National University Corporation Shizuoka University

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Laser sustained plasma using argon, xenon, krypton, hydrogen and methane for onboard laser-based thruster

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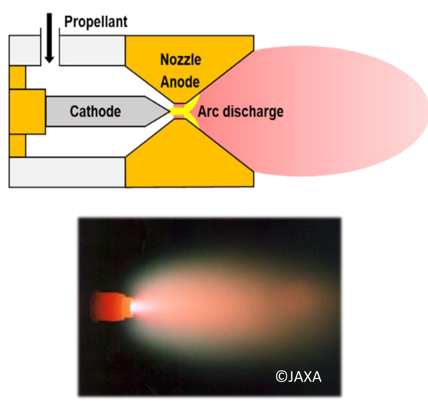
Background

Arcjet

Merit
- ✓ Highest thrust density in EP
- ✓ Simple structure and low cost

Problems
- ✓ Low I_{sp} : 600s (N_2H_4)-1000s (H_2)
- ✓ Short life time ~**1000 h**

Cathode erosion



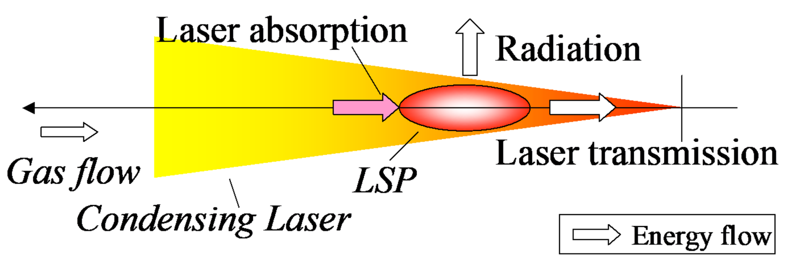
Structure of arcjet and photo

Then, currently, arcjets including elecrtro-thermal thruster has been replaced by other electric propulsion.

Laser Sustained Plasma

Advantages of LSP
- ✓No electrode erosion ⇒ operation time is limited by laser
- ✓Higher temperature (LSP : 10,000 K) than arc discharge (7500 K)

⇒ Higher I_{sp} $I_{sp} \propto \sqrt{T}$



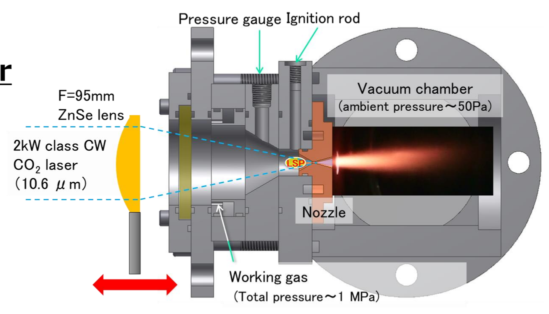
Conceptual figure of laser sustained plasma

Estimation of LSP thruster performance

Application of wind tunnel to thruster

In our previous study, laser driven plasma wind tunnel was developed to simulate high speed atomic oxygen flow in LEO.

Assuming the operation gas is H_2 instead of O_2, thrust performance is estimated.



Laser driven plasma wind tunnel (Matsui, M., AIAA J, 52, 2014, 1806)

I_{sp} : LSP > Arcjet
η_t : LSP < Arcjet (But comparable to water cooling arcjet)

Life time: LSP >> Arcjet

Estimated thrust performance

	LSP(O_2)	LSP(H_2)	*Arcjet(H_2)
Isp	375 s	1400 s	1000 s
Thrust efficiency	22% (Water cooling)	-	45% (radiation cooling)

*Riehle M., AIAA 95-2507

Selection of laser source

CO_2 laser
- ✓ Low energy efficiency
- ✓ Large and heavy
- ✓ Maintenance

...Not suitable for LSP thruster

Laser diode (LD)
- ✓ High energy efficiency
- ✓ Compact and light
- ✓ Operation time > 10,000 h

Comparison of high power lasers

	CO_2	Fiber	LD
Maximum power	20kW	500kW	1MW
Energy efficiency	10%	30%	60%
BPP* (5 kW)	6	2.5	100
Size (5 kW)	3m²	1m²	0.1m²
Wavelength	10.6μm	1.07μm	940nm
Optics	Zn-Se	glass	glass
Maintenance	yes	No (>10,000h)	No (>10,000h)

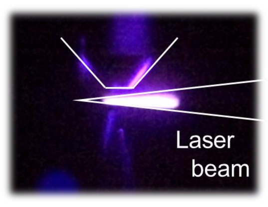
*BPP: Beam Parameter product

LD LSP thruster has potential to exceed to arcjet

Objectives

Previous research

Using 1kW LD,
- ✓ Xe LSP could be generated.
- ✓ Ar LSP could not be generated.



Xenon LD LSP

But, Xe costs too much and is too heavy (low I_{SP}).

Objectives

Following gases were used to generate LSP
- ✓ H_2/Xe
  to reduce average molecular weight
- ✓ CH_4 , CH_4/Xe and CH_4/Ar
  to reduce LSP threshold power using atomic oxygen absorption
- ✓ Kr
  to replace Xe

Laser absorption process

Conventional laser absorption process using CO_2 laser (10.6μm)

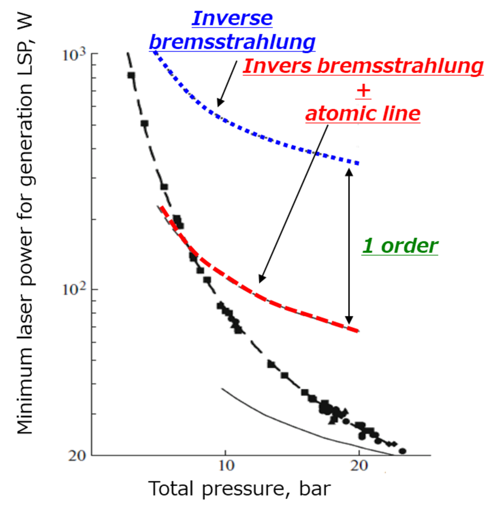
Inverse bremsstrahlung

For fiber laser (1.07μm),

Inverse bremsstrahlung
+
Atomic line absorption

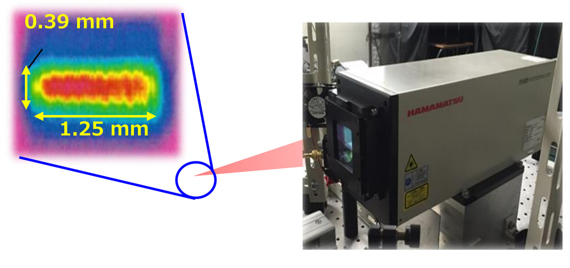
Decrease in threshold power

Since carbon (CH_4) has many atomic lines around NIR range, LSP threshold power may be reduced.

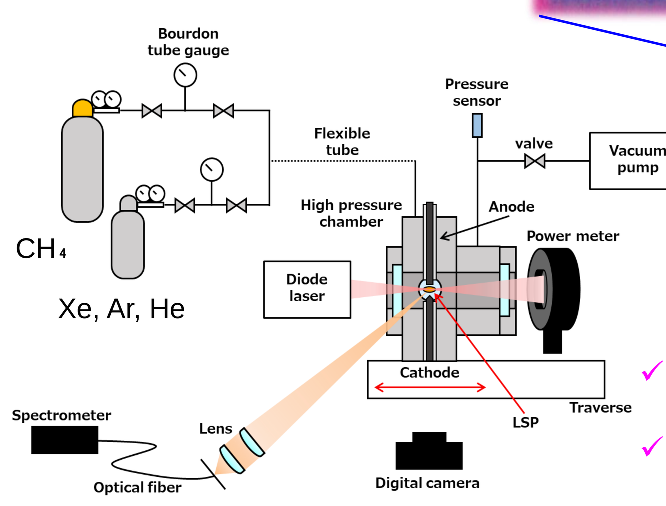


Minimum laser power for Xe LSP generation (Zimakov et al., Plasma Phys. Rep., 42, 2016, 68-73.)

Experimental Apparatus



Beam focusing characteristics



Experimental apparatus

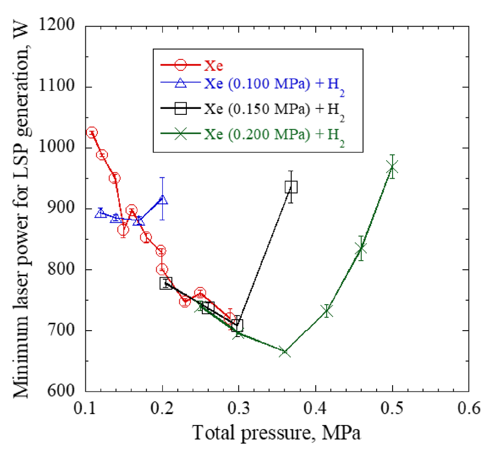
High power diode laser

Laser power	1.1 kW(Max) 4.3 kW(Max)
Wavelength	940 nm

- ✓ Seed plasma was generated by arc discharge
- ✓ Laser beam focuses on seed plasma

Results and Discussions

H_2 /Xe LSP generation



Minimum laser power to generate H_2/Xe LSP for the total pressure

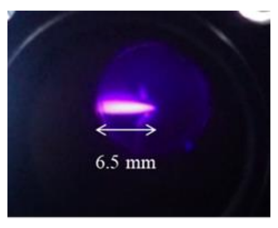
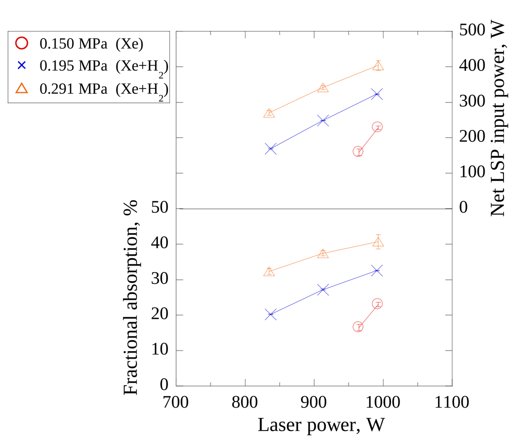


Photo of H_2/Xe LSP

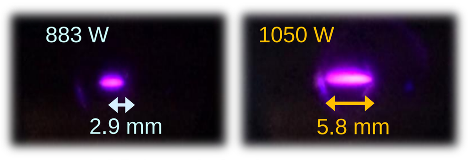
Experimental conditions

	Value
H_2	0.02-0.30 MPa
Xe	0.10 – 0.20 MPa

- ✓ Threshold laser power has minimum for each mixing ratio.
- ✓ Threshold laser power of H_2/Xe is almost same with that of pure Xe.
- ✓ Minimum Xe ratio is 40%, which corresponds to I_{SP} of 196 s.



Net input power and fractional absorption of H_2/Xe LSP (Xe: 0.15 Mpa, H_2: 0.045 MPa, 0.141 MPa)



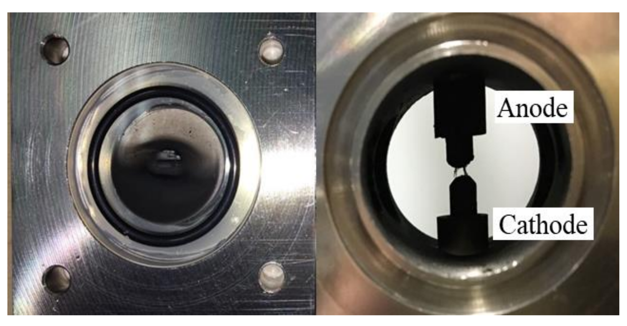
LSP length for laser power (Xe: 0.1 Mpa, H_2: 0.09 MPa)

- ✓ Fractional absorption increased with laser power, because LSP length increased.
- ✓ Addition of H_2 also increased fractional absorption though Xe pressure was fixed.
- ✓ Maximum fractional absorption of H_2/Xe LSP was **40.7 %**.

CH_4 LSP generation

Experimental conditions

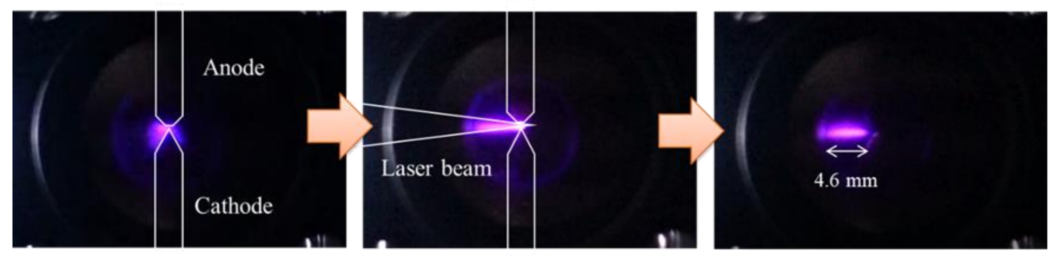
Parameters	Value
Total pressure	0.100 Mpa
Mass flow rate	10 slm
Laser power	1050 W



Picture of High pressure chamber after LSP generation experiment

- ✓ *CH_4 LSP could not be generated*
- ✓ *Inside of the chamber was covered with sooty*
- ✓ *Arc discharge was unstable and stopped due to short circuit by soot.*

CH_4/Xe LSP generation

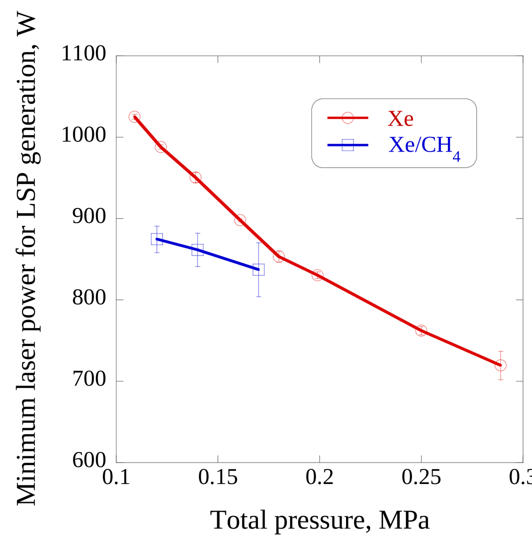


Arc discharge / Arc discharge + Laser beam / LSP

Experimental conditions

Gas	Value
CH_4	0.020-0.100 MPa
Xe	0.100 MPa
Laser power	807-1050 W

CH_4/Xe LSP could be generated!

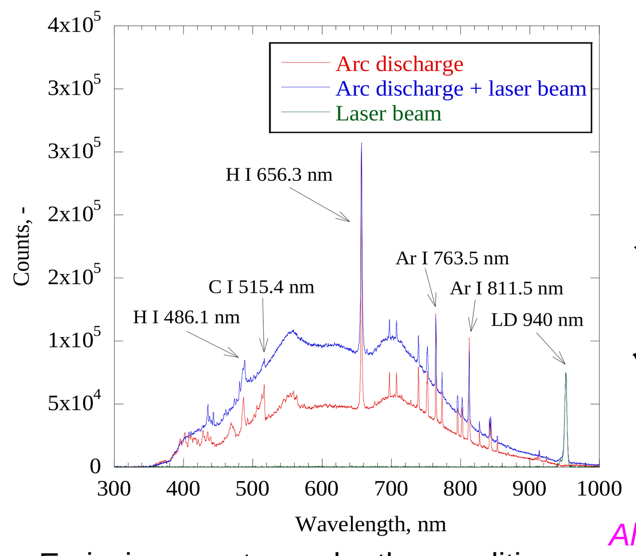


Minimum laser power to generate CH_4/Xe LSP for the total pressure

- ✓ Generation threshold was about 850 W .
- ✓ Maximum CH4 ratio was 41 % because of the unstable arc discharge by soot.
- ✓ Generation threshold of CH_4/Xe was lower than pure Xe LSP.

Atomic line absorption of CI might reduce the threshold laser power.

CH_4/Ar LSP generation



Emission spectra under the conditions of 0.10 MPa and 20 vol. % of methane

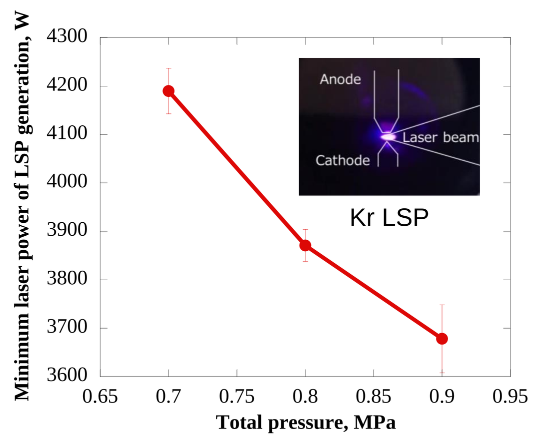
Arc discharge
- ✓ *Line spectra of C, H and Ar were confirmed*

Arc discharge + laser beam
- ✓ *Emission intensity increased*

Laser beam
- ✓ *Plasma disappeared*

Although laser beam was absorbed by plasma, CH_4/Ar LSP could be generated.

Kr LSP generation



Generation threshold of Kr LSP

Experiment conditions

	Kr
Total pressure	0.700 - 0.900 Mpa
Laser power	Max 4.3 kW

- ✓ Threshold laser power decreases with pressure.
- ✓ Threshold power of Kr LSP was much higher than Xe LSP of 530 W @ 1MPa.

Considering ionization energy of Xe, Kr and Ar, Ar LSP might not be generated by 4 kW class LD.

Summary

As a result of LD LSP generation using following gases,

- ➢ **H_2/Xe LSP**
  - ✓ CH_4/Xe LSP could be generated.
  - ✓ Minimum Xe ratio was 40 %, resulting in I_{sp} of 196s.
  - ✓ Maximum fractional absorption was 40.7 %.
- ➢ **CH_4 LSP, CH_4/Ar LSP**
  - ✓ CH_4 LSP and CH_4/Ar LSP could not be generated.
- ➢ **CH_4/Xe LSP**
  - ✓ CH_4/Xe LSP could be generated.
  - ✓ Since threshold power of CH_4/Xe was lower than Xe, atomic line absorption would be effective.
- ➢ **Kr LSP**
  - ✓ Kr LSP could be generated.
  - ✓ Minimum threshold power of 3700 W was much higher than Xe LSP of 530 W.

Acknowledgements

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