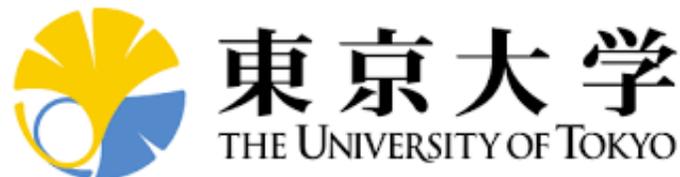


パルスレーザー駆動MHD発電に関する研究

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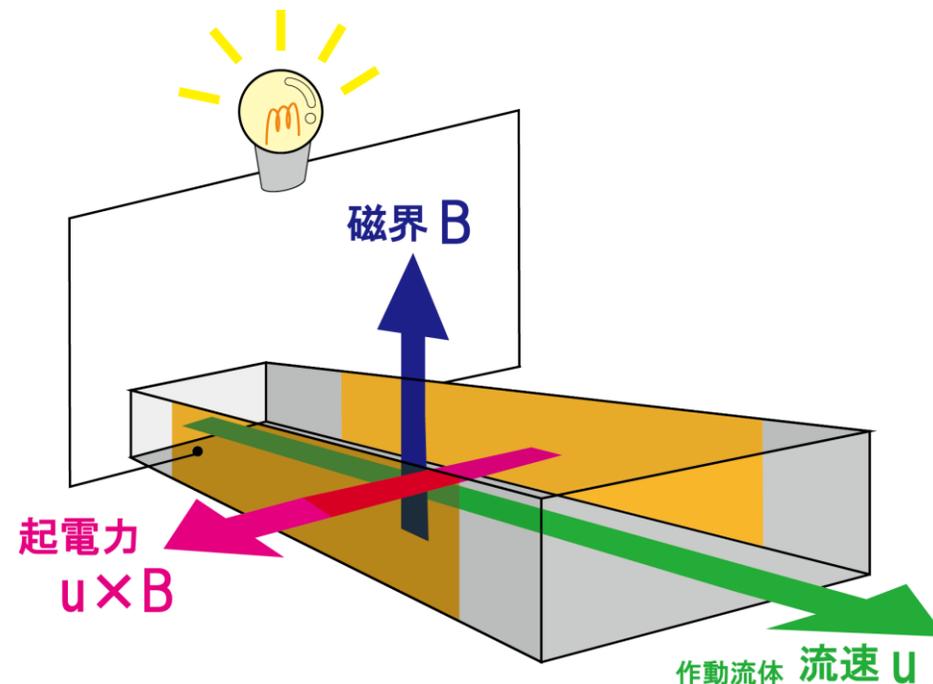
電磁流体力学(MHD)発電の原理

MagnetoHydroDynamics

Electromotive Force $\mathbf{u} \times \mathbf{B}$

Power Output $\propto \sigma |\mathbf{u}|^2 / B^2$

$\left\{ \begin{array}{l} \mathbf{B} : \text{magnetic flux density [T]} \\ \mathbf{u} : \text{velocity of fluid [m/s]} \\ \sigma : \text{electrical conductivity [S/m]} \end{array} \right.$



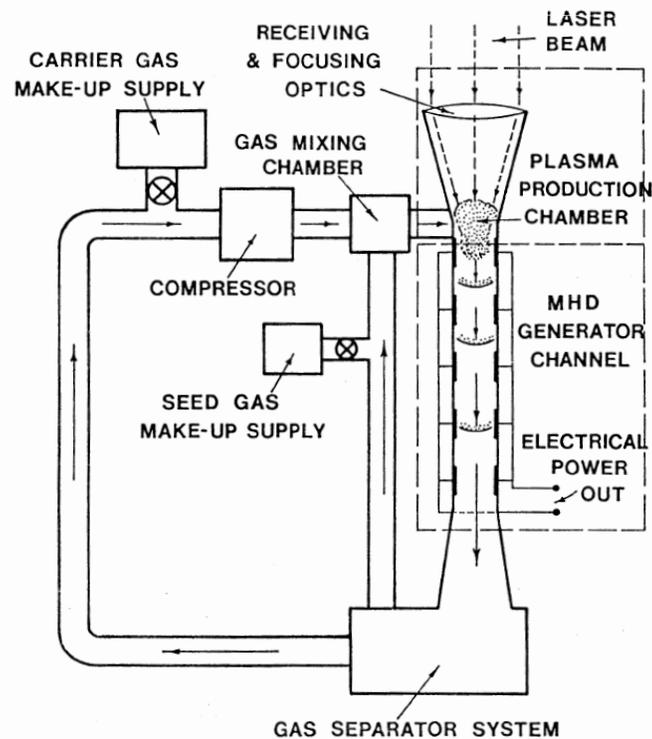
MHD発電機(発電チャネル)の概略

- 作動流体の熱エネルギーを電気エネルギーに直接変換できる。
- タービンなどの機械的稼動部が無く、高温の作動流体を利用しやすい。

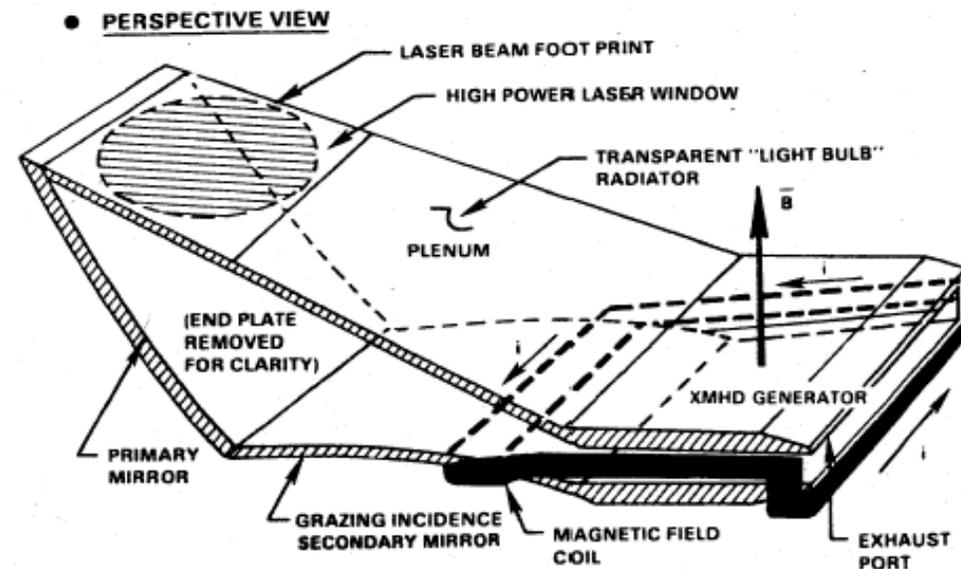
Laser-Driven MHD Power Generation Systems

As a candidate of space-based laser-to-electrical power converter

N.W.Jalufka, "Laser Production and Heating of Plasma for MHD Application" NASA TP-2798,1988
Maxwell,C.D. and Myrabo,L.N." Feasibility of Laser-Driven Repetitive-Pulsed MHD Generation", AIAA-83-1442



CW-laser-driven
(Jalufka, 1988)



Pulsed-laser-driven
(Maxwell and Myrabo, 1983)

Hypersonic MHD Propulsion System Integration for the Mercury Lightcraft

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 † Department of Mechanical Engineering, Montana State University, Bozeman, MT.

Abstract. Introduced herein are the design, systems integration, and performance analysis of an exotic magnetohydrodynamic (MHD) slipstream accelerator engine for a single-occupant "Mercury" lightcraft. This ultra-energetic, laser-boosted vehicle is designed to ride a 'tractor beam' into space, transmitted from a future orbital network of satellite solar power stations. The lightcraft's airbreathing combined-cycle engine employs a rotary pulsed detonation thruster mode for lift-off & landing, and an MHD slipstream accelerator mode at hypersonic speeds. The latter engine transforms the transatmospheric acceleration path into a virtual electromagnetic 'mass-driver' channel; the hypersonic momentum exchange process (with the atmosphere) enables engine specific impulses in the range of 6000 to 16,000 seconds, and propellant mass fractions as low as 10%. The single-stage-to-orbit, highly reusable lightcraft can accelerate at 3 Gs into low Earth orbit with its throttle just barely beyond 'idle' power, or virtually 'disappear' at 30 G's and beyond. The objective of this advanced lightcraft design is to lay the technological foundations for a safe, very low cost (e.g., 1000X below chemical rockets) air and space transportation for human life in the mid-21st Century - a system that will be completely 'green' and independent of Earth's limited fossil fuel reserves.

INTRODUCTION

The objective of the present effort is to lay down the technological foundations for advanced air and space transportation, using 'Highways of Light' - for which the principal infrastructure is a grid of remote energy-beaming power plants located either in space or on the ground. In the mid-21st Century, extremely energetic laser-propelled 'lightcraft' will ride these virtual energy 'highways' - no longer burdened with massive on-board fuel loads. The present paper investigates a representative engine/optics/airframe design for an advanced laser-electric type of airbreathing propulsion for a minimum-volume, single occupant space capsule.

The conceptual design for a one-place, laser-boosted Mercury lightcraft was recently reviewed in [1], covering the engine/optics/airframe integration process and geometry for the 'lift-off' propulsion mode - a rotary pulsed detonation thruster [2]. The present paper focuses on the hypersonic propulsion mode - which is based on a magnetohydrodynamic (MHD) slipstream accelerator (Fig. 1). In essence, this engine momentarily transforms the transatmospheric acceleration path into an extremely long electromagnetic 'mass-driver.' The hypersonic engine relies on action-at-a-distance forces to electromagnetically scavenge reaction mass from the atmosphere - for efficient momentum exchange. The MHD engine is derived from an earlier Rosa



Lightcraft being propelled by laser

<https://en.wikipedia.org/wiki/Lightcraft>

concept [3-5] for an electric airturborocket cycle called the 'MHD fanjet,' designed for single-stage-to-orbit flights with an on-board nuclear electric powerplant.

Figure 1 gives a side view of the Mercury lightcraft with its shroud retracted for MHD operation. The principal components of the MHD engine are the: a) laser-induced "airspike" [6] to externally pre-compress the inlet air while simultaneously reducing forebody drag and heat transfer; b) annular MHD air accelerator, inclusive of 24 strut-type electrode-pairs, and 2-Tesla (Helmholtz-type) superconducting magnet [7-8]; c) four laser-heated, hydrogen-fueled MHD generators (also with superconducting magnets) that are rocket-driven and open-cycle [9-10]; and, d) solid state, power-electronics system to connect (i.e., for switching, load management, etc.) the four MHD generators to the annular MHD air accelerator. The following sections discuss the conceptual design, physics, and performance estimates for these ultra-energetic, hypersonic engine components.

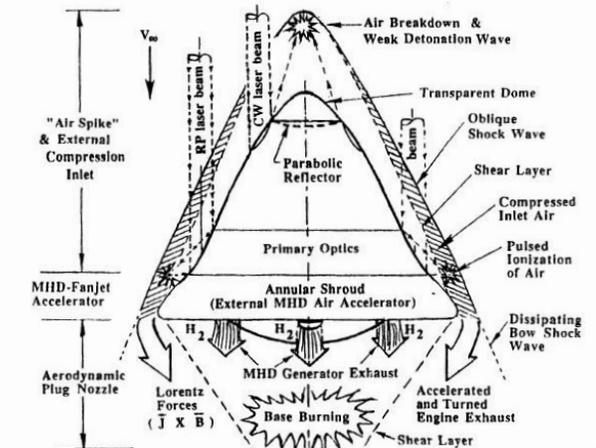


FIGURE 1. Hypersonic MHD Slipstream Accelerator Mode for the Mercury Lightcraft.

MHD SLIPSTREAM ACCELERATOR CONCEPT

The heart of the MHD slipstream accelerator is a pair of simple superconducting magnetic field coils, arranged in a Helmholtz configuration to produce an azimuthal magnetic field - directed radially outward through the annular shroud (Fig. 2). Once energized prior to lift-off, these well-insulated superconducting magnets will need no additional power in flight. Note in Figs. 1 & 2 that the external MHD accelerator 'duct' is formed by the annular stream-tube of inlet air that is trapped between the bow shock wave and the external shroud surface.

The applied 2-Tesla magnetic field cuts at right angles to the slipstream air in this annular MHD channel which is divided into 24 sections, each about 28-cm wide. The

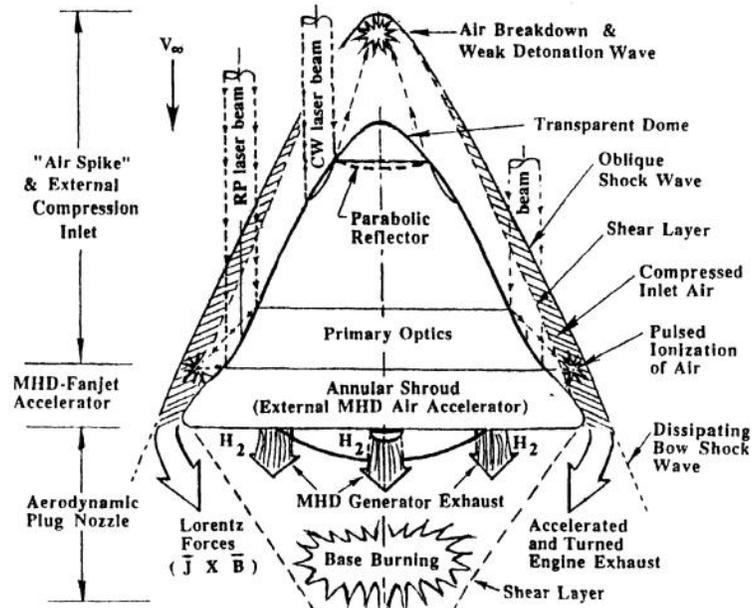


FIGURE 1. Hypersonic MHD Slipstream Accelerator Mode for the Mercury Lightcraft.

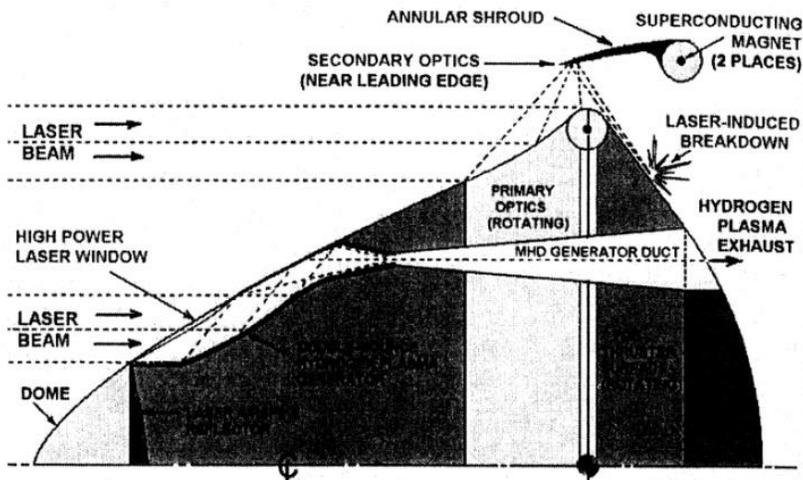


FIGURE 4. Refined optical trains for hydrogen plasma generators and PDE thruster mode.

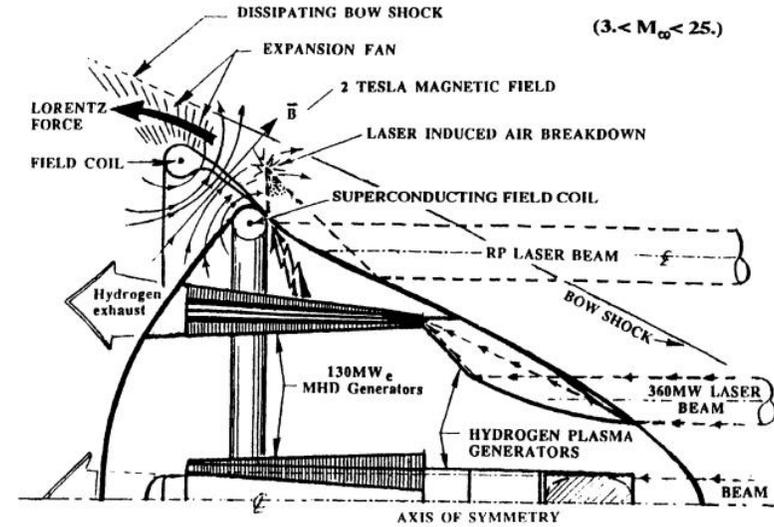


FIGURE 2. Cutaway view showing principal MHD engine components.

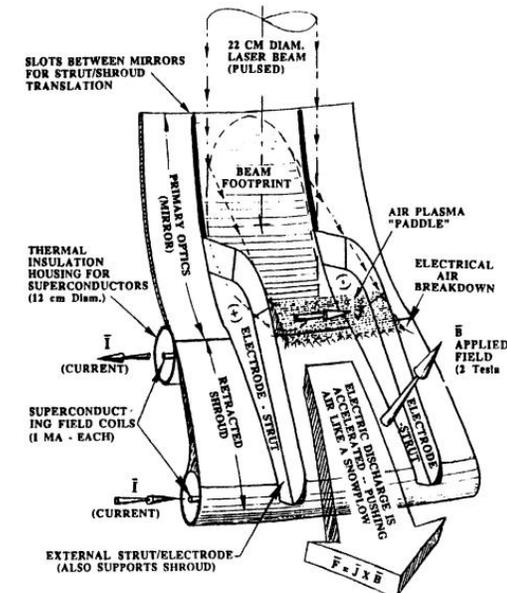


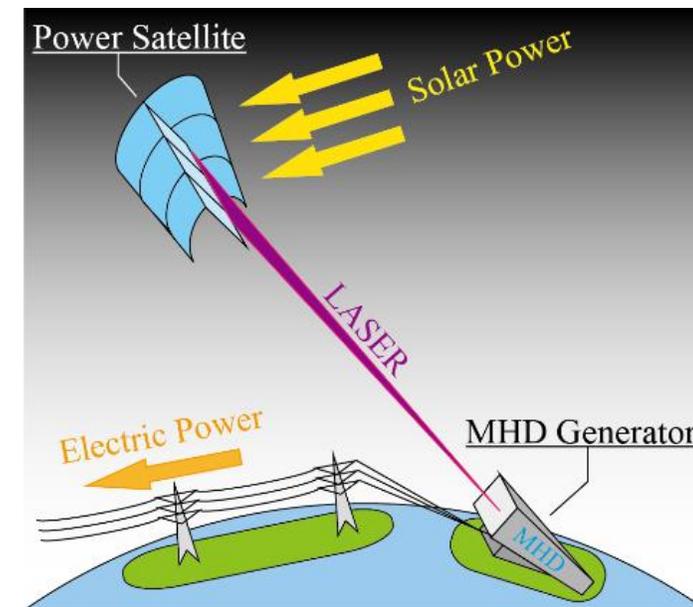
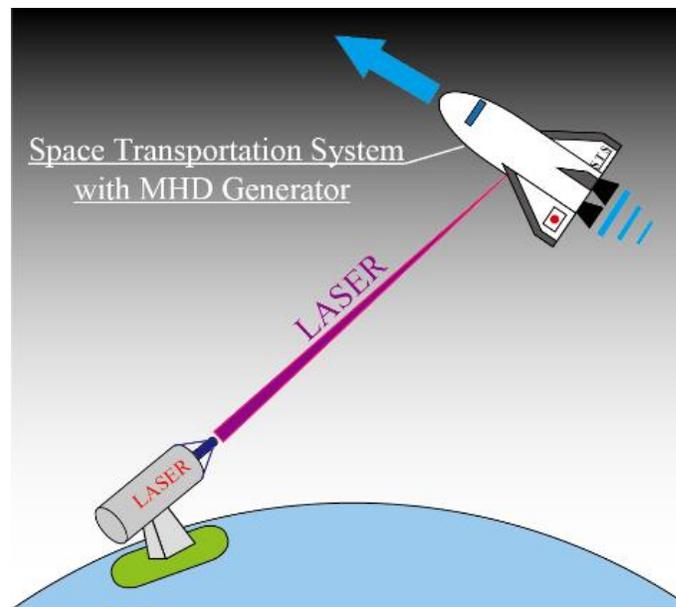
FIGURE 3. Close-up view of MHD slipstream accelerator, showing electrode/struts, superconducting magnets, primary optics, and retracted shroud. (Section shown is 1/12th of the annular shroud.)

レーザー + MHD発電の可能性

- (我々が知る限り)1980年代に多くの提案がなされているが、いずれも単なる提案や簡単な解析的な見通しに終わっている。
- そのほとんどが宇宙におけるレーザーから電気へのエネルギー(パワー)変換装置としての利用が念頭におかれている。

応用例

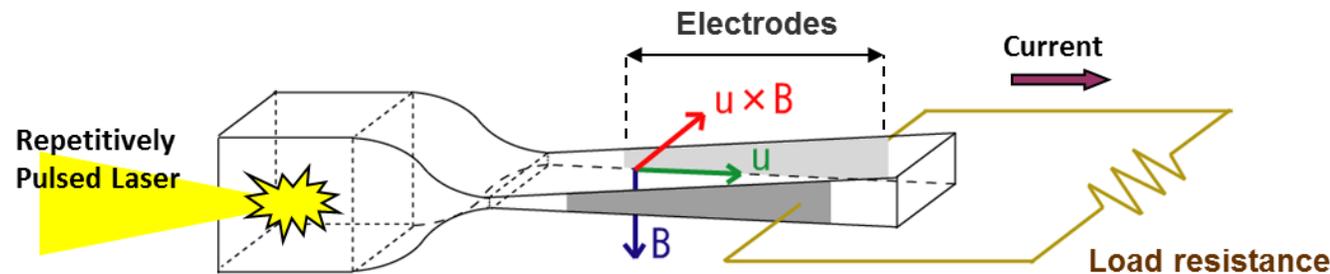
- ✓ レーザー推進機における電源
- ✓ 深宇宙における超長距離電力送電装置
- ✓ 宇宙太陽光発電システム(SSPS)における地上側電力変換装置



⇒ 航空宇宙分野においては魅力的な発電システムとなりえる

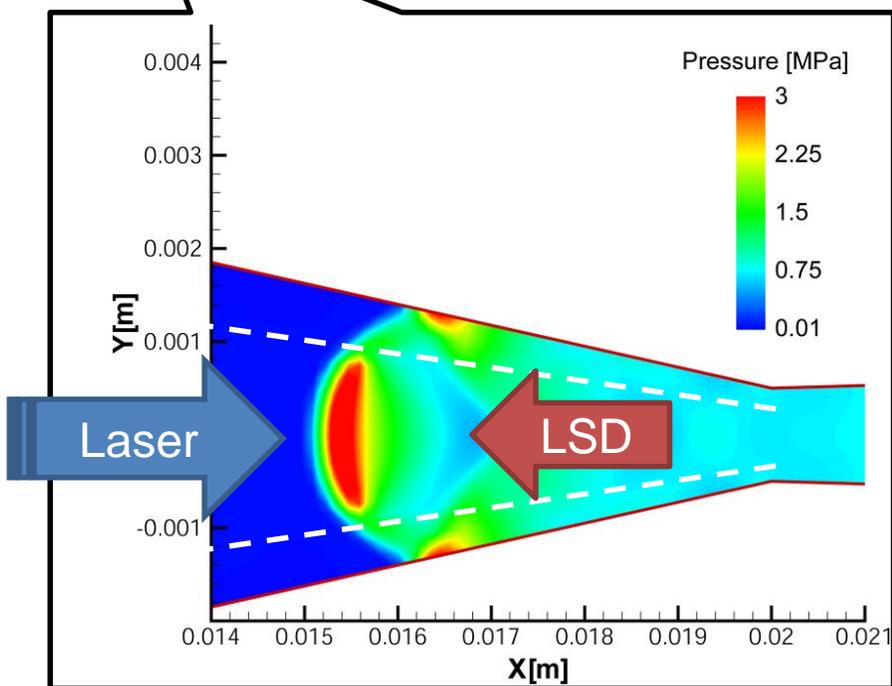
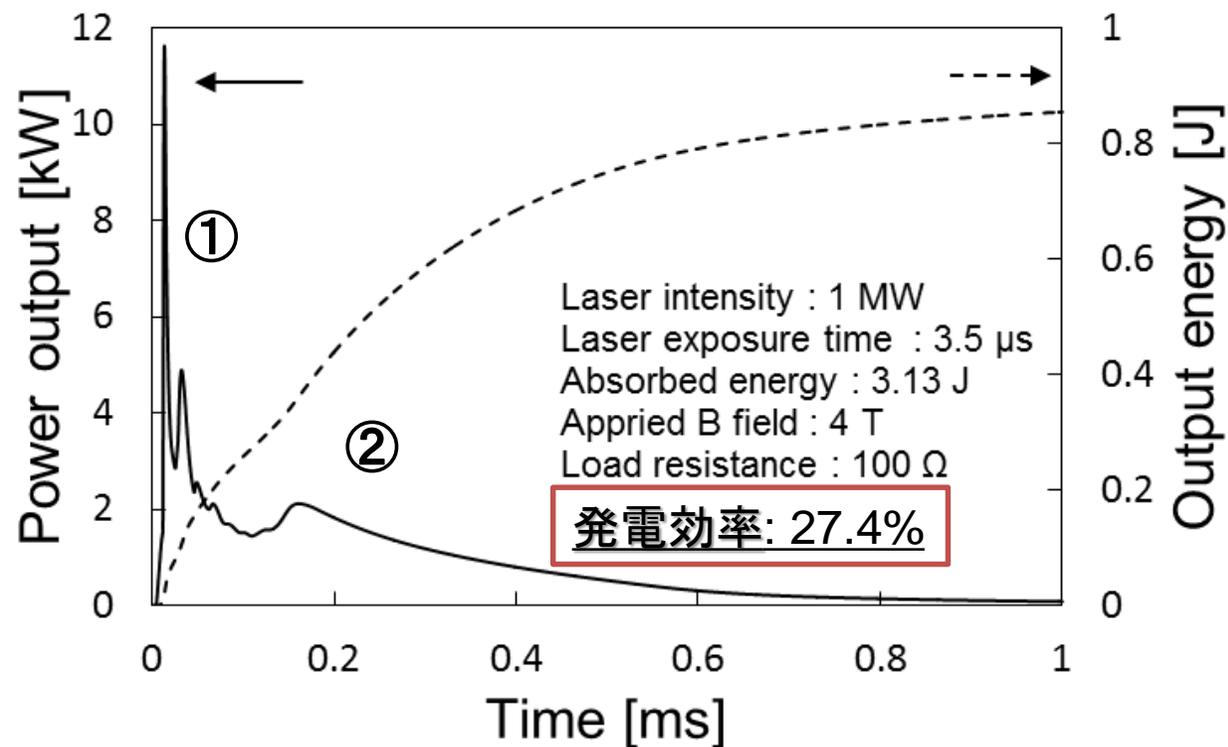
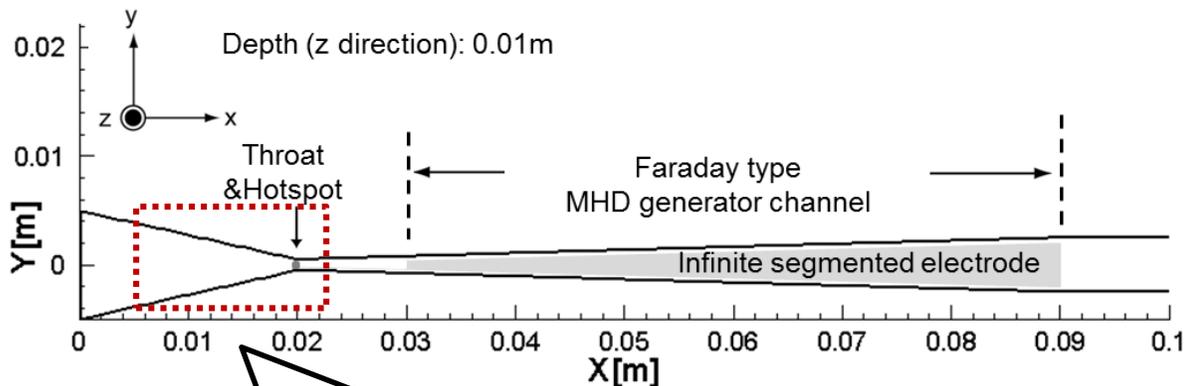
東工大奥野研グループにおけるレーザーMHD研究の推移

- 2007年頃より, 数値シミュレーションによる研究から開始
 - ✓ レーザーと作動気体の相互作用として逆制動放射過程を考慮
 - ✓ 準1次元 or 2次元計算によるレーザー支持デトネーションの挙動と発電性能
- 2010年頃より, パルスレーザー加熱を模擬したパルス放電加熱による発電実験を開始
- 2014年に, CO₂パルスレーザーにより駆動されるMHD発電の原理実証実験。原始的ながら世界初の試み。



パルスレーザーを熱源として利用するMHD発電のイメージ

数値シミュレーションによる発電性能評価の例



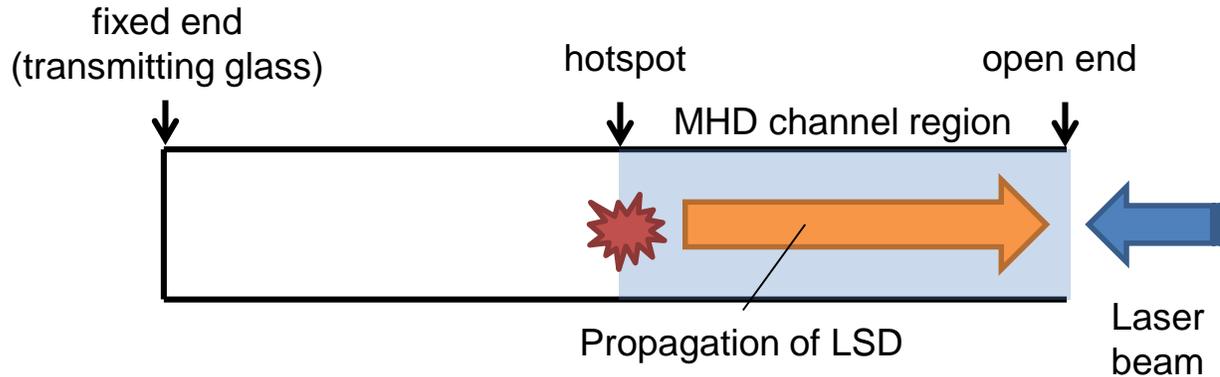
レーザー入射中の圧力分布

- ① 上流へ伝播したLSD波が上流端に到達した後、反射して下流部へ流れ、発電領域へ入ることにより発生する出力
- ② 発電機内部に残留している高温・高圧の作動流体が膨張波とともに外部へ流出する際に発生する出力

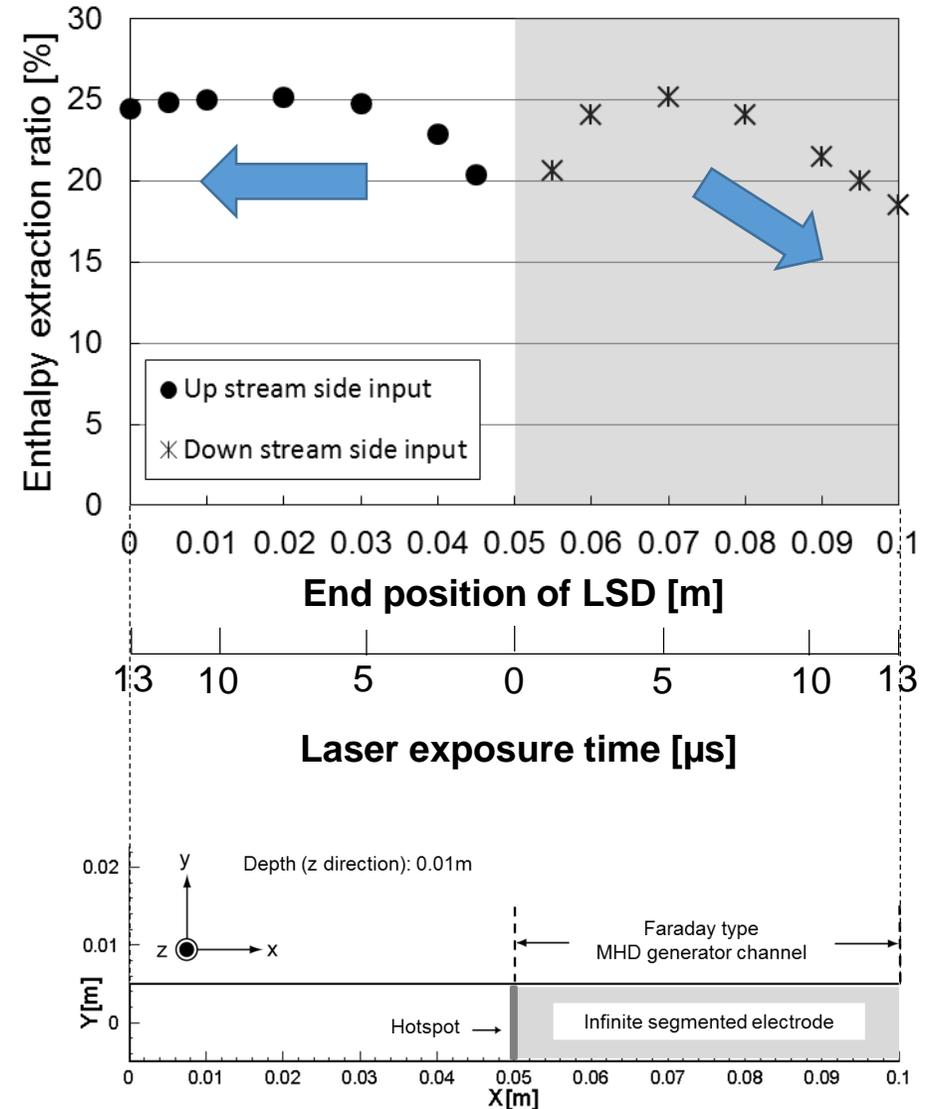
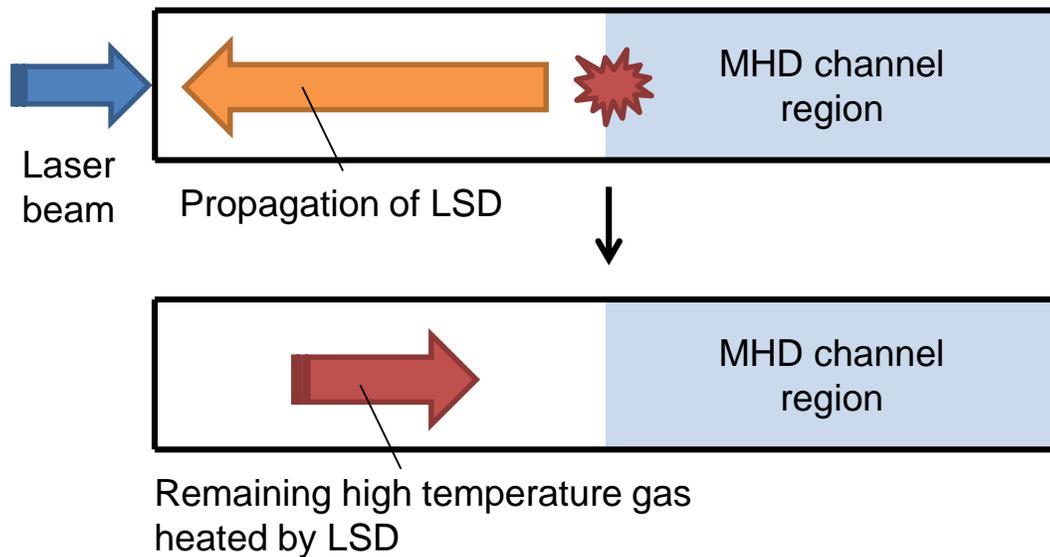
M. Matsumoto, T. Murakami and Y. Okuno: *Trans. JSASS*, **51**, 164-169, 2008
 松本正晴, 高木成郎, 奥野喜裕: *電気学会論文誌A*, **135**, 379-384, 2015
 松本正晴, 高木成郎, 奥野喜裕: *日本航空宇宙学会論文集*, **62**, 170-176, 2014
 M. Matsumoto, S. Takagi and Y. Okuno: *Proc. of AJCPP* (Mar 2014, Jeju, Korea)

レーザーの入射方向依存性(下流入射か？上流入射か？)

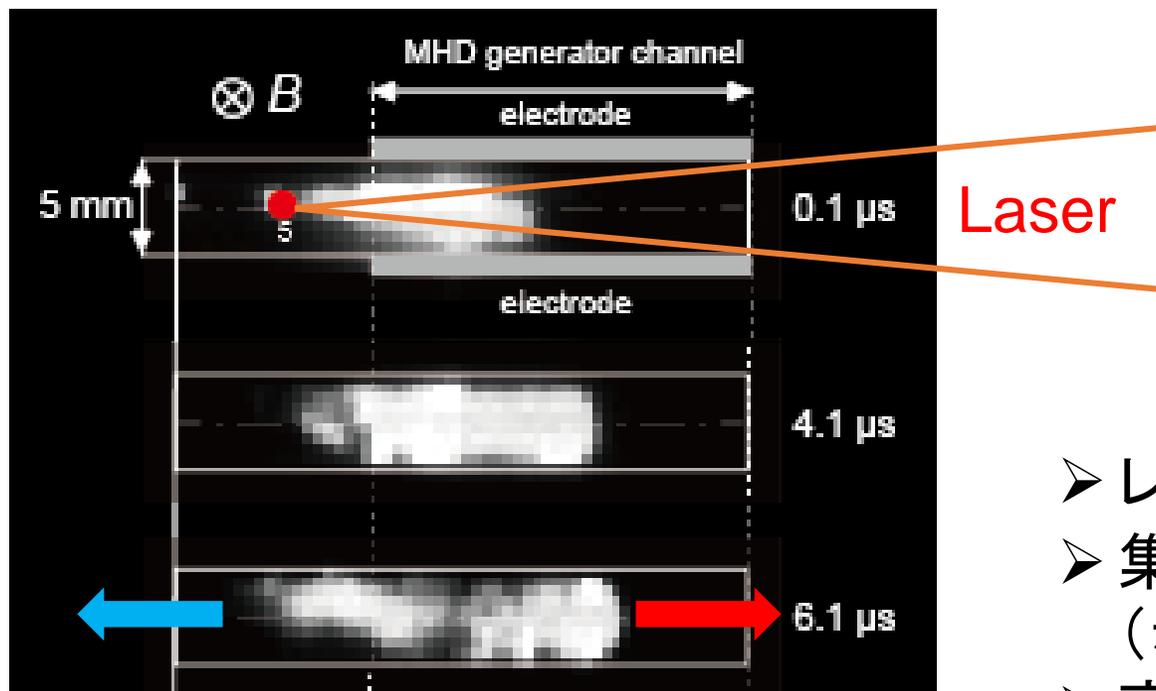
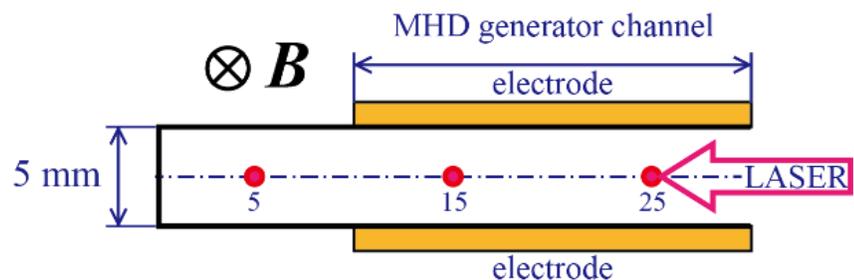
“downstream input”



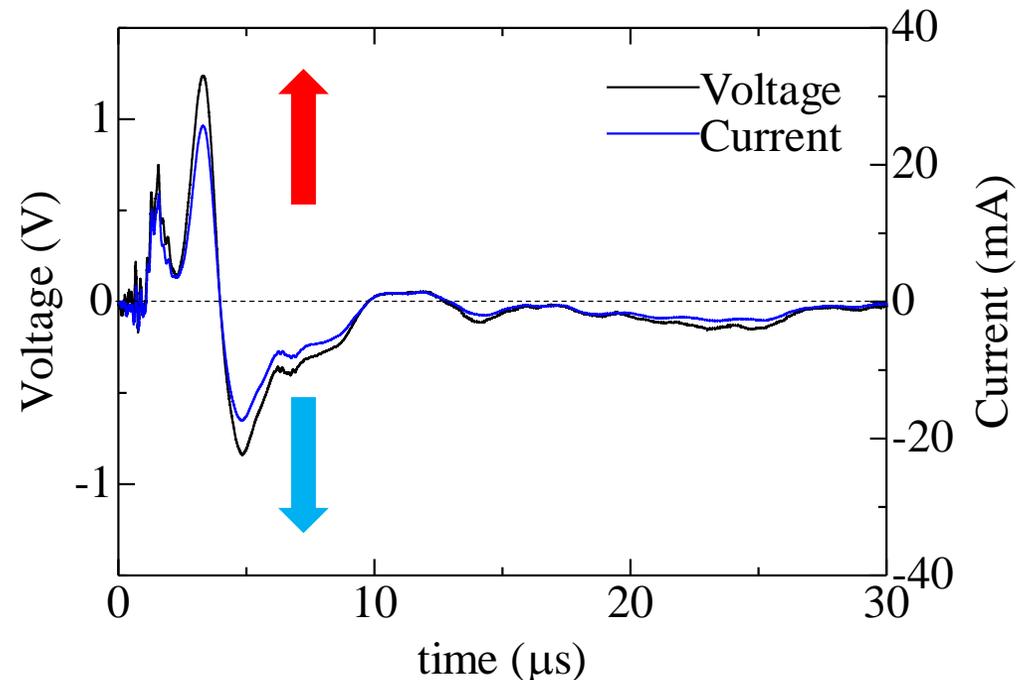
“upstream input”



パルスレーザー駆動MHD発電実験(～2015年度)

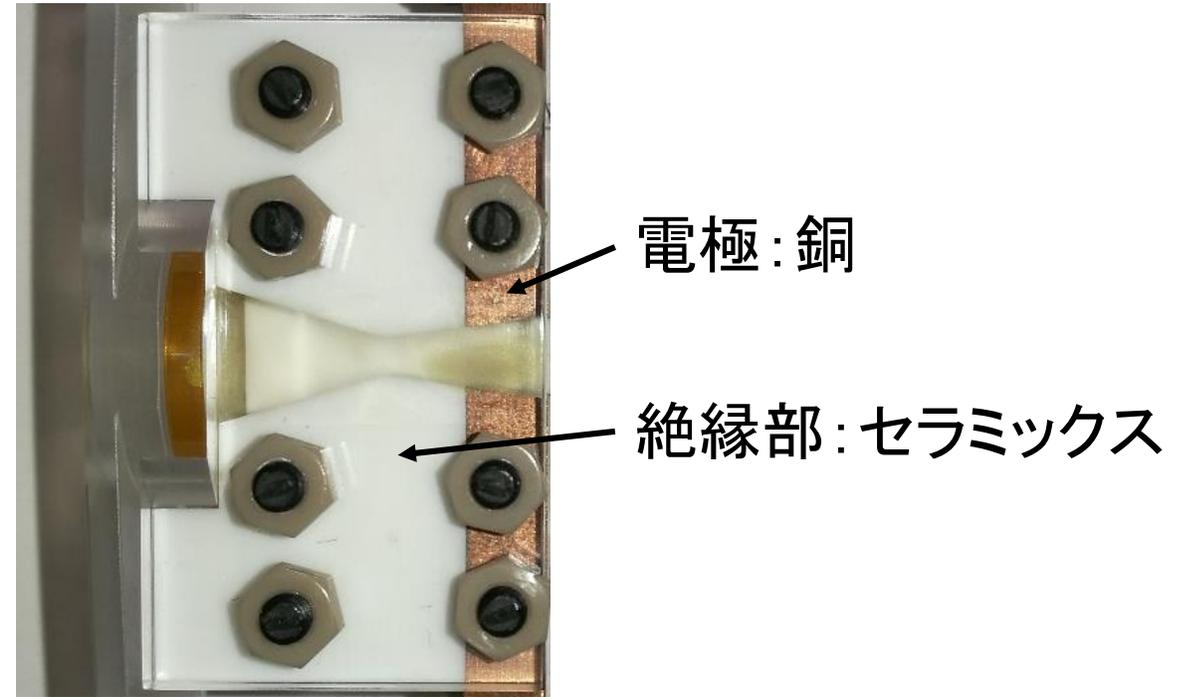
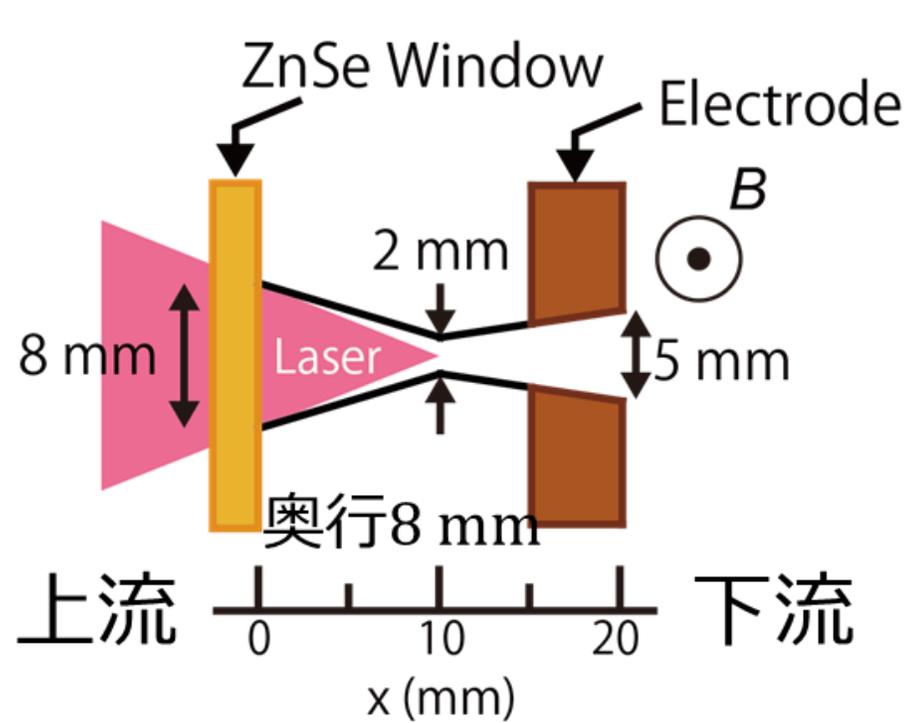


実験時の発電機内の写真



- レーザーのみを熱源とする発電が実証
- 集光位置によっては、流れが左右に分かれて(赤と青)電極間に流れる電流を打ち消しあう
- 高性能化が課題

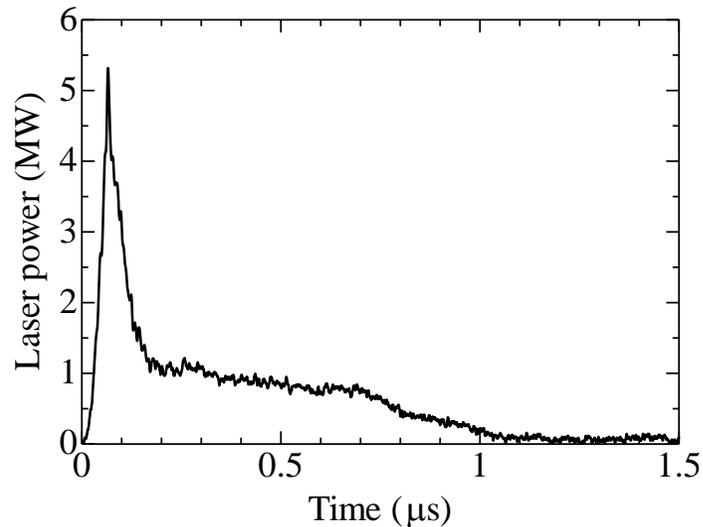
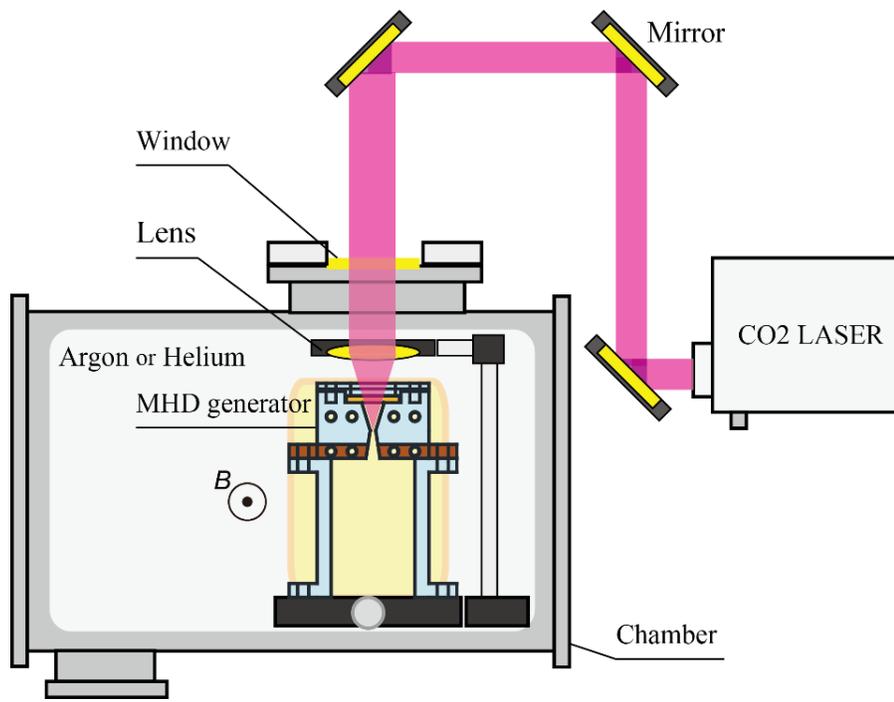
ノズル付き形状発電機(2016年度～)



- レーザーはZnSeレンズを通り, 発電機上流側から入射し, ノズル部に集光される
- 等高さ発電機と比較して, ノズル設置に伴う1) 下流への一方向流による負の電流電圧(逆流)の抑制と, 2) 流速増加による発電出力の向上, が狙い

実験装置および実験条件

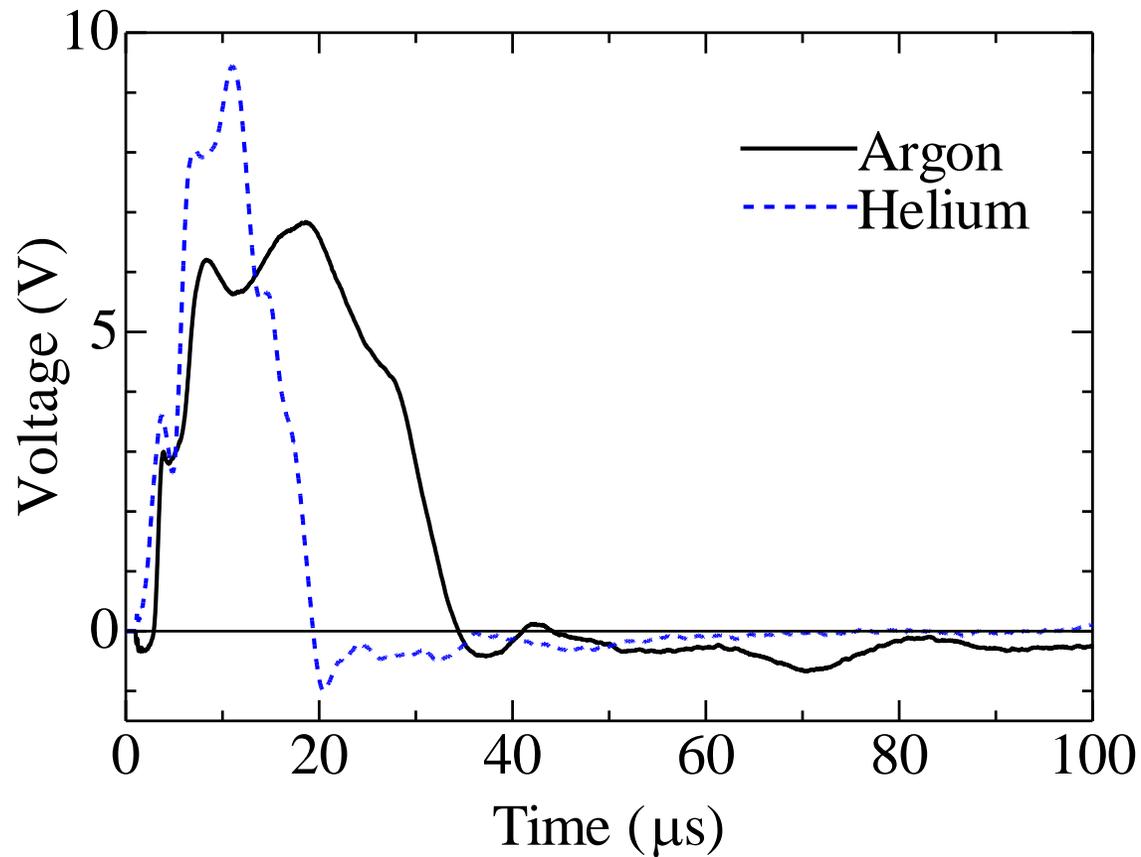
チャンバー内には予め作動気体を充填しておき，発電機も永久磁石とともに設置しておく。



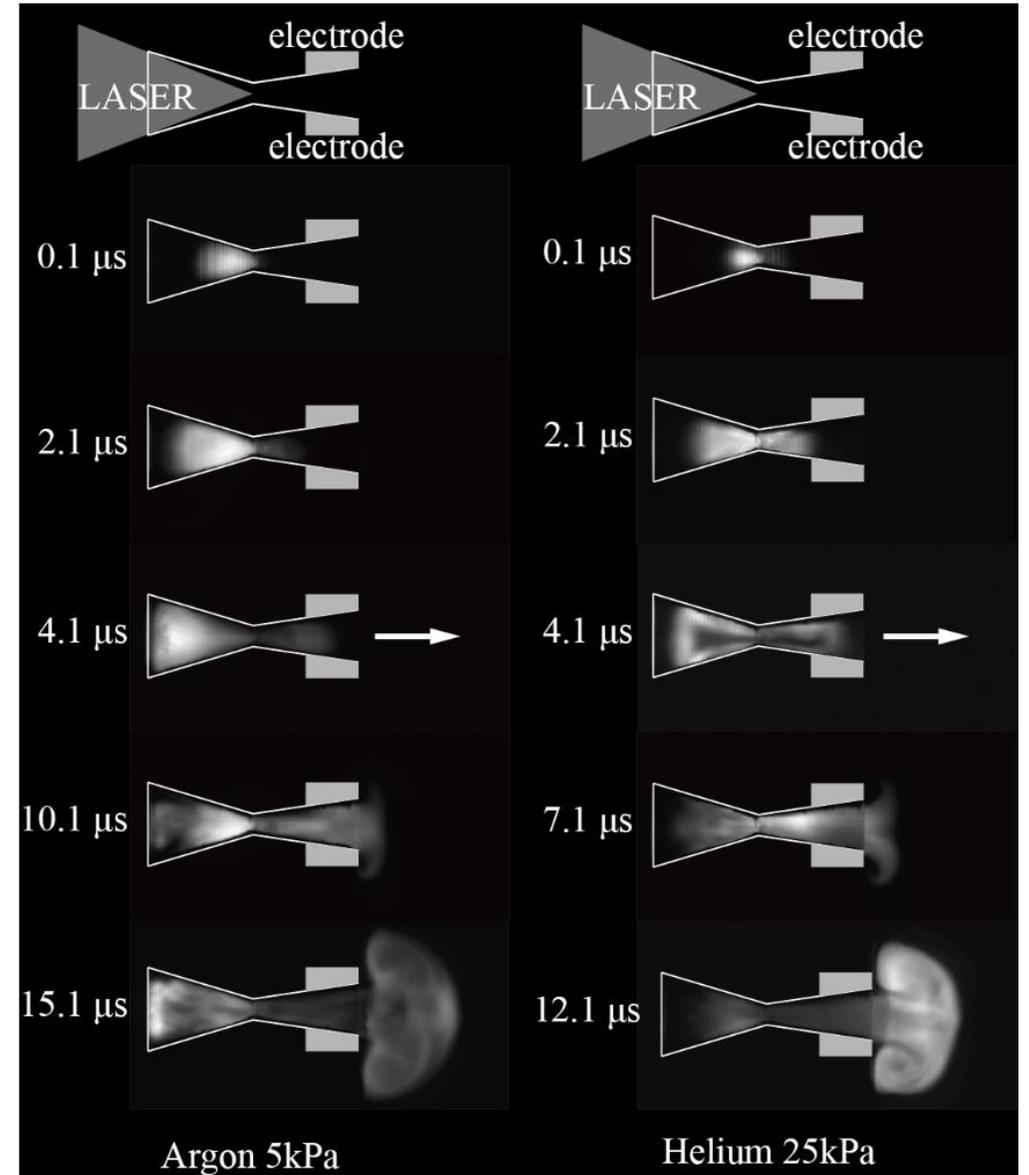
レーザーパワーの時間変化

Working Gas	Argon, Helium
Pressure	5 kPa~100 kPa
Load Resistance	Open, 1 Ω ~1 k Ω
Magnetic Flux Density	0.68 T
Laser Energy	~1 J
Pulse Width	~1 μs
Focal Length of the ZnSe Lens (Spot Diameter)	38.1 mm (~0.02 mm)

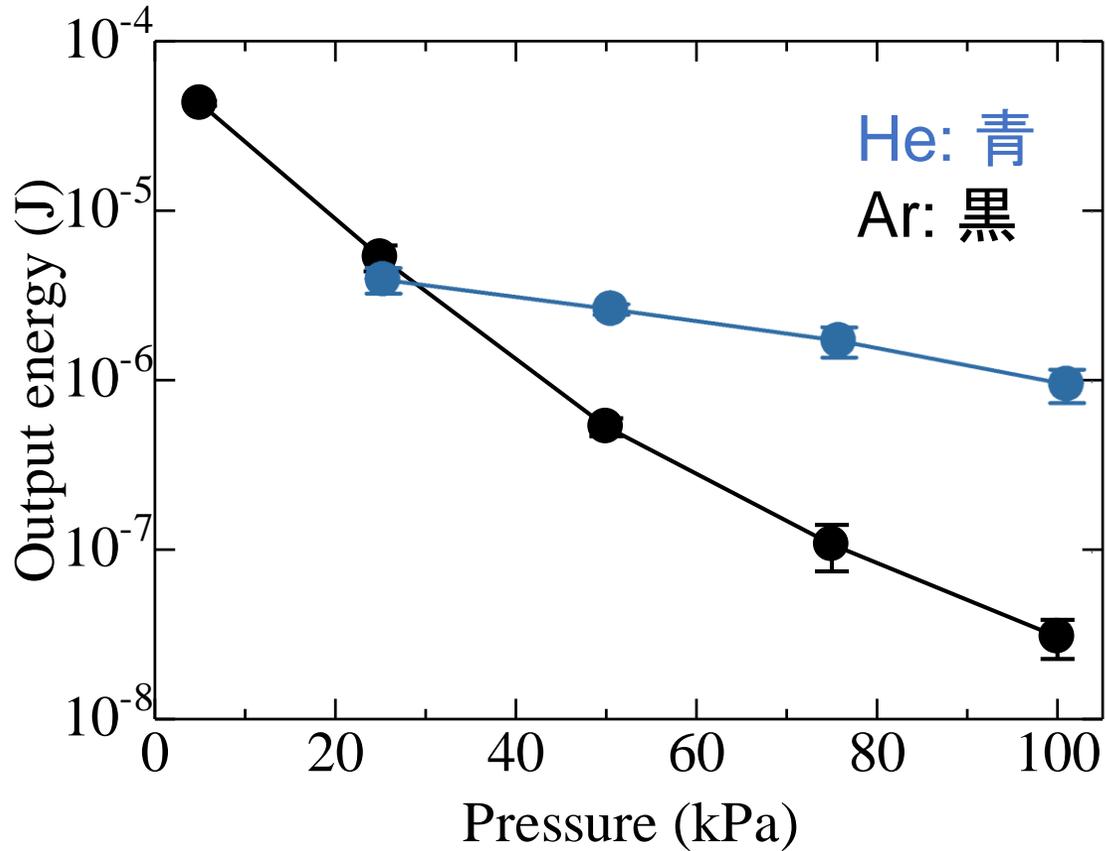
開放電圧, ならびにプラズマ挙動



発電機下流方向への一方向流により発生した正の開放電圧が発生した後、わずかに負の開放電圧が発生。



レーザー入射1回当たりの出力エネルギーの初期圧力依存性

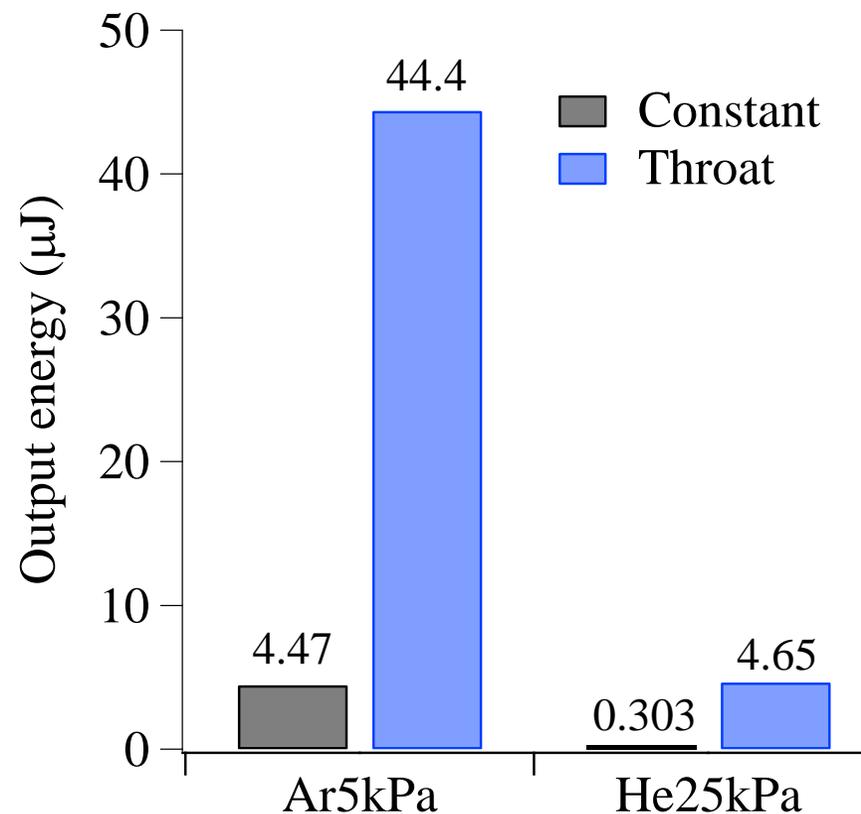
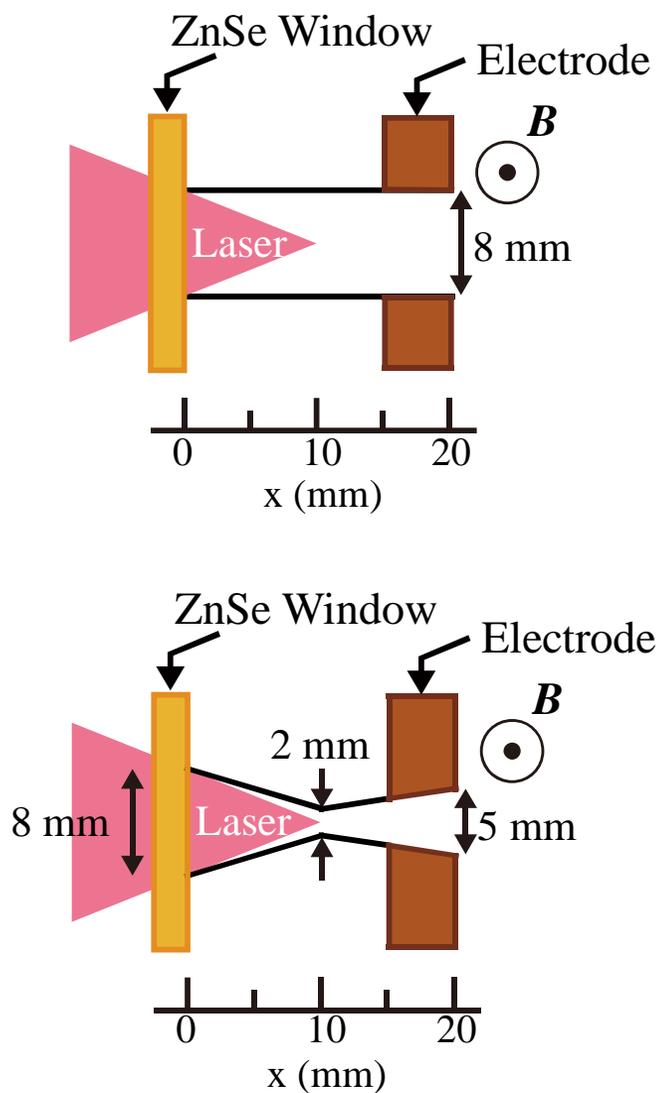


➤ Arの場合、初期圧力の低下に伴い、出力エネルギーは増加し、最大で $44.4 \mu\text{J}$ (5 kPa) が得られた。

➤ Heの場合、出力エネルギーの初期圧力依存性はArと比較して弱く、最大で $4.65 \mu\text{J}$ (25 kPa) が得られた。

Arは初期圧力が低いほど、レーザー入射による温度(電気伝導度)上昇が顕著になる一方、HeではArほどの温度の初期圧力依存性が見られないことが理由。

等高さ発電機との比較



ノズルを設置した効果により流速が増加した結果、出力エネルギーの増加が見られた。

まとめと今後の課題

パルスレーザー駆動MHD発電に関する研究のこれまでの経緯と、最近の実験結果について述べた。

➤ 更なる高磁束密度印加 (0.68 T ⇒ 4 T)

MHD発電の発電出力は磁束密度の2乗に比例することから、高い磁束密度を印加することで出力の向上が期待できる。

➤ 作動気体としてXeを利用

Arより電離ポテンシャルが低い気体であるXeを作動気体とすることで、出力の向上が期待できる。

➤ 高強度レーザーの利用

発電機サイズはレーザー強度に依存しており、現状ではミニチュアサイズの発電機しか利用できないことから、高強度のレーザーが望まれる。