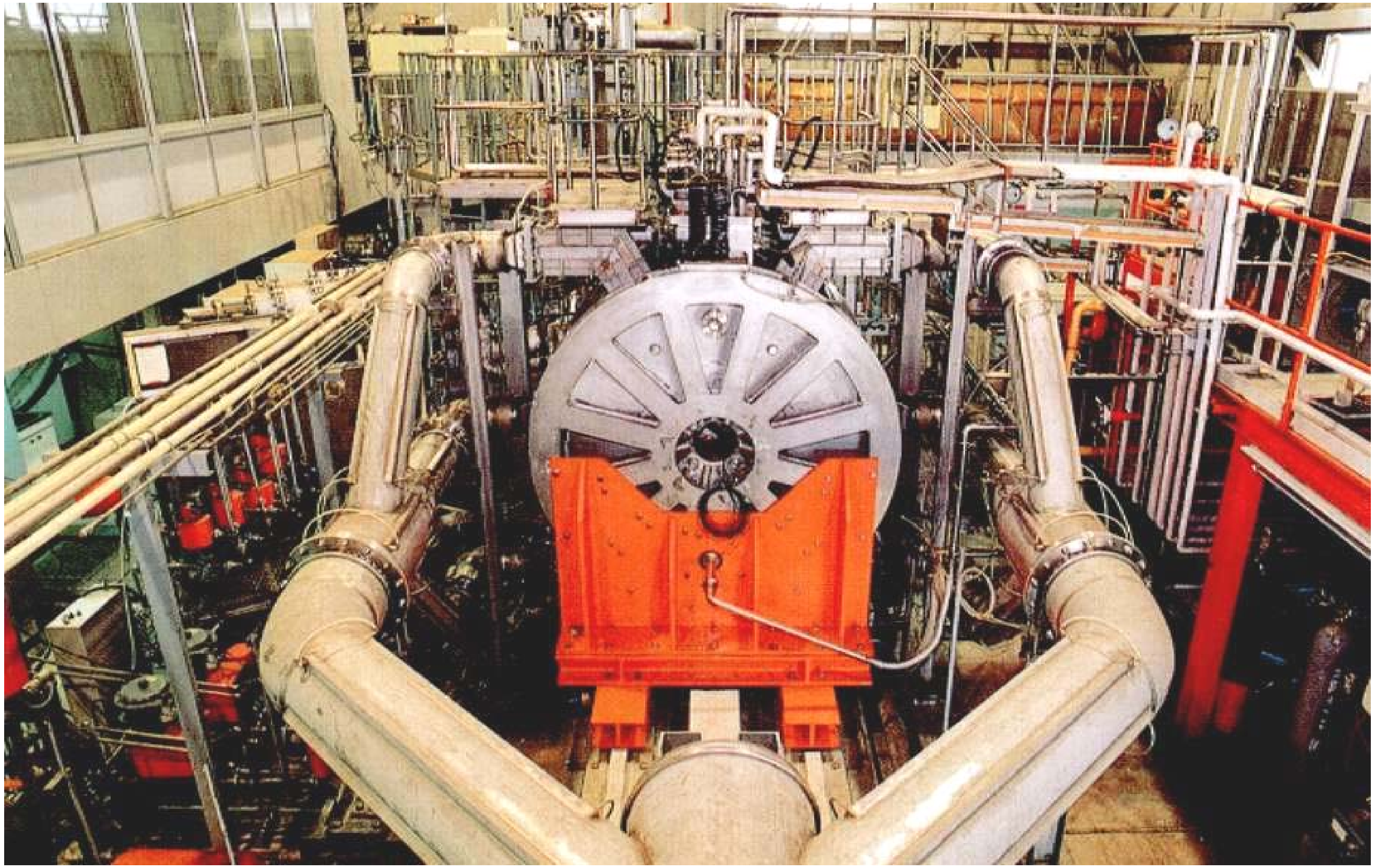
Fuji-1 Blow-Down Facility



(1981 – 1999)

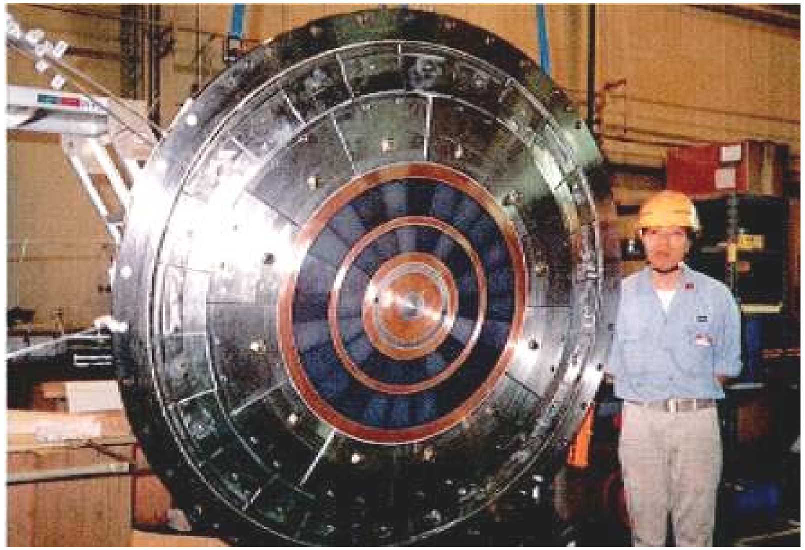


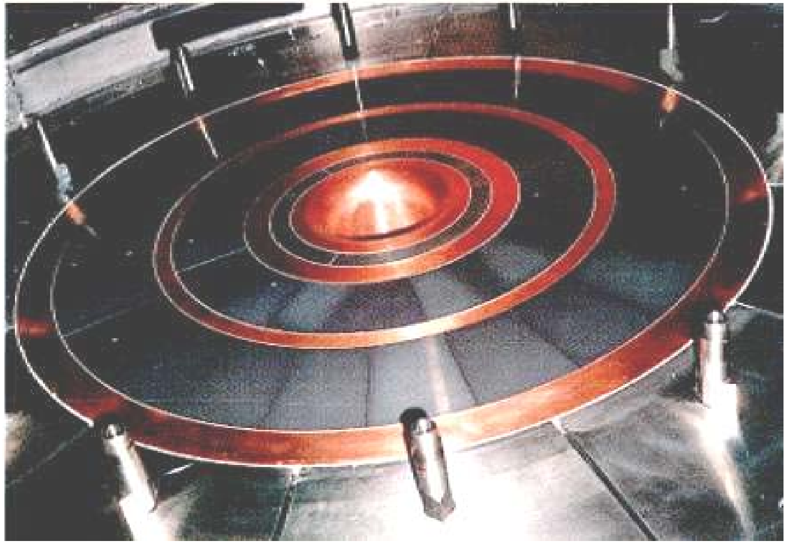
Fuji-1 Blow-Down Facility



Fuji-1 Blow-Down Facility

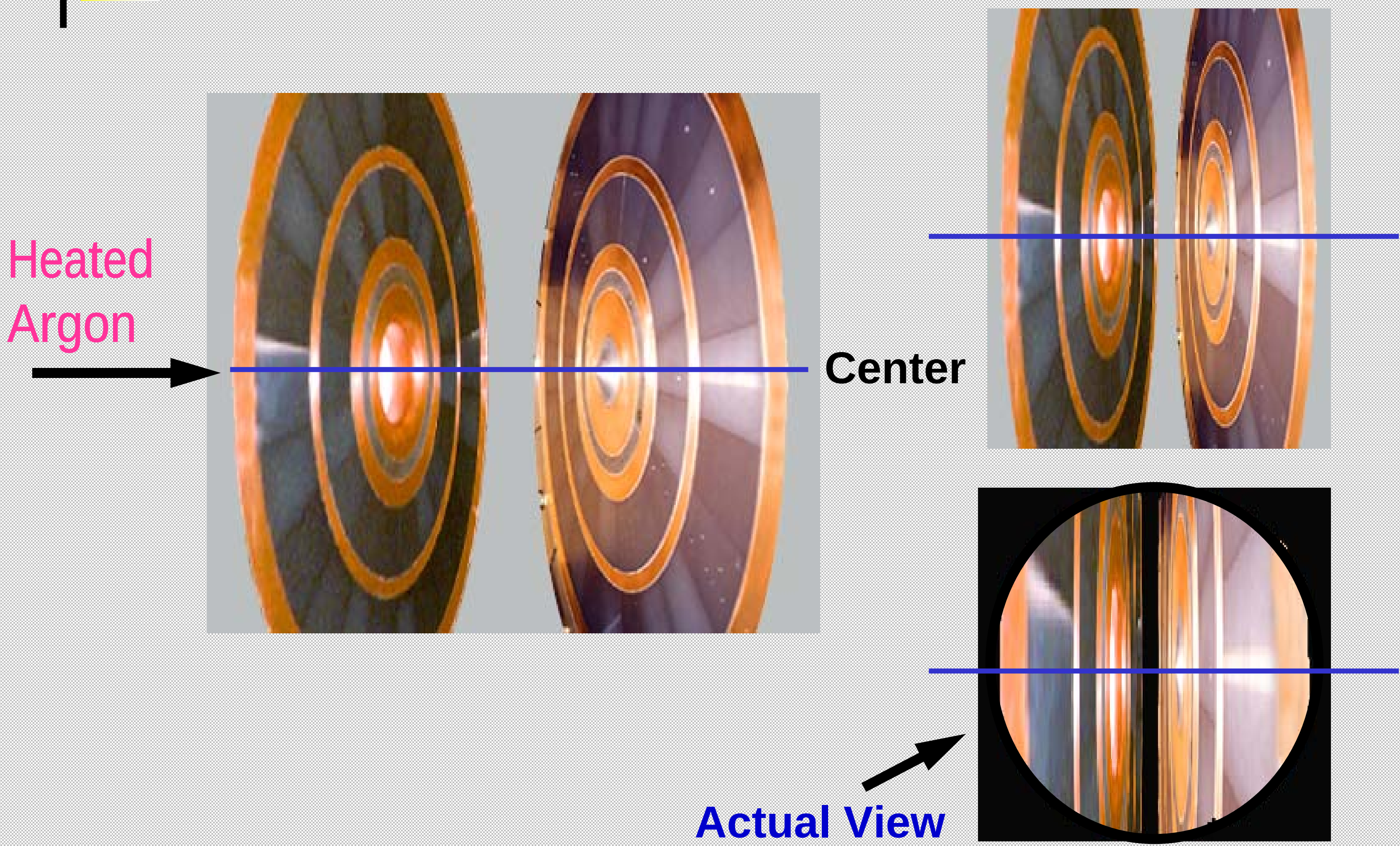
Disk MHD Generator





Disk MHD Generator installed in Fuji-1 Facility

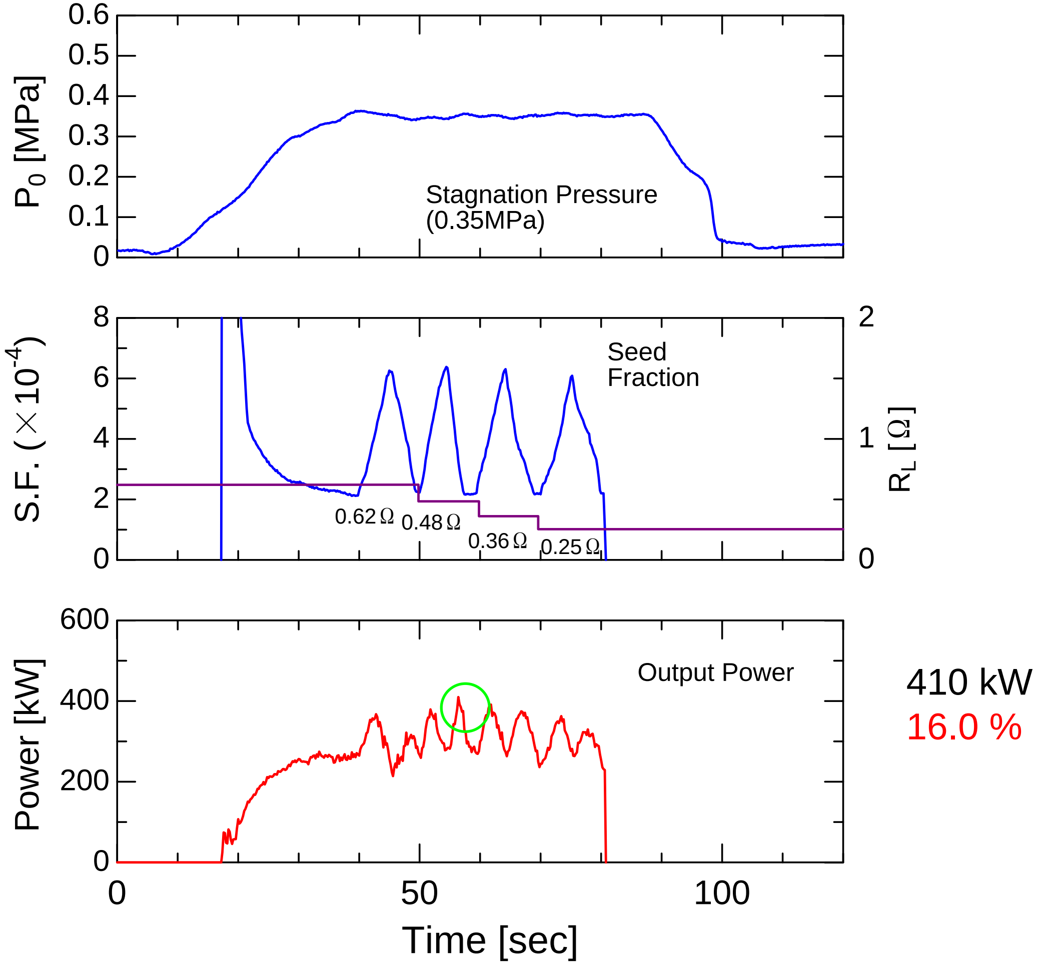
Video footage



Video footage

Center

Produced by Prof. Yamasaki



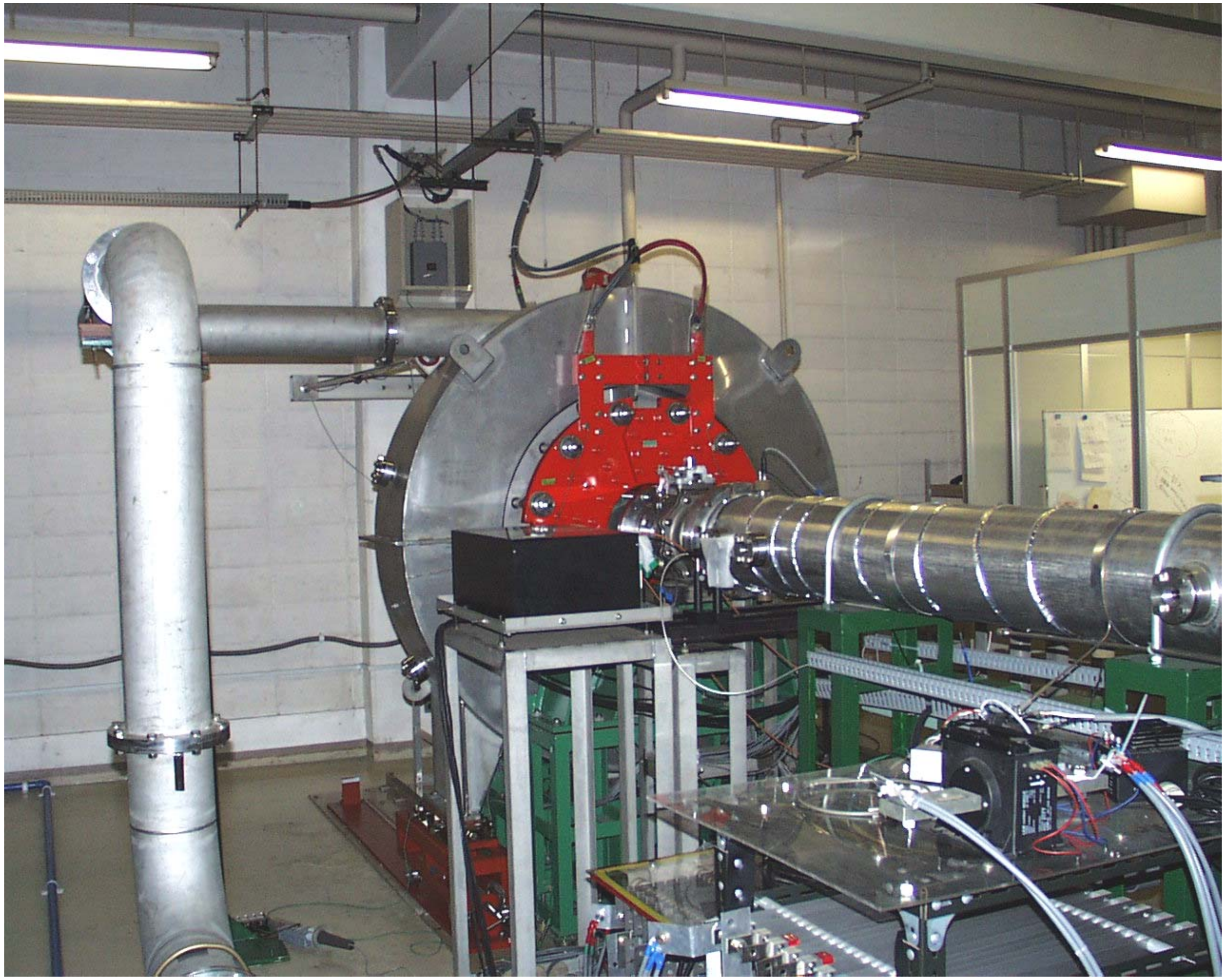
Time variations of working conditions and output power (Run A4127)

Typical Experimental Conditions and Results

Run Number	A4118	A4126	A4127
Stagnation Pressure [MPa]	0.434	0.545	0.351
Stagnation Temperature [K]	1980	1973	1914
Thermal Input [MW]	3.24	3.99	2.57
Seed Fraction [$\times 10^{-4}$]	2.9	3.7	3.3
Load Resistance [Ω]	0.48	0.48	0.48
Max.Power Output [kW]	506	544	410
Max.Enthalpy Extraction [%]	15.6	13.6	16.0

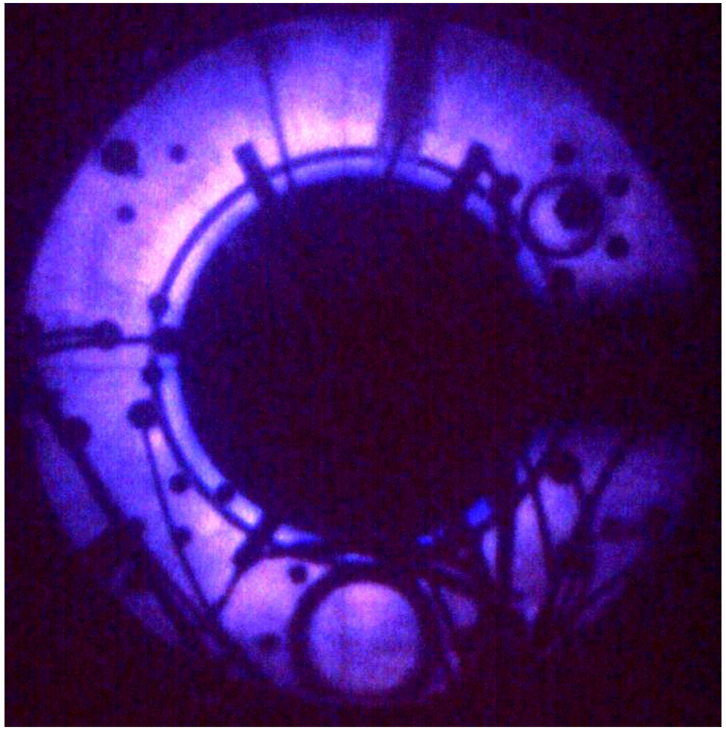
Power Generation Experiments in Shock-Tunnel Facility

- Demonstration of high performance
- Clarification of Non-equilibrium plasma and MHD Flow behavior

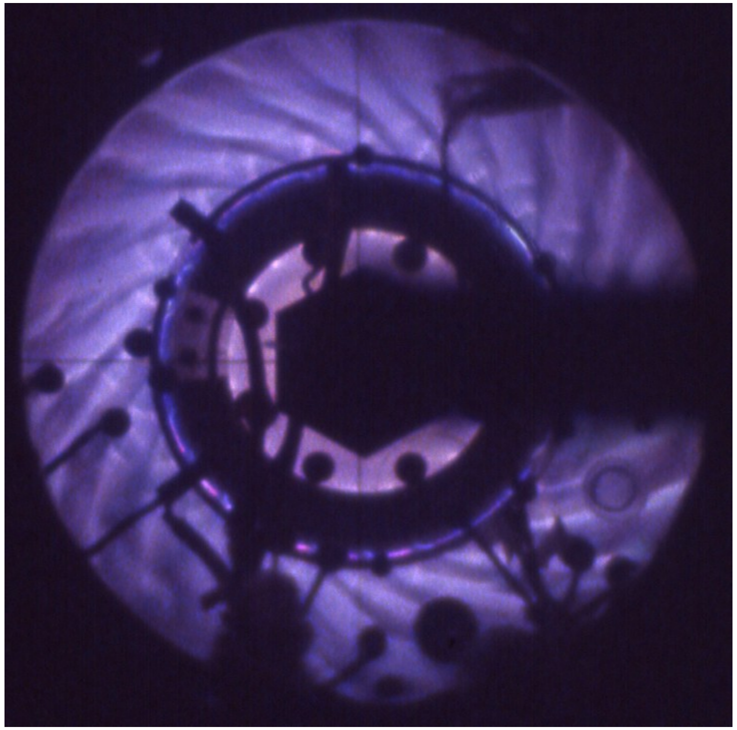


Shock-tube Facility

Typical discharge structure



Radial-flow **generator**



Swirl-flow **generator**

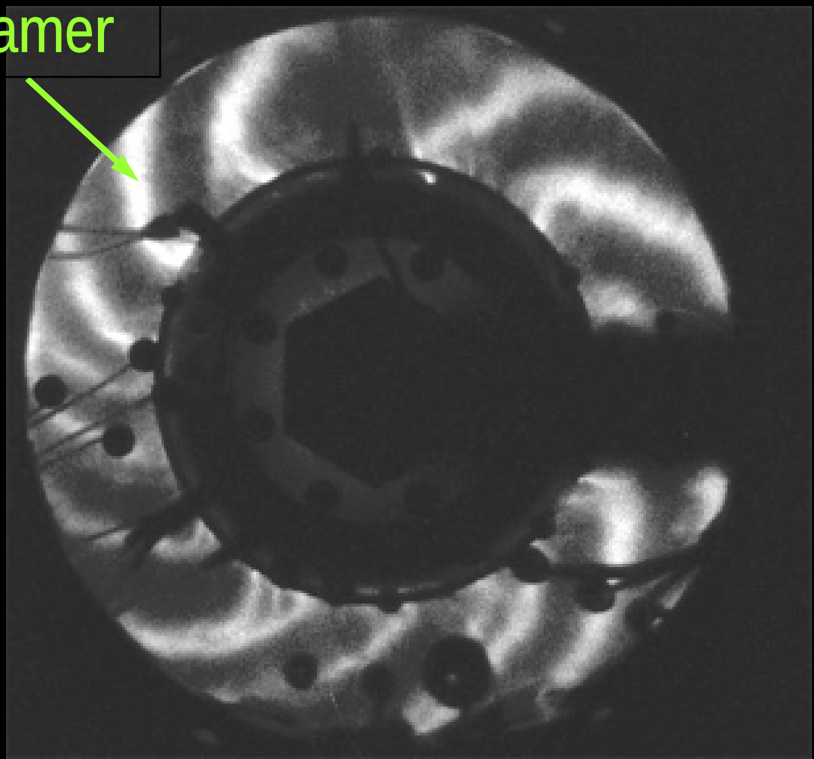
Shock Tunnel facility :

- **Plasma behavior : Ionization Instability => Fully Ionized Seed**
- **Demonstration of High Enthalpy Extraction Ratio and Isentropic Efficiency**

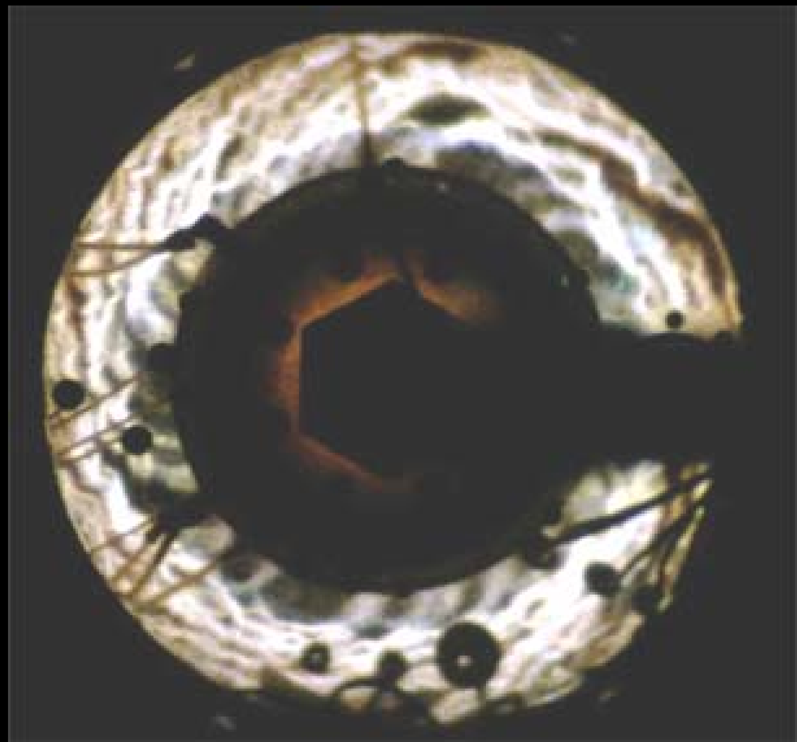
Discharge Structure in Disk MHD Generator with Inlet Swirl Vanes

From Prof. Yamasaki

Black and white



Color



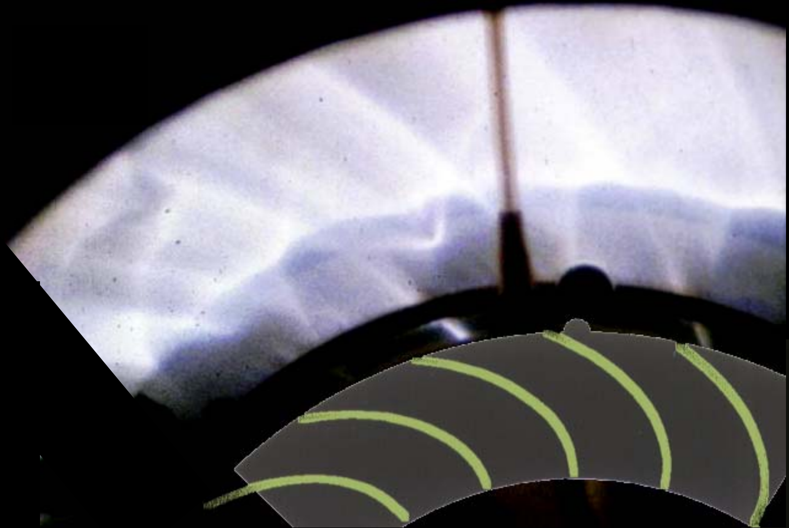
(A) S.F.=1.60×10^{-4}, R_L=0.16 ohm

E.E. =10.1 %, η_{ad}= 21.8 %

(B) S.F.=1.66×10^{-3}, R_L=0.14 ohm

E.E. =18.6 %, η_{ad}= 38.6 %

Discharge Structure in Disk MHD Generator with Inlet Swirl Vanes

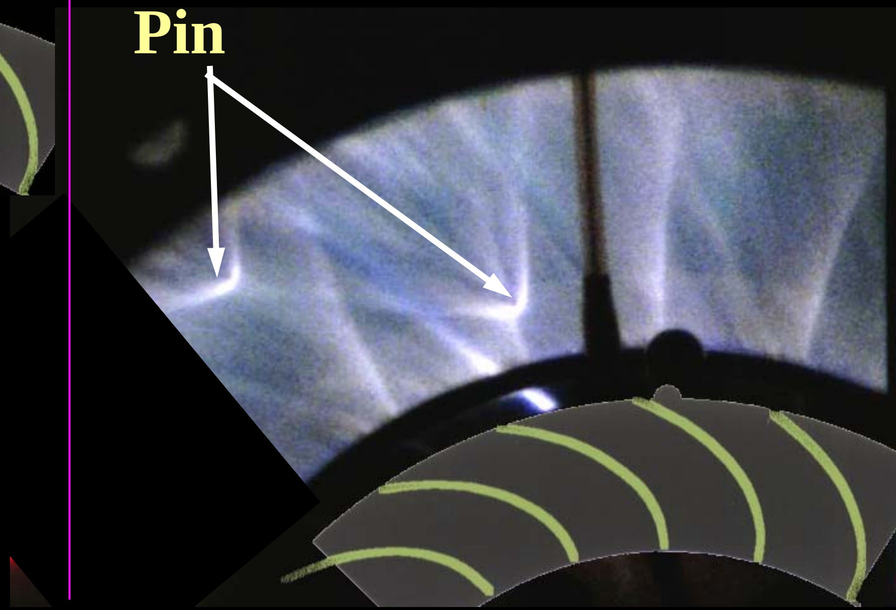


Flow with Shock Wave

S.F.=3.8×10^{-4}, R_L=0.34 ohm
E.E. =18.4 %, η_{ad}= 34.9 %

S.F.=3.1×10^{-4}, R_L=0.21 ohm
E.E. =20.2 %, η_{ad}= 48.3 %

Shock-less Flow



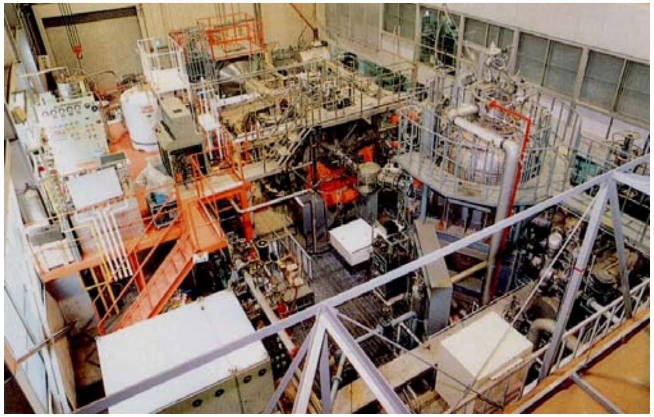
From Prof. Yamasaki

Typical Experimental Conditions and Results

Generator Channel	RLN1	RLN2	IS-1(Swirl)	
Working gas	Ar/Cs	Ar/Cs	Ar/Cs	He/Cs
Stagnation pressure (MPa)	0.24	0.28	0.24	0.14
Stagnation temperature (K)	2000	～2500	2400	～2200
Thermal Input (MW)	1.57	3.48	2.13	3.61
A_{exit} / A_{throat}	14.4	4.25	5.91	5.91
Seed fraction	9.0×10^{-4}	12.4×10^{-4}	6.4×10^{-4}	4.5×10^{-4}
Load resistance (Ω)	0.22	0.10	0.14	0.62
Magnetic flux density (T)	2.7	3.0	3.0	3.0
Output Power (kW)	**408**	**569**	**540**	**1112**
Enthalpy Extraction Ratio (%)	**26.5**	**17.2**	**25.4**	**30.8**
Isentropic efficiency (%)	**37.4**	**46.2**	**54.3**	**63**

Thermal Input based on 0 K

Current Status and Target

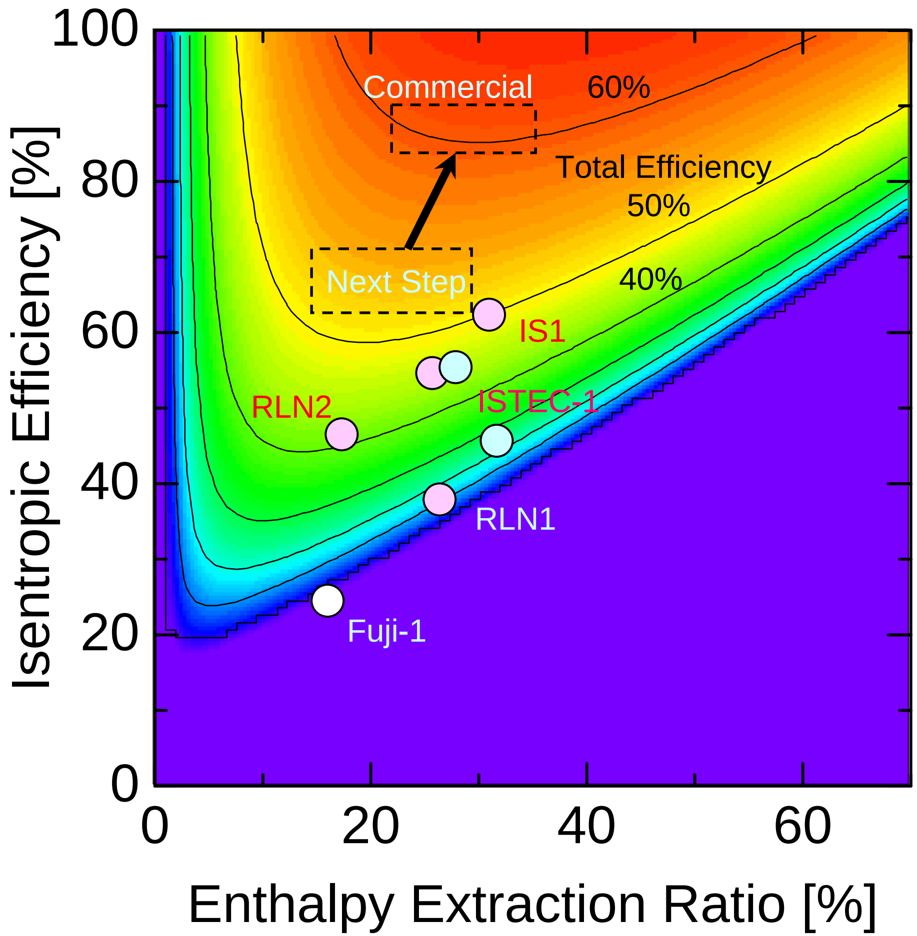


"Fuji1-1" Blow- down facility

Time duration ～1 minute

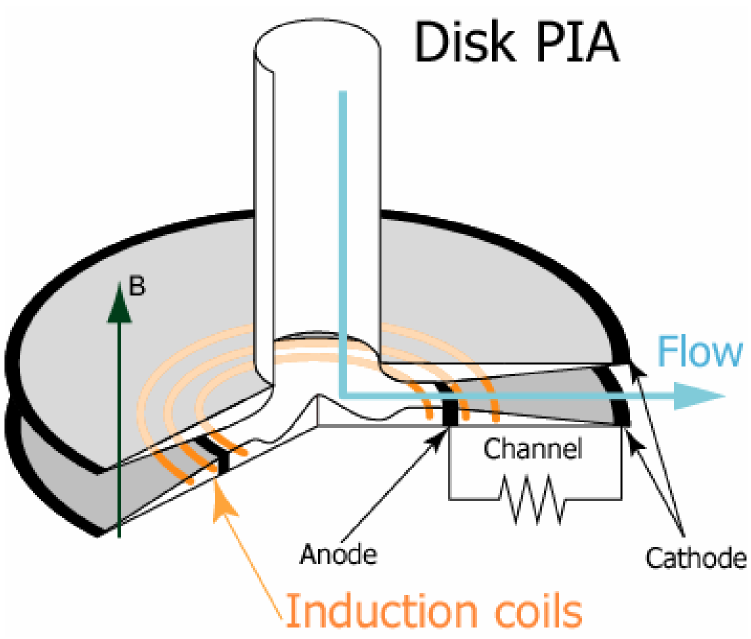
Shock- tunnel facility

Time duration ～10 msec



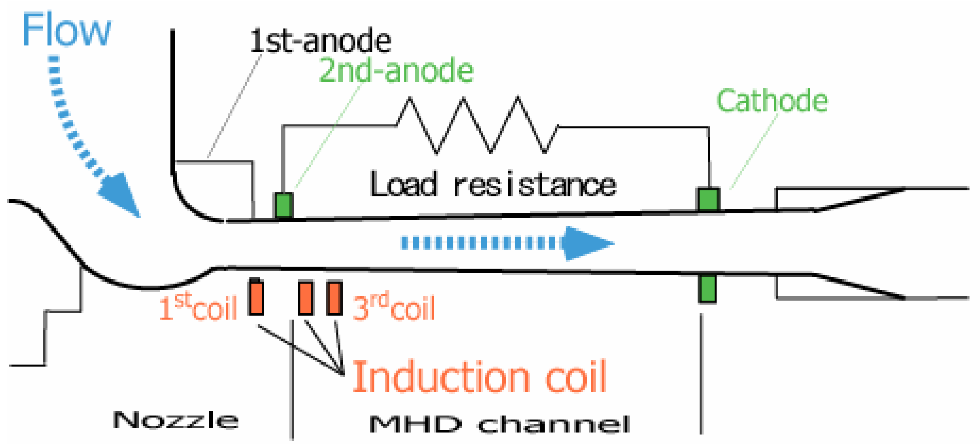
Improvement of Generator Performance by Applying RF Electromagnetic Field

Tokyo Institute of Technology
Energy Sciences

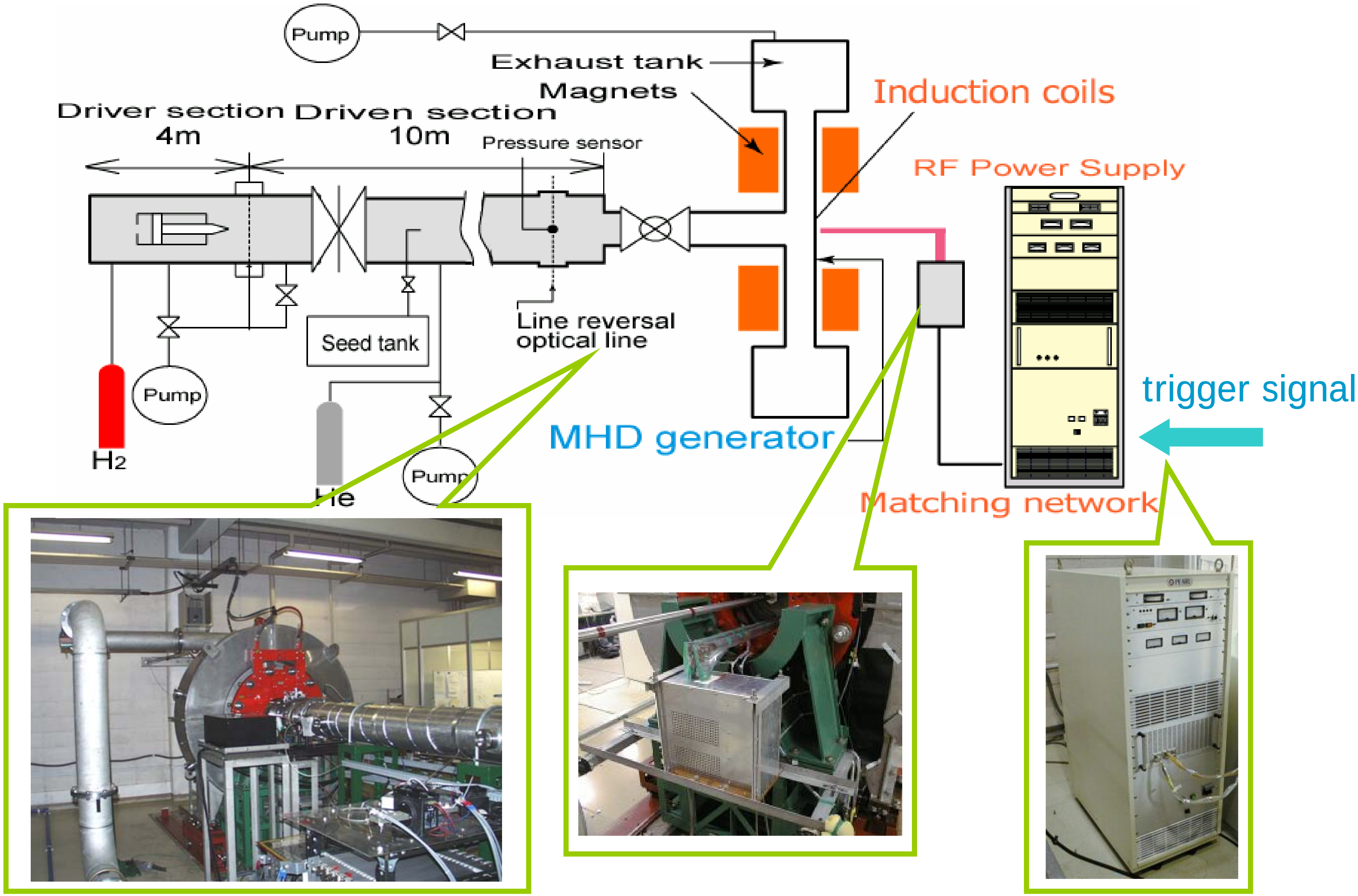


Three RF induction coils are embedded in one side of the disk wall

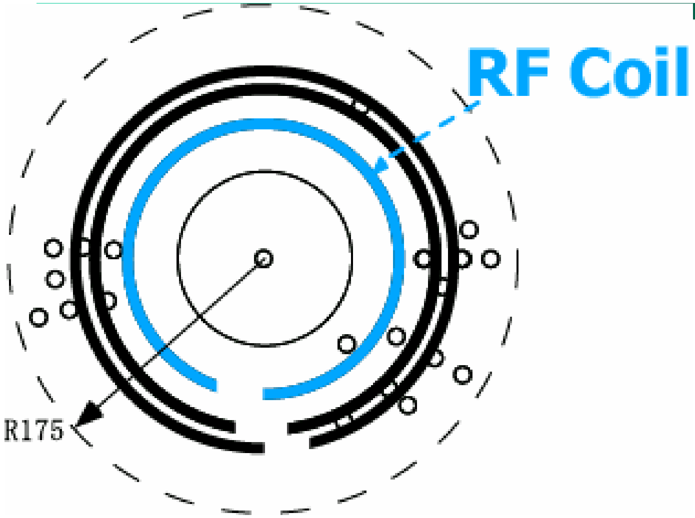
RF-power is supplied to the innermost coil (1st coil) and the outermost coil (3rd coil)



Shock tunnel driven MHD facility



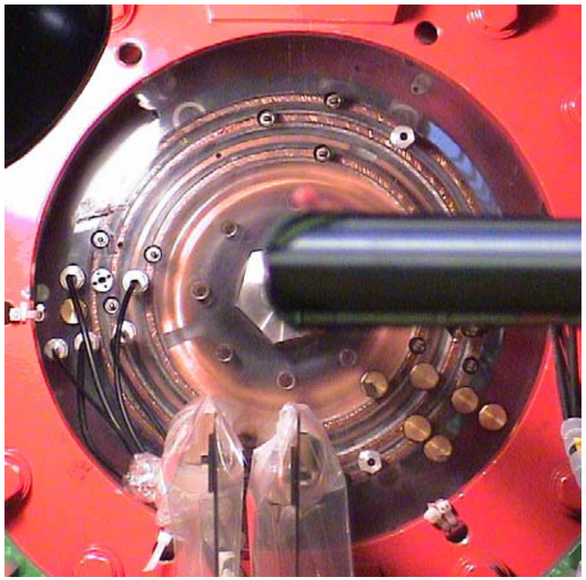
Plasma Structure

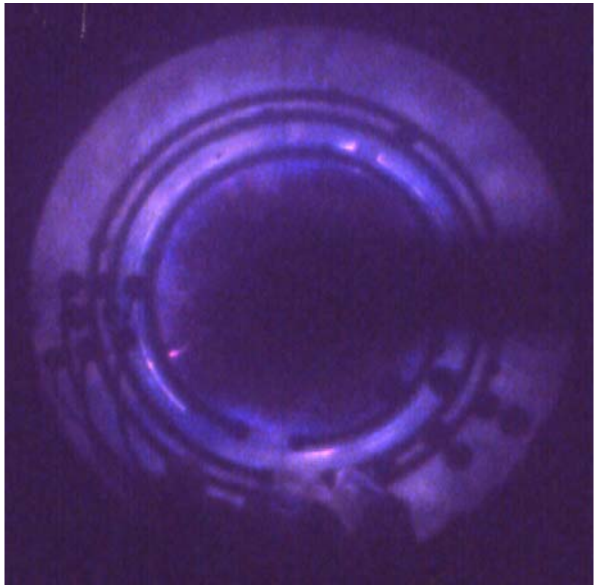


Frame rate : 5900FPS

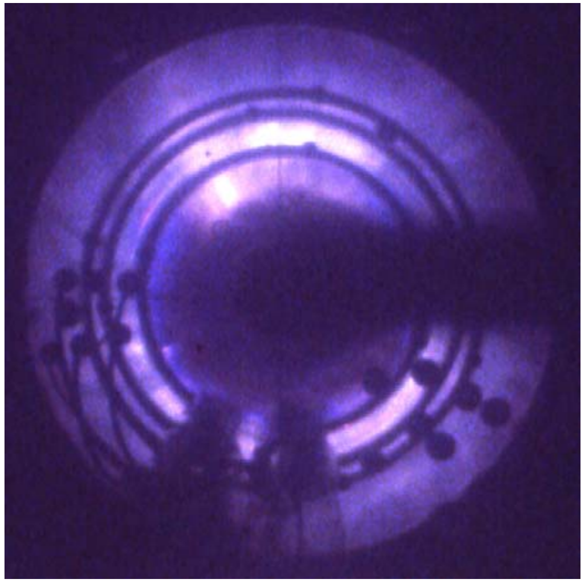
Exposure time: 8.5[μ sec]

$\odot$ B



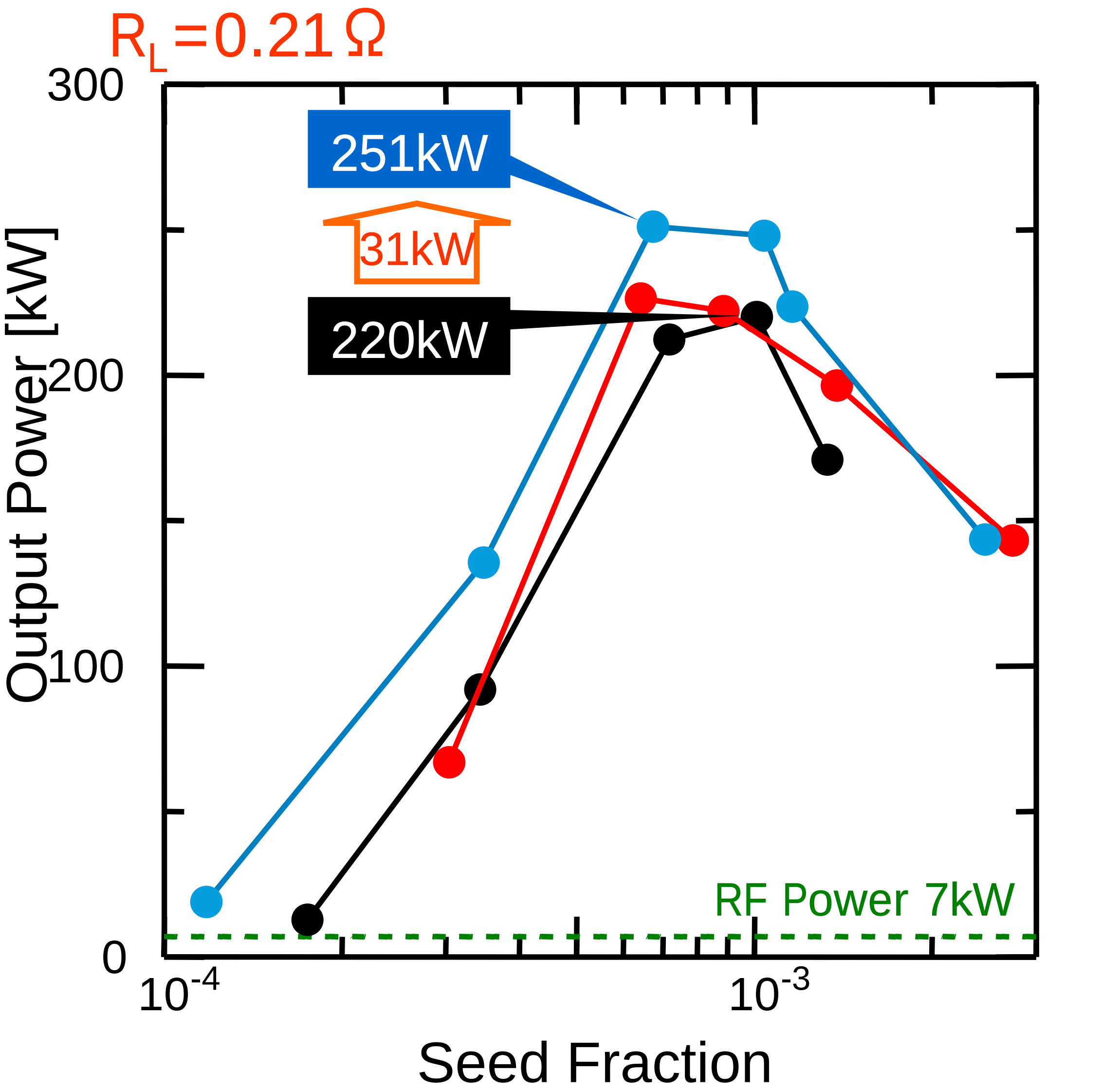


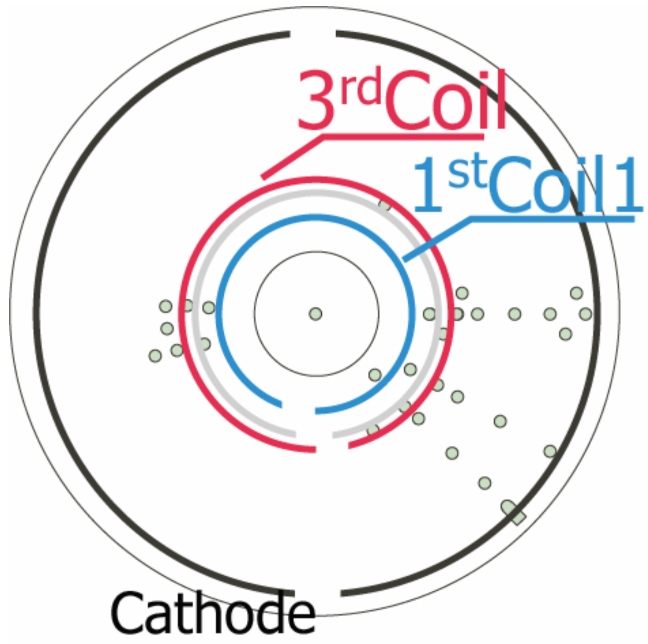
Without applying RF-power



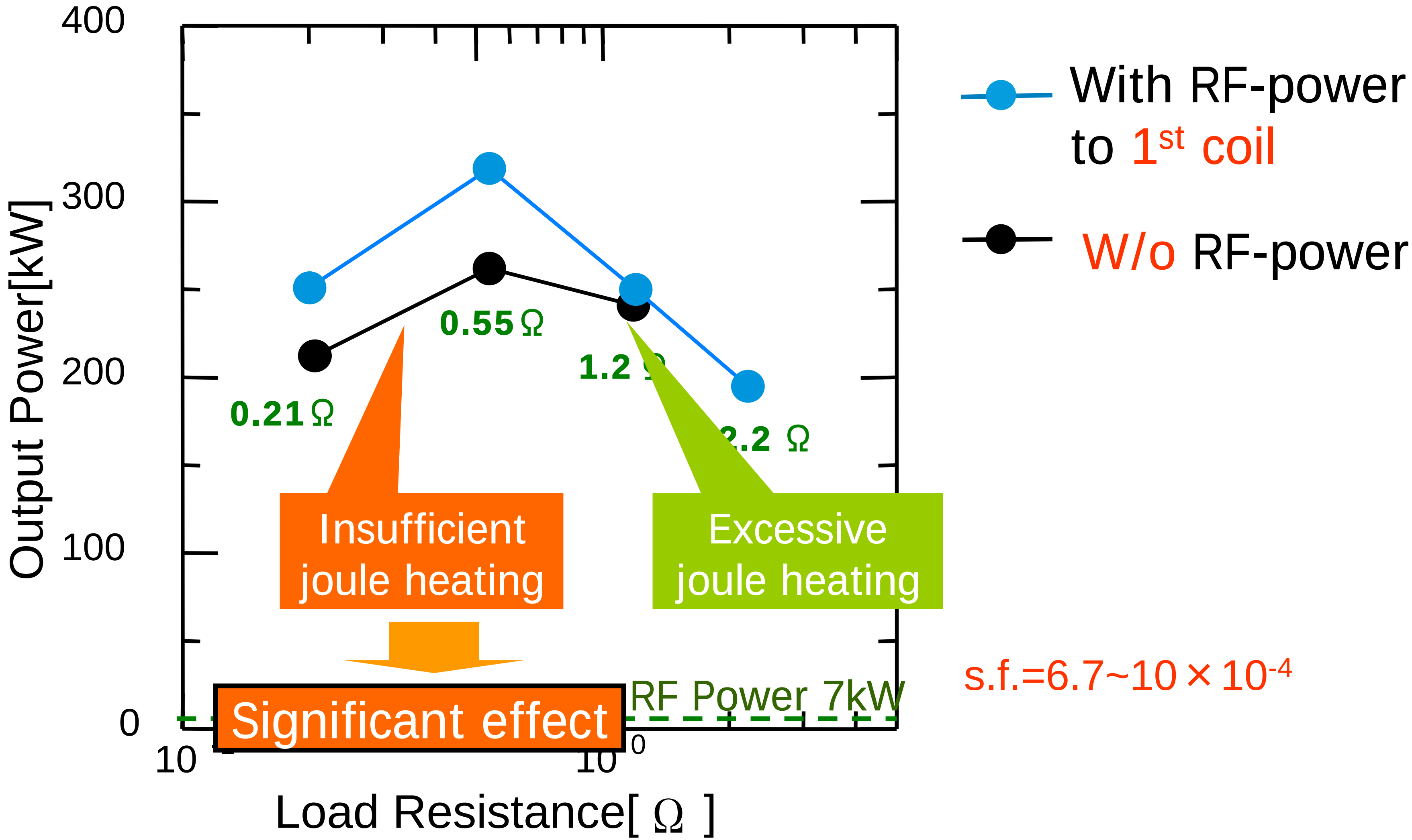
With applying RF-power

Output Power against Seed Fraction



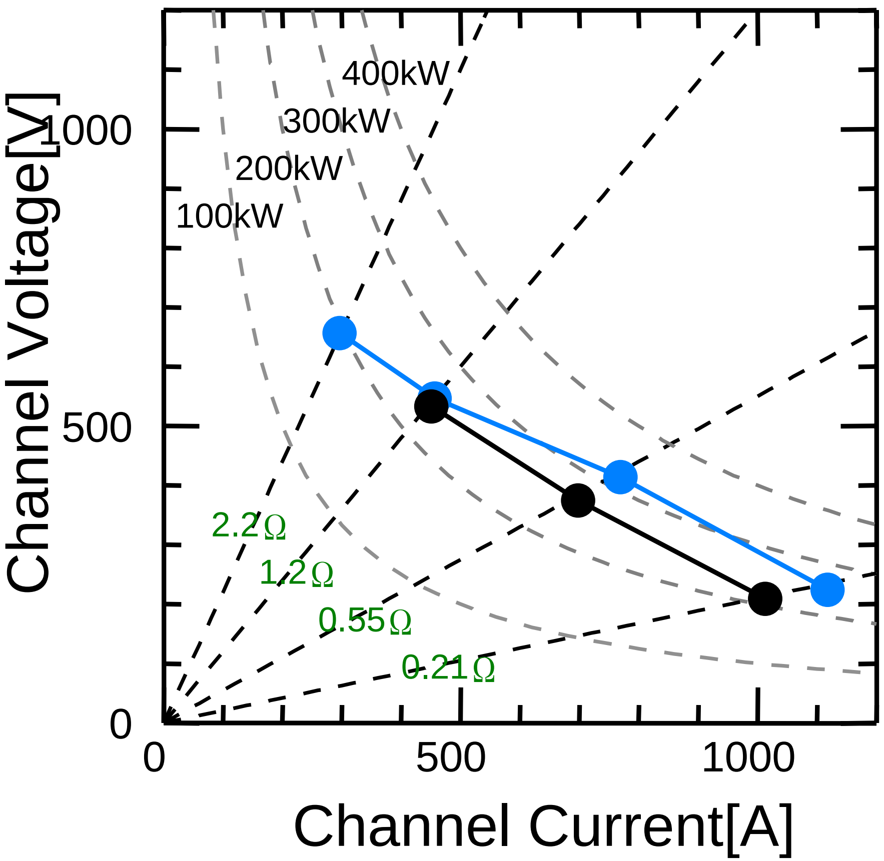


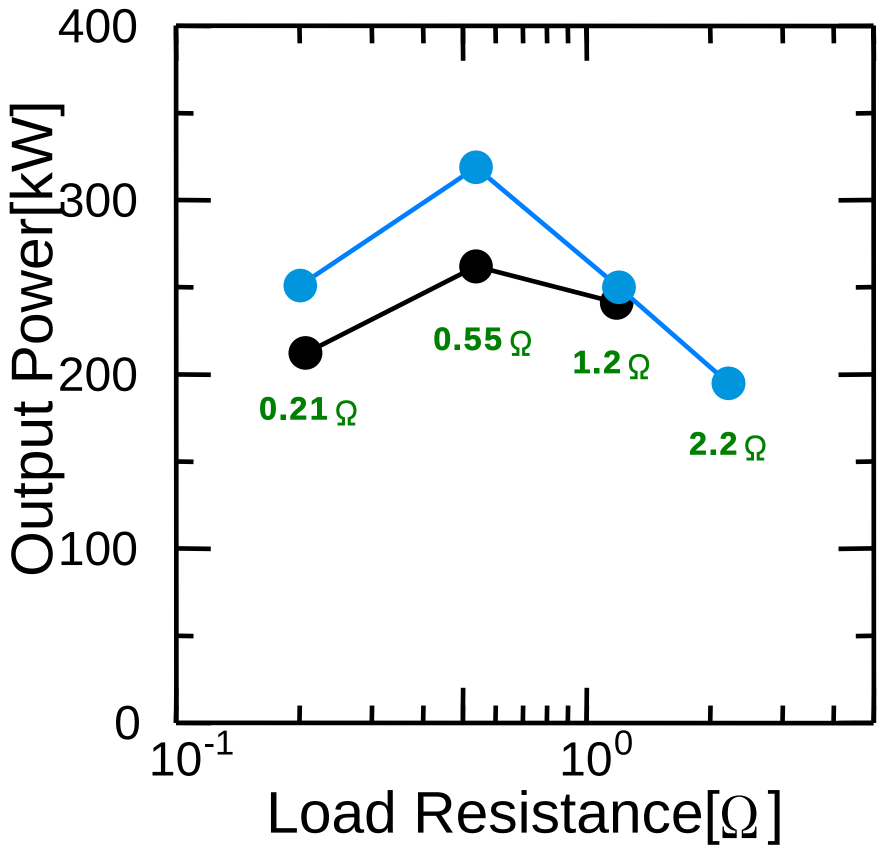
Influence of Difference in External Load Resistance



Voltage-Current Characteristics

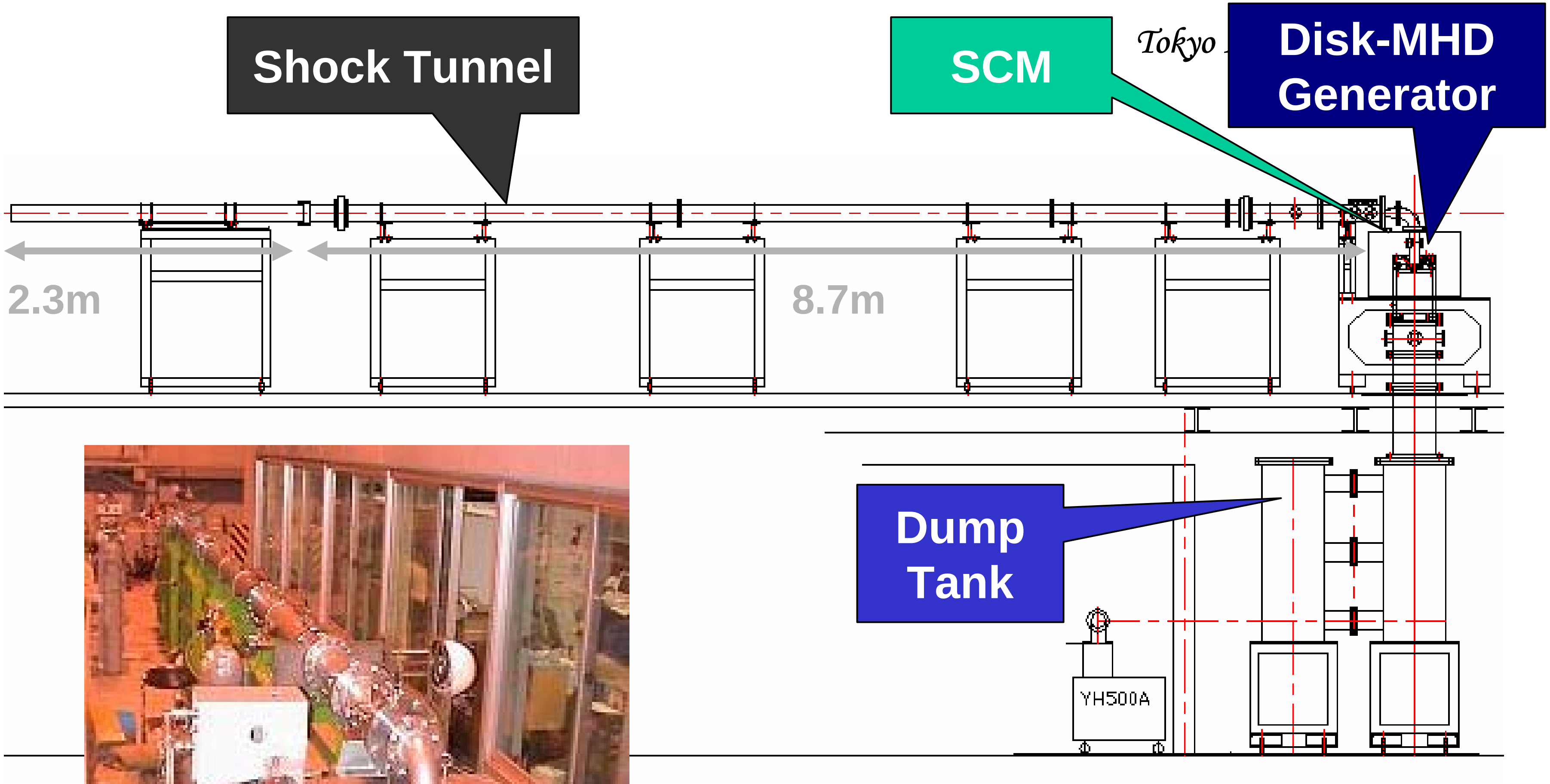
s.f.=6.7~10×10^{-4}





W/o RF-power

With RF-power to 1st coil

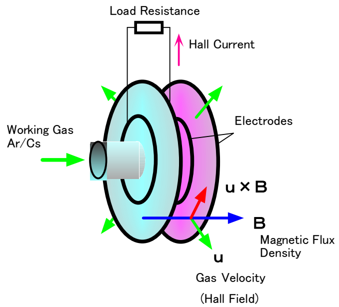


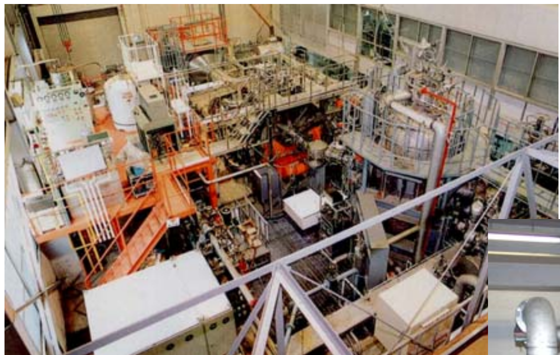
Shock tunnel + SCM Facility

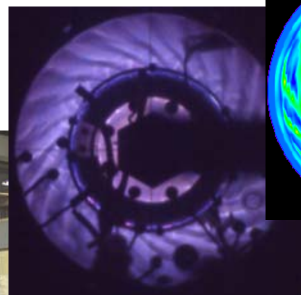
=> *To Next Stage !*

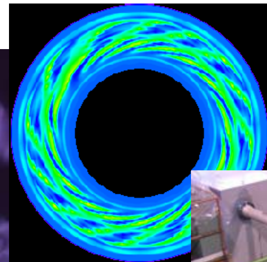
Studies of MHD Electrical Power Generation with Closed Loop Experimental Facility

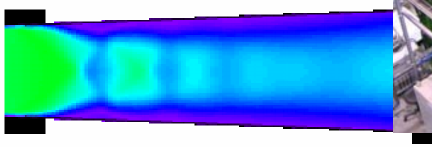
Y. Okuno, T. Murakami, H.Yamasaki
Department of Energy Sciences
Tokyo Institute of Technology





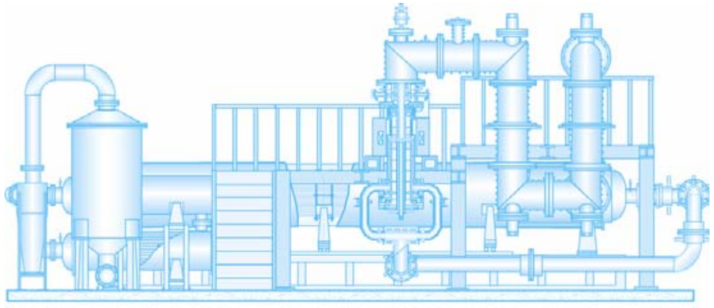




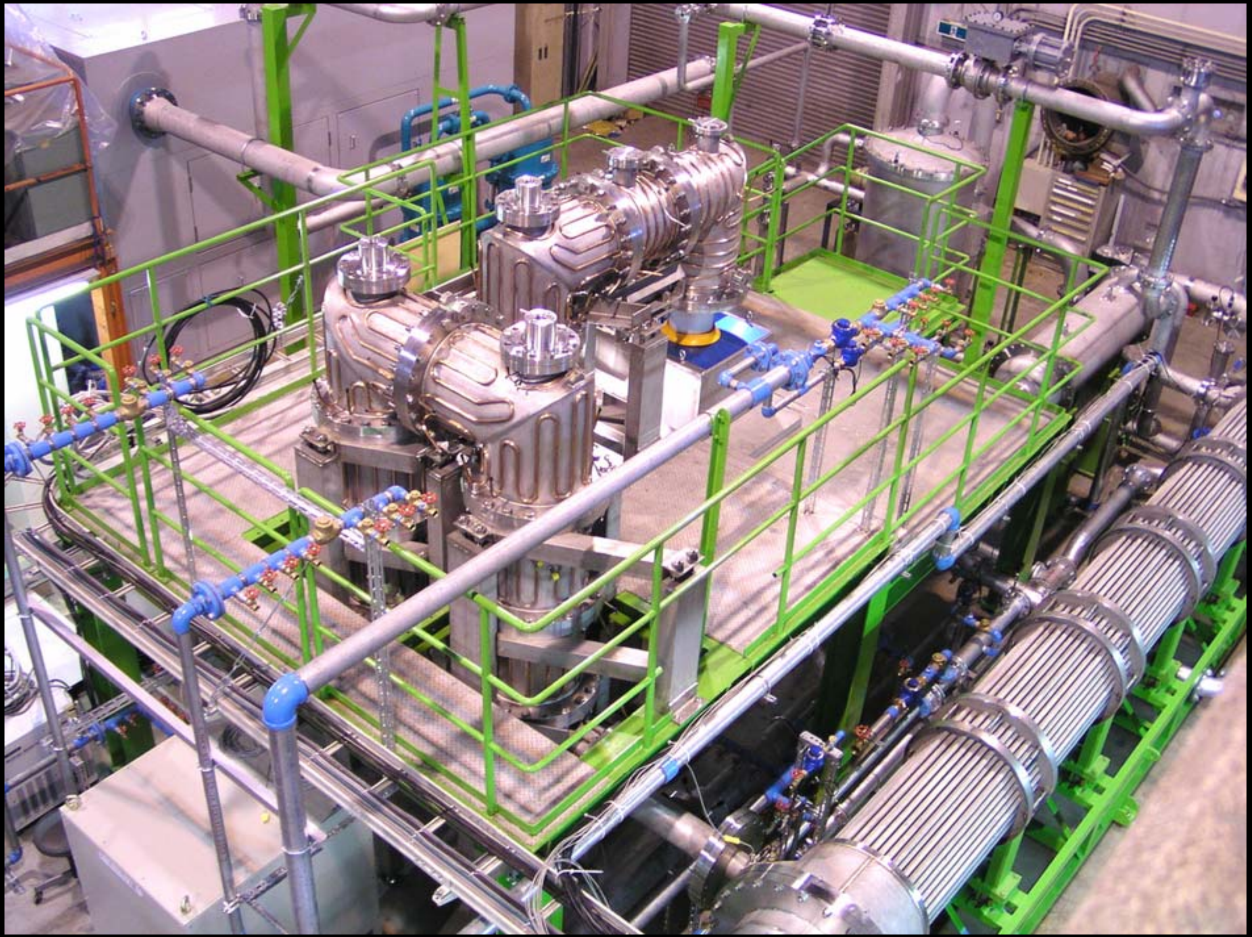


Contents

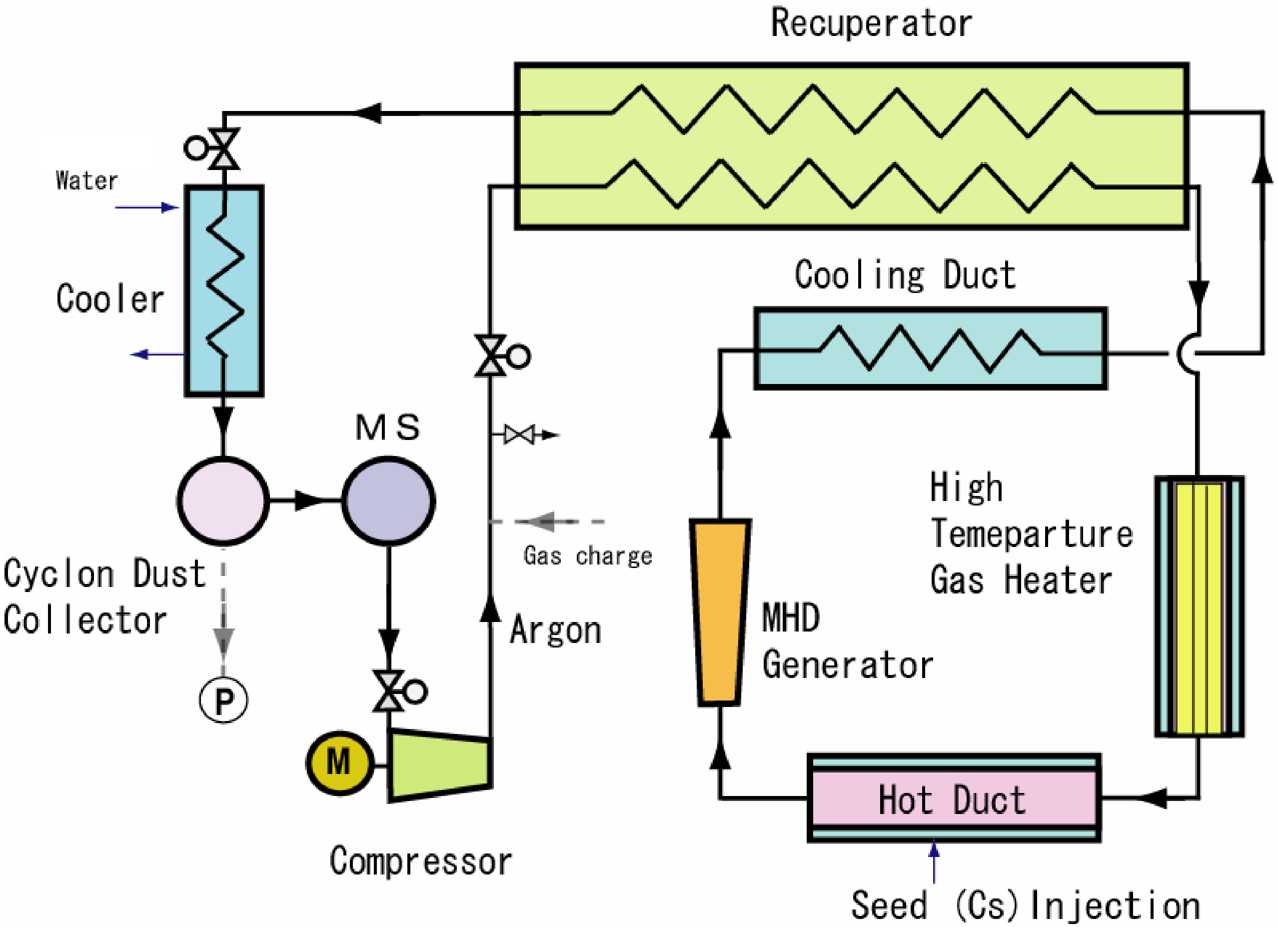
Closed Loop Experimental Facility for CCMHD



Supersonic Closed Loop Experimental Facility for CCMHD Power Generation



Closed Loop Experimental Facility



Tokyo Institute of Technology
Energy Sciences

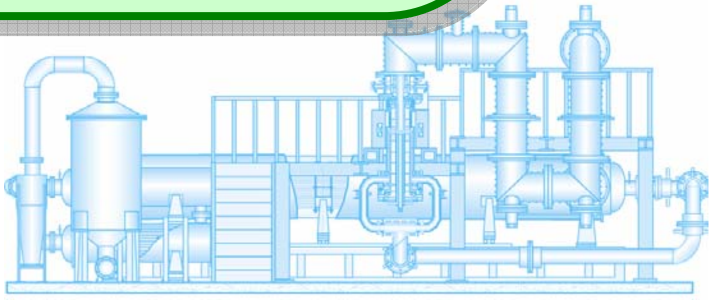
Supersonic Closed Loop Experimental Facility for CCMHD Power Generation

Main objectives

The aim of the experiment with " CLEF " is

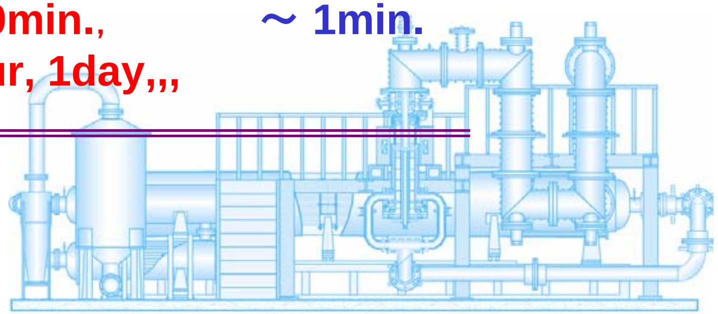
not to achieve the large output power and high enthalpy extraction ratio

but to demonstrate
the long time continuous power generation with high temperature heat recovery.

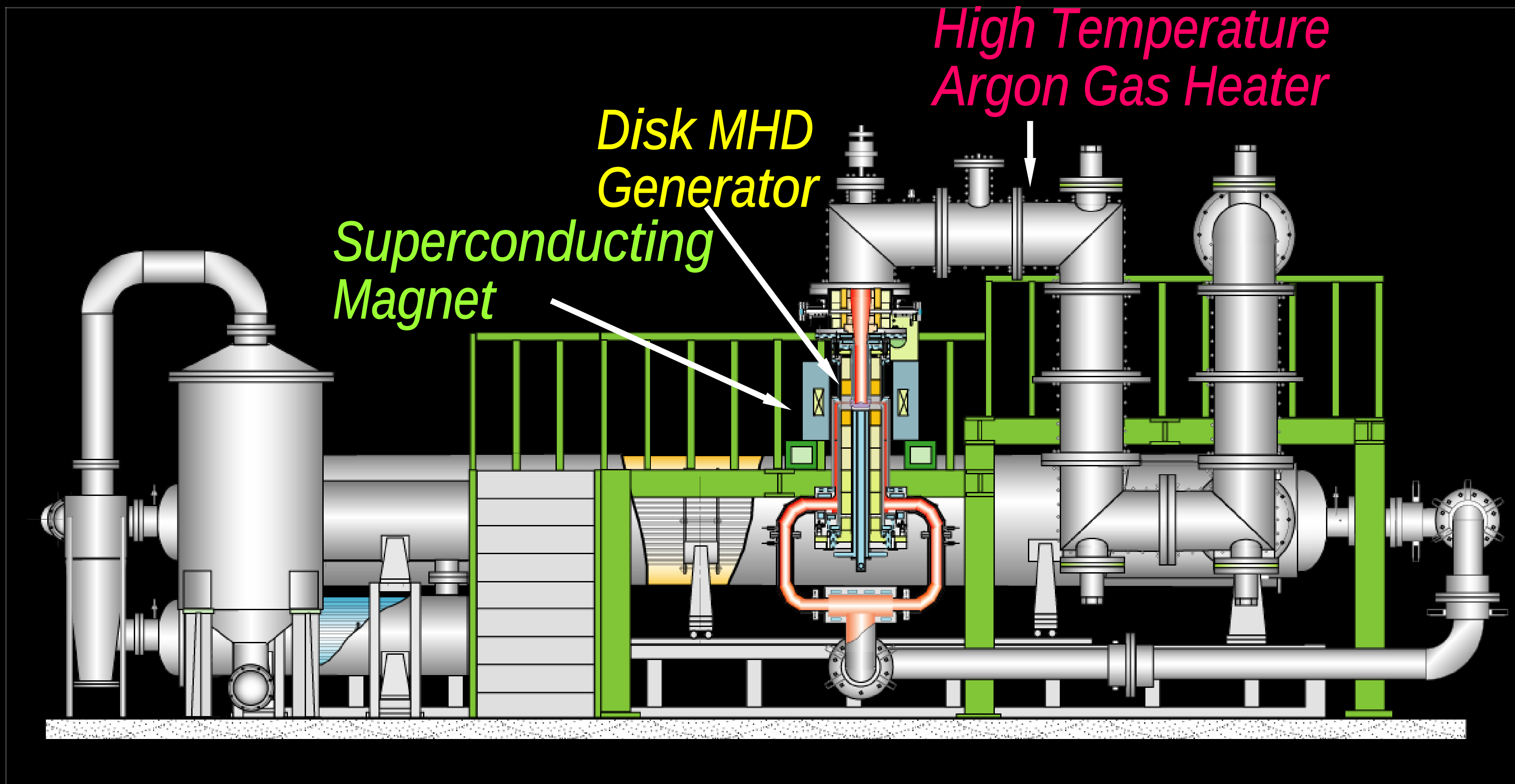


Specifications

	CLEF	Fuji-1
Stagnation Pressure [MPa]	～ 0.4	0.43
Stagnation Temperature [K]	1850 - 1900	1980
Magnetic Flux Density [T]	4.0	4.6
Thermal Input [MW]	0.5	3.2
Seed Fraction [$\times 10^{-4}$]	< 3	2.9
Load Resistance [Ω]	0 - 10	0.48
Pressure Ratio	< 8 (Comp.)	～ 10 (Tank)
Max.Enthalpy Extraction [%]	5 ～ 10	15.6
Max.Power Output [kW]	25 ～ 50	506
Duration of Power Generation	> 10min., 1hour, 1day,,,	～ 1min.

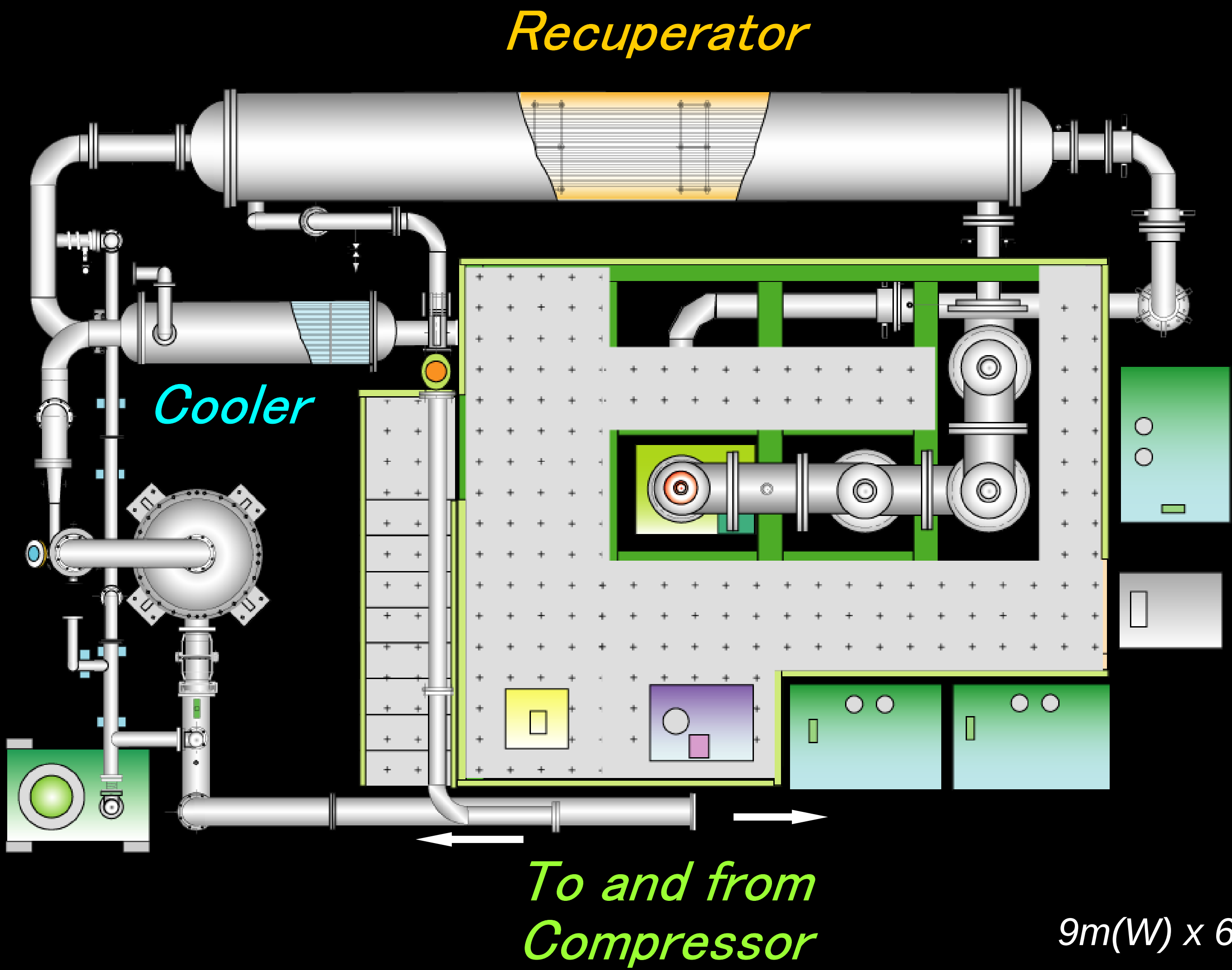


Closed Loop for CCMHD Power Generation



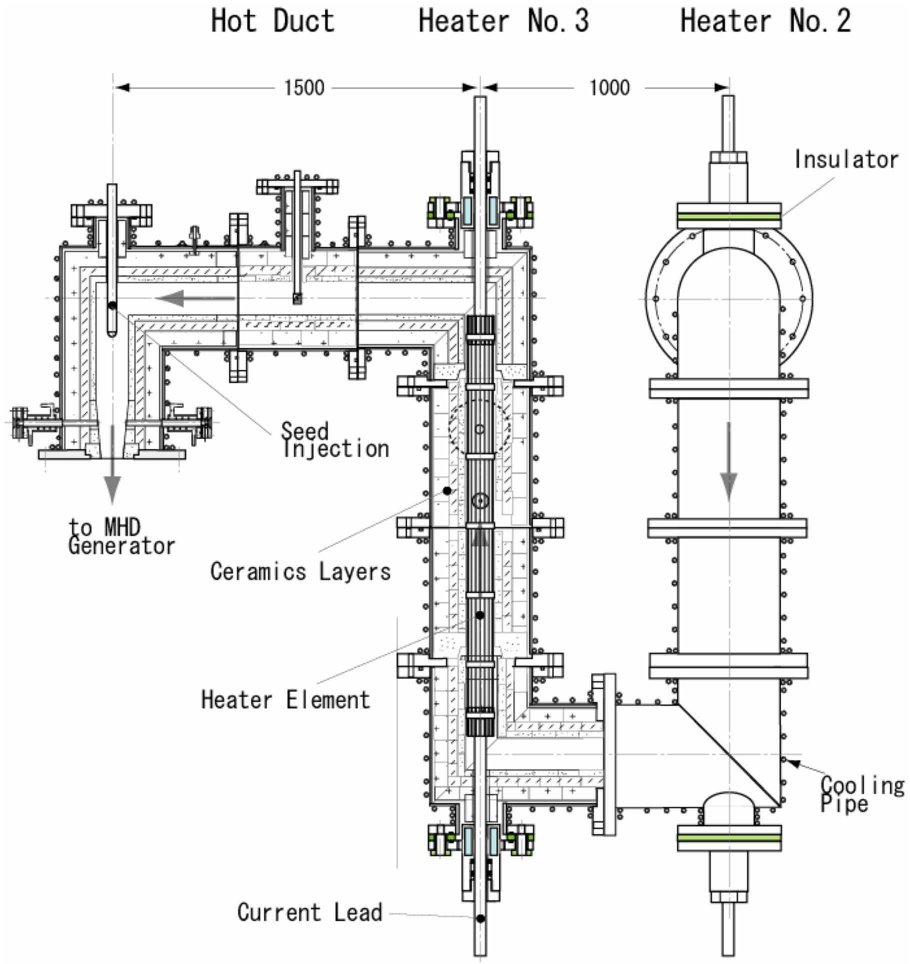
9m(W) x 4m(H)

Closed Loop for CCMHD Power Generation



9m(W) x 6m(L)

High Temperature Gas Heater



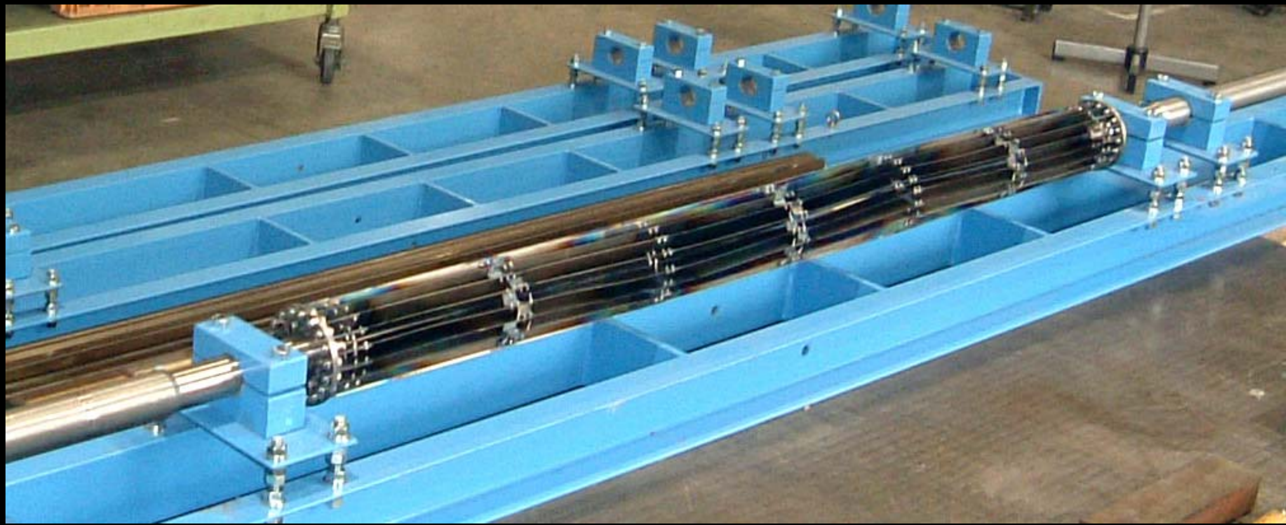
Heater No.1 (∼100kW)
890K => **1200K**

Heater No.2 (∼130kW)
1180K => **1680K**

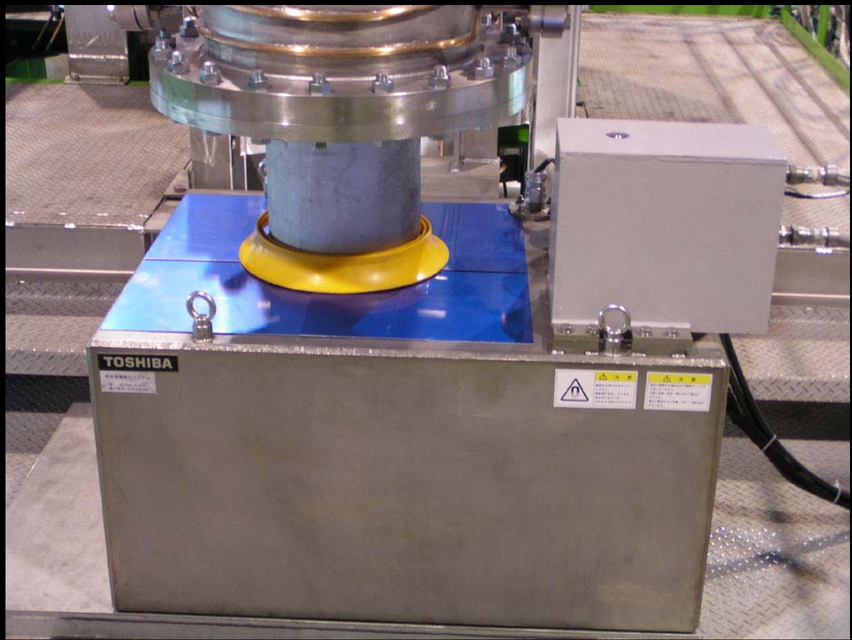
Heater No.3 (∼ 90kW)
1650K => **1900K**

=> **1850K** (exit of hot duct)

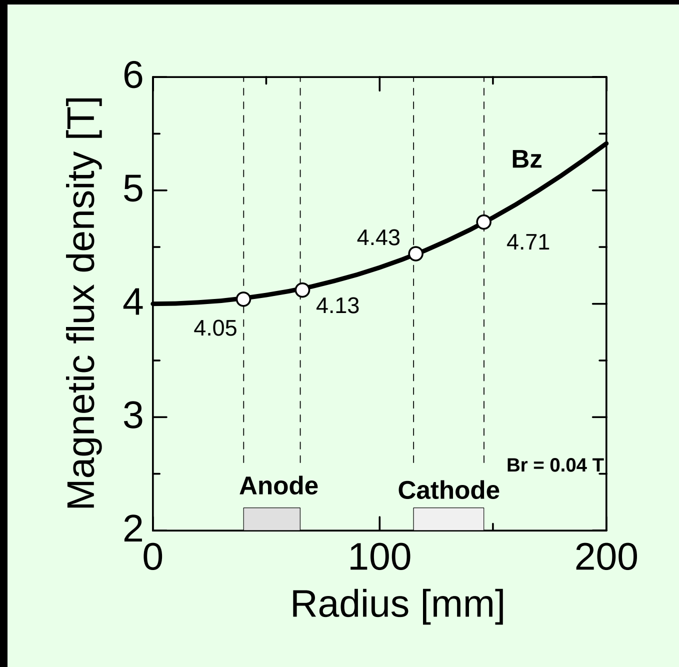
Tungsten Heater Element / Ceramic Thermal Insulator



Liquid Helium Free Superconducting Magnet



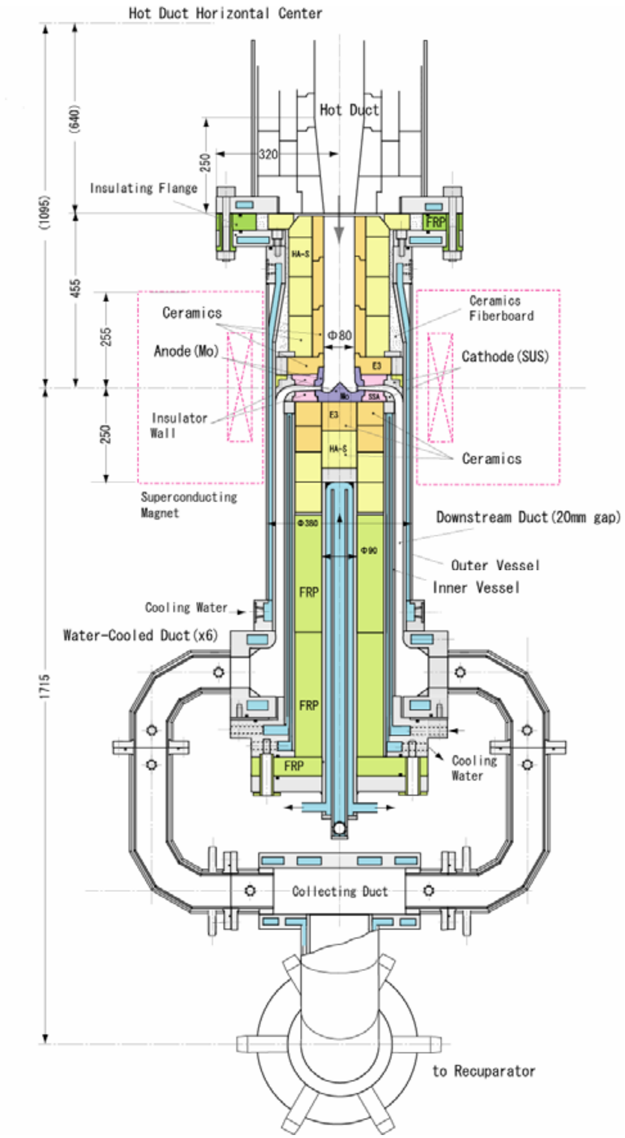
Magnetic flux density :
4.0 T (center) – 5.4 T (edge)
Bore diameter : 400 mm (vertical)

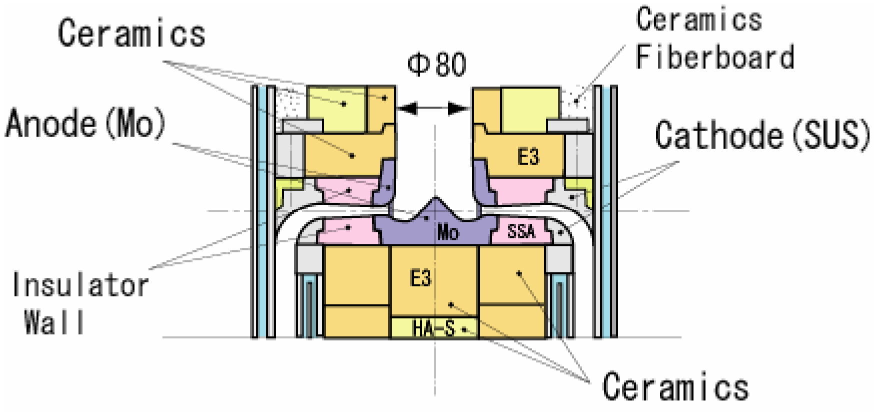


Operating temperature : 4 K
Type : 2 stage GM (Gifford-McMahon) cryocooler

Tokyo Institute of Technology
Energy Sciences

Disk MHD Generator

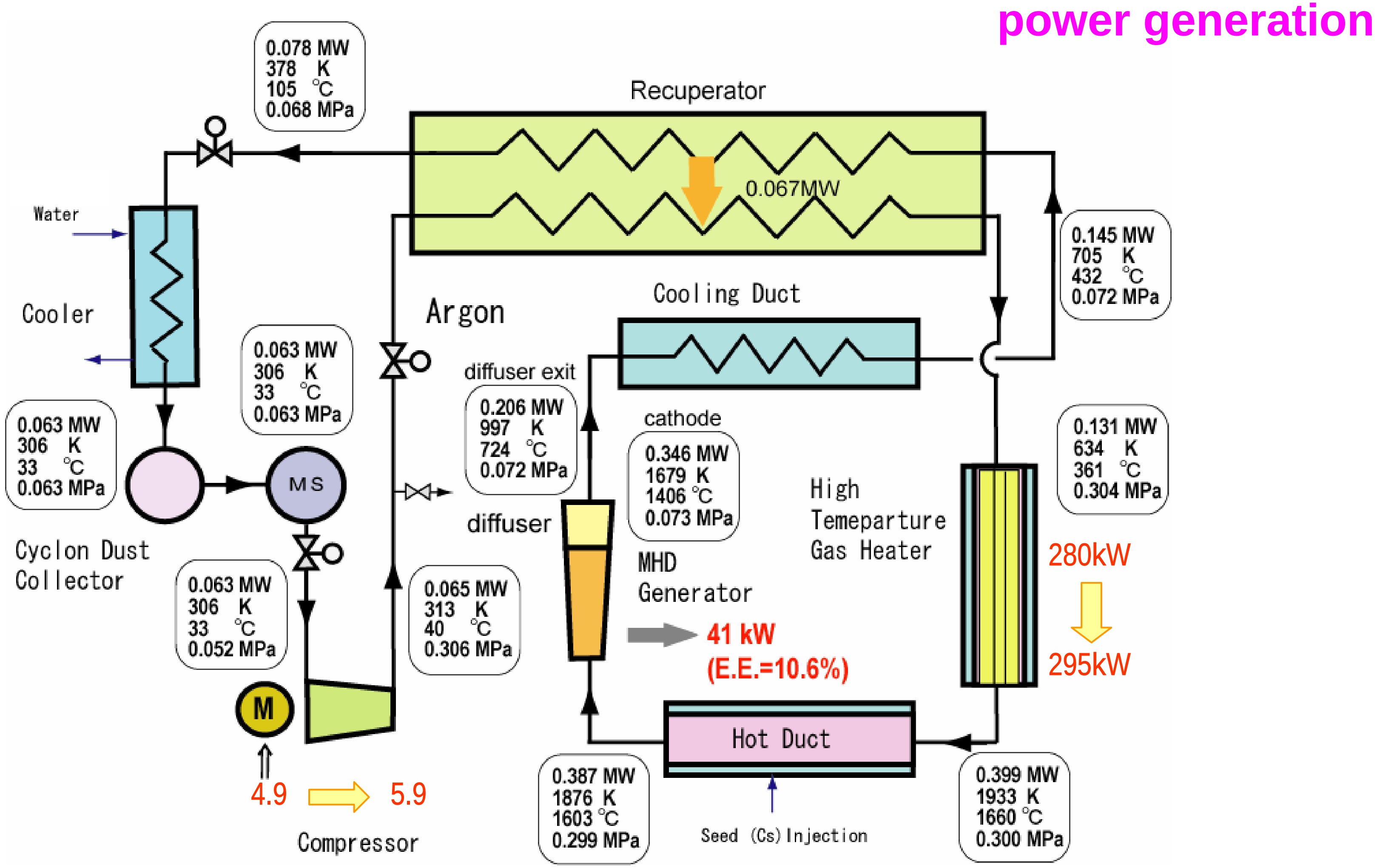




MHD Generator Channel

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

Energy and Pressure Balance (q1d - calculation)



Progress and Plan

2003 – 2004 :

Room temp. argon gas circulation test

(Compressor operation, etc.) **<= Successfully demonstrated**

2004 – 2005 :

700K, 1300K argon gas circulation test

(Heater operation, etc) **<= Successfully demonstrated**

2006 – 2007 :

1650K argon gas circulation test **<= Successfully demonstrated**

(2006/06/15-19)

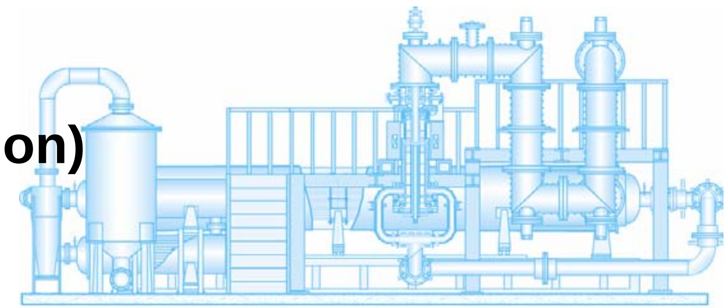
- **1850-1900K argon gas circulation test**

  (High temp. full operation)

2007 – :

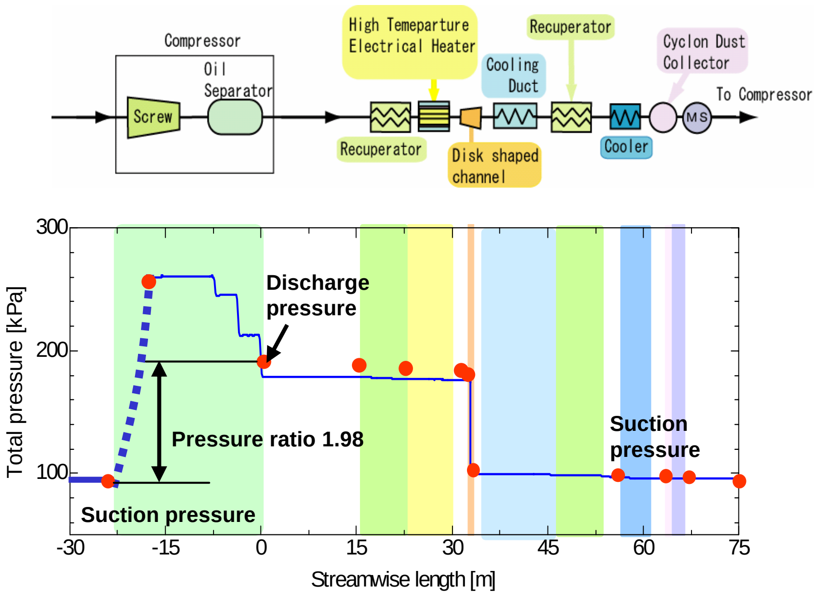
MHD power generation test

(=> Long time continuous operation)

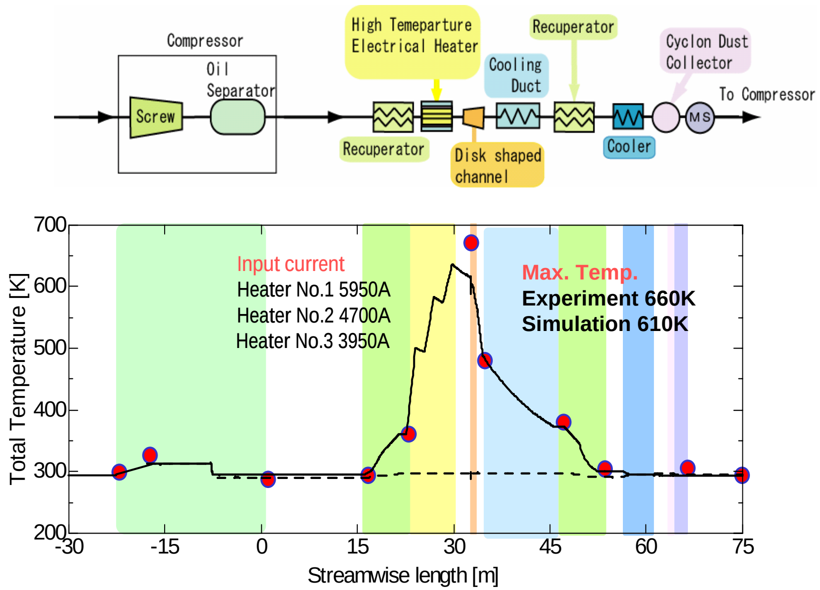


Typical distributions of gas properties along the loop

No power generation



(a) Distribution of total pressure



(b) Distribution of total temperature

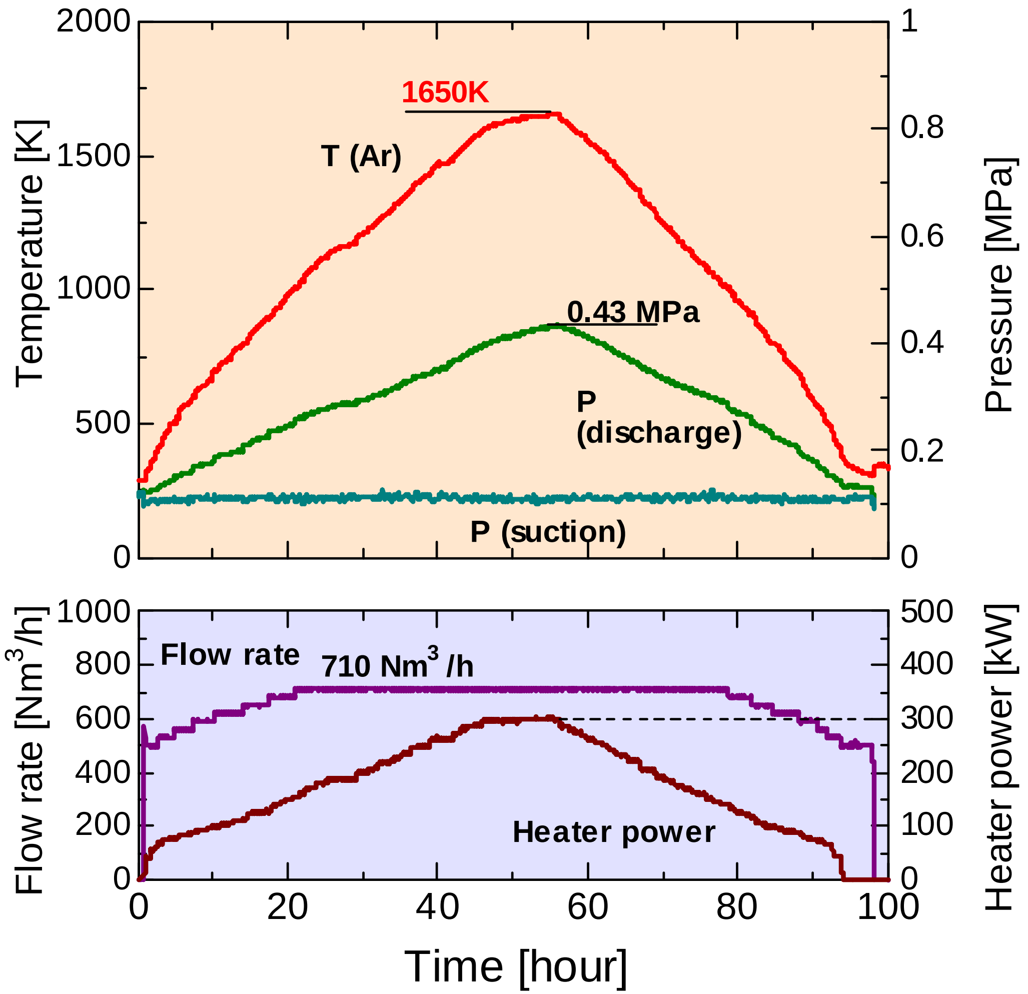
Comparison in low temperature argon gas circulation test

(● : experiment, —— : q1d - simulation)

Tokyo Institute of Technology
Energy Sciences

Ar Gas Circulation Test in CLEF (Run12)

2006/06/15-19



Closed Cycle MHD Power Generation

Highly Efficient Energy Converter to Electricity with High Temperature Gas

- **Various Energy Source Utilization （FF, GCR, STE, BE） ⇔ Open Cycle MHD**
- **Heat Cascading (GT,ST Combined) & Heat Recovery System (MHD Single)**
- **Partial Load Operation & quick Response (MHD Plasma Supersonic Flow)**

Research and Development

- **Demonstration of <u>More Highly Efficient</u> Power Generation**
- **Development of High Performance <u>Heat Exchanger</u>**
- **More Precise <u>Design and Evaluation</u> of CCMHD Power Generation System**

Research Activities at Tokyo Institute of Technology

- **Plasma Stability and Power Generation ---- Ionization Instability => Fully Ionized Seed**
- **Shock Tunnel facility --- Highest Enthalpy Extraction Ratio and Isentropic Efficiency**
- **Fuji-1 Blow down Facility --- Power Generation demonstration during 1 minute**
- **Closed Loop Experimental Facility --- Continuous Electrical Power Generation !**