Pilot-PSI装置における核融合炉壁材料への定常・パルスプラズマ複合照射実験

Experiment of steady-state/pulse combined plasma irradiation to fusion reactor wall materials on Pilot-PSI

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Outline

1. Introduction
2. Pilot–PSI device and experimental setup
   - Diagnostics, plasma parameter, samples
3. Experimental result
   - IR emission, Spectroscopy, High-speed camera, floating potential
4. Summary

Introduction

- Vapor shielding effect

In fusion reactor, it is concerned that melting and erosion of the wall materials by high-heat and particle loads such as Edge Localized Modes(ELMs) and Disruptions. On the other hand, the heat flux generates a vapor cloud in front of the materials surface. Interacting the vapor and subsequent heat load, total heat load to the surface could be mitigated.

Experimental evaluations are required to validate the prediction of that effect by the numerical simulation.

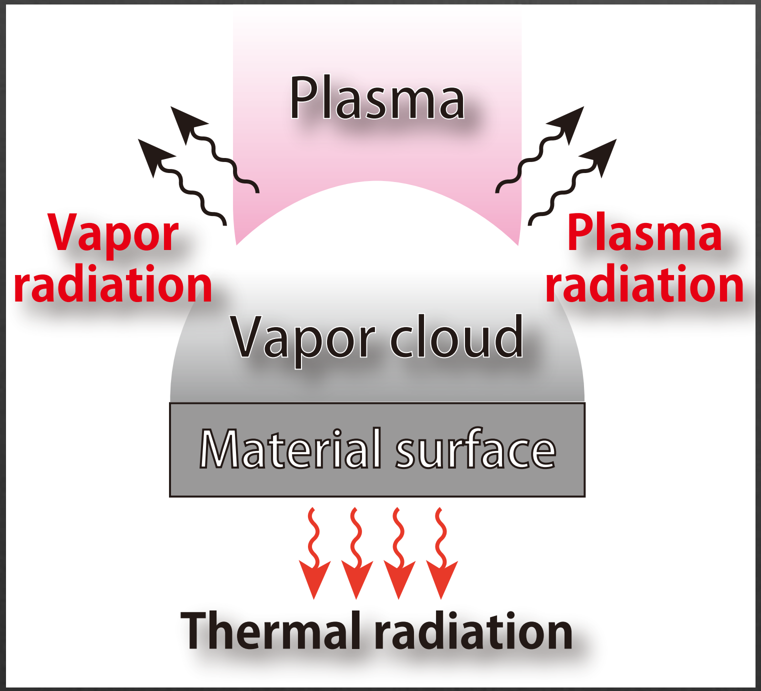
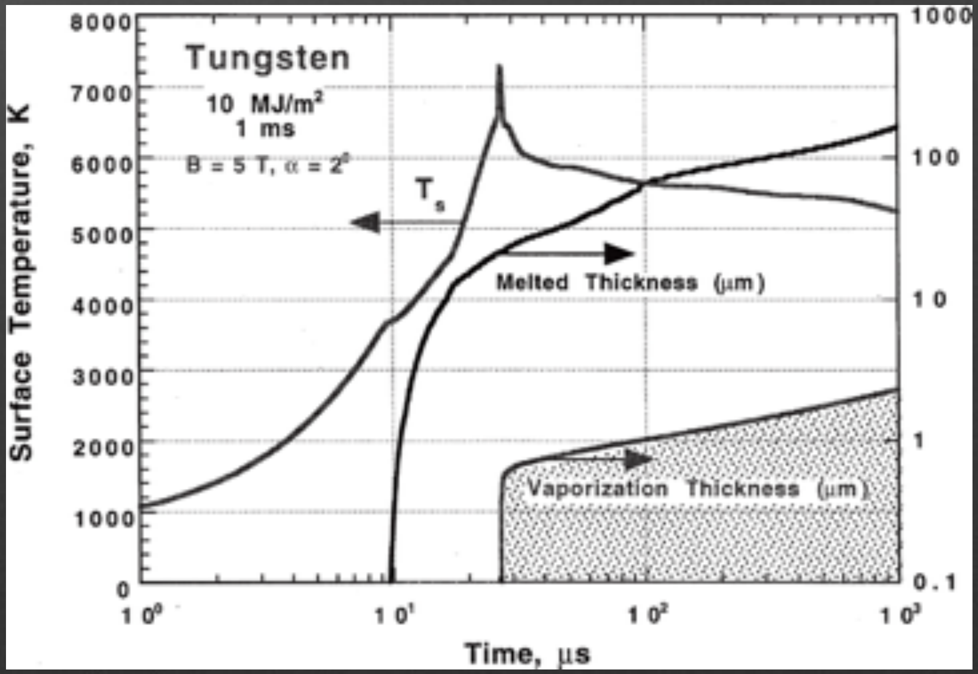


Image of vapor shielding effects

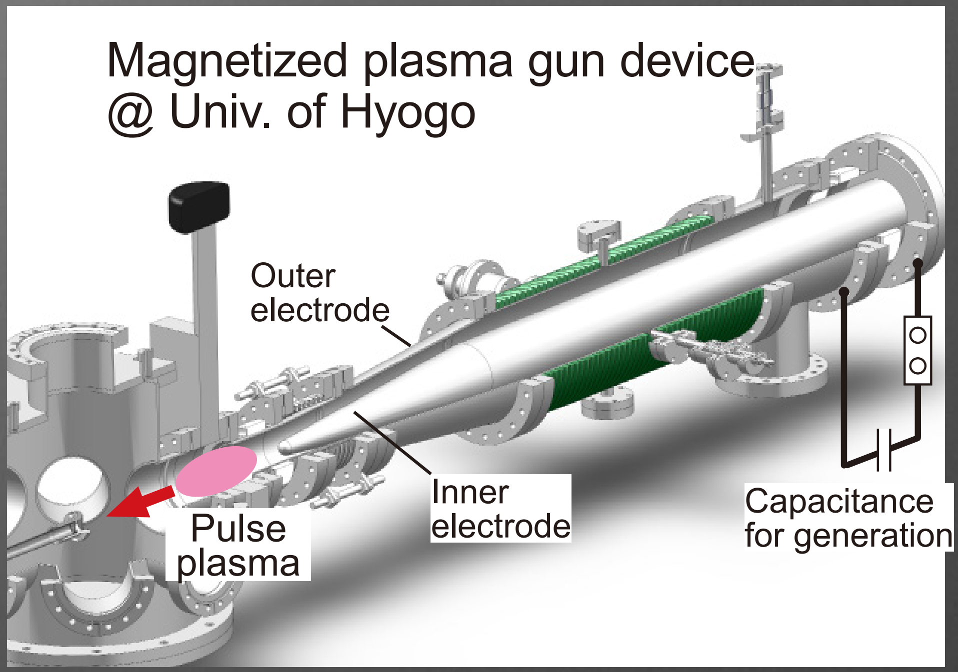


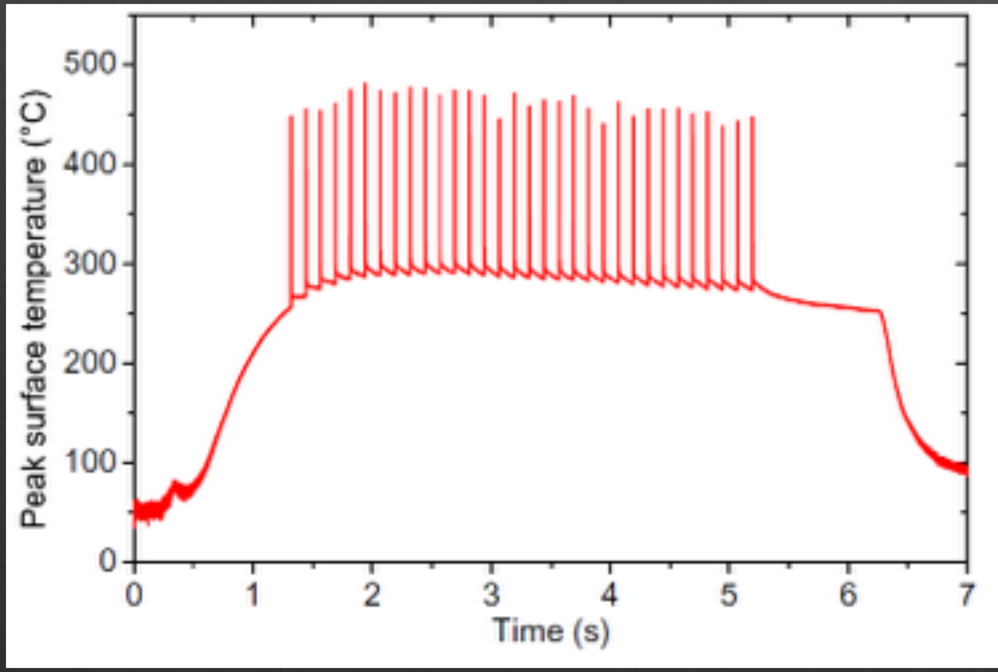
Ref.: A Hassanein at el J. Nucl. Mater. (1999)

Introduction

- Necessity of combined plasma irradiation experiment

We have been focused to Edge Localized Mode (ELM)-like heat and particle load to fusion reactor wall materials by using Magnetized Coaxial Plasma Gun devices(MCPG)



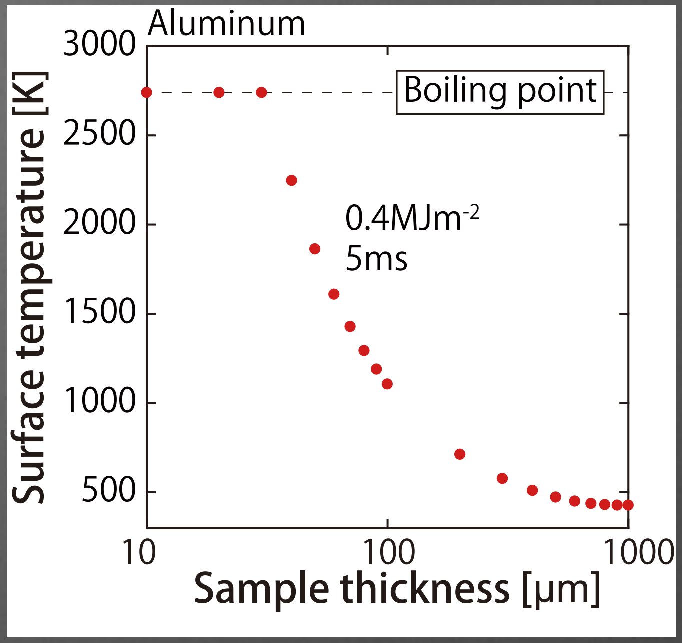


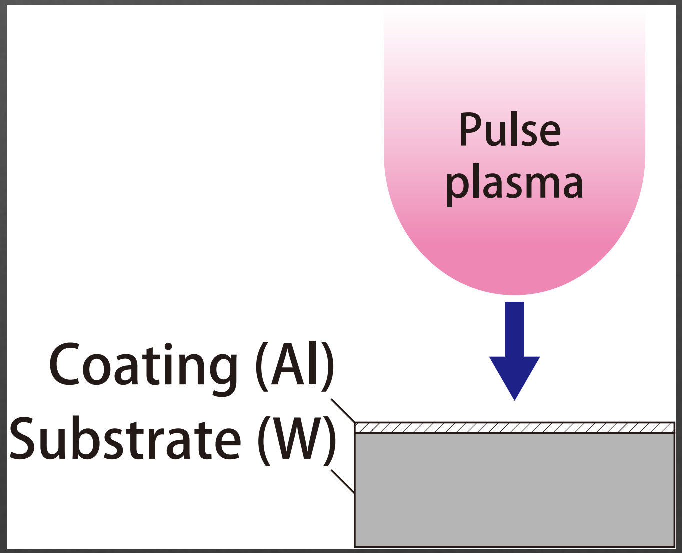
Considering actual fusion reactor, experimental evaluations of the vapor shielding effect by simulating not only ELM but also steady-state heat and particle loads are required.

Ref.: T W Morgan et al Plasma Phys. Control. Fusion (2014)

Approach & Purpose

- **Using thin samples**
  - It is easy to generate vapor of materials by using thinner samples.
  - The support for the thinner samples is required.





- **Experimental purposes**

- **Vapor generation in Pilot-PSI**
- **To investigate the effect of the vapor to the plasma**

Pilot-PSI device

- Liner plasma generator

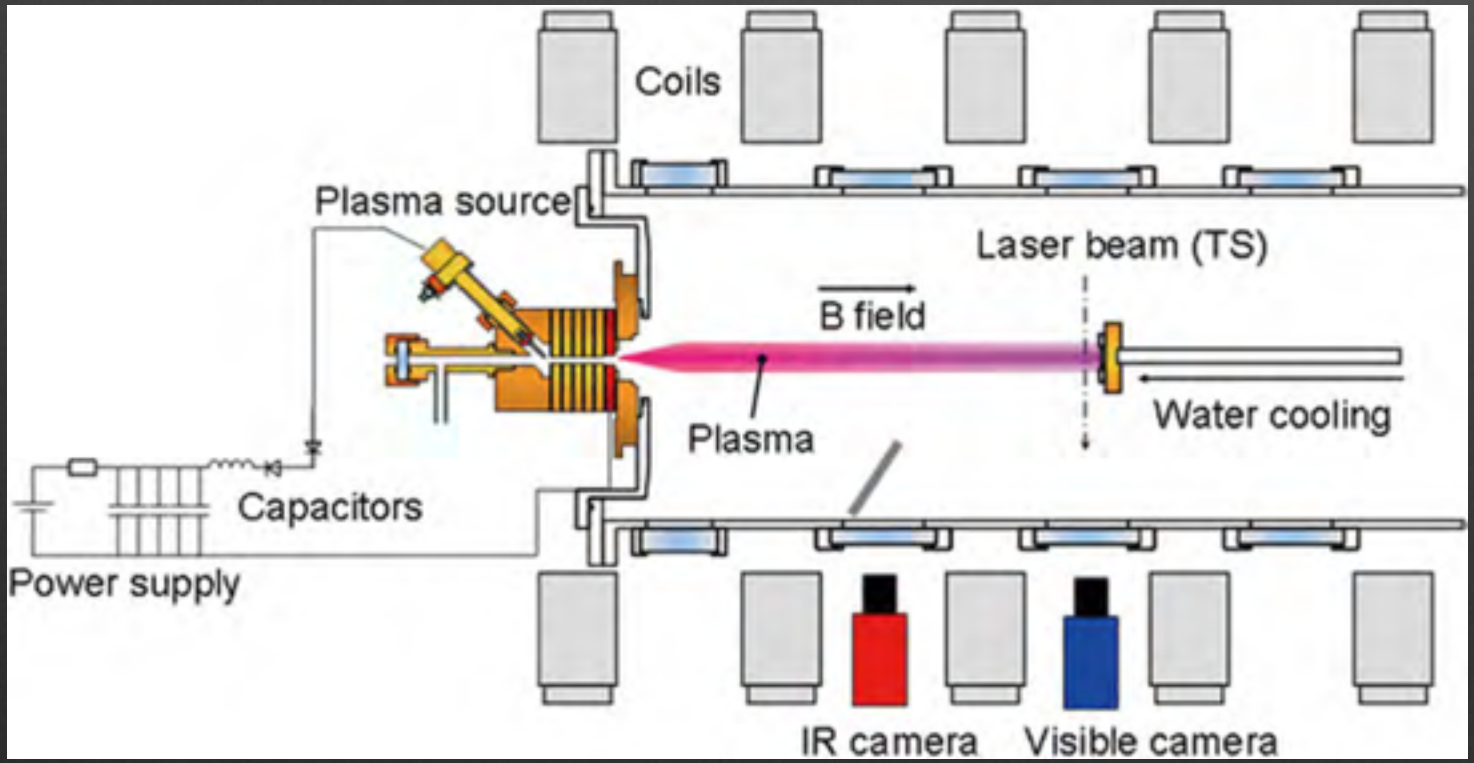
Pilot-PSI, which is a liner plasma generator, generates cylindrical plasma by discharging a cascaded arc source.

- Plasma parameter

	Te [eV]	n_e [$\times 10^{20}$ m^{-3}]	Pulse length [ms]
Steady-state plasma	~0.6	0.79	–
Pulse plamsa	~5	10	~1

- Heat flux
  - ~110MW/m^2
  - ~0.06MJ/m^2

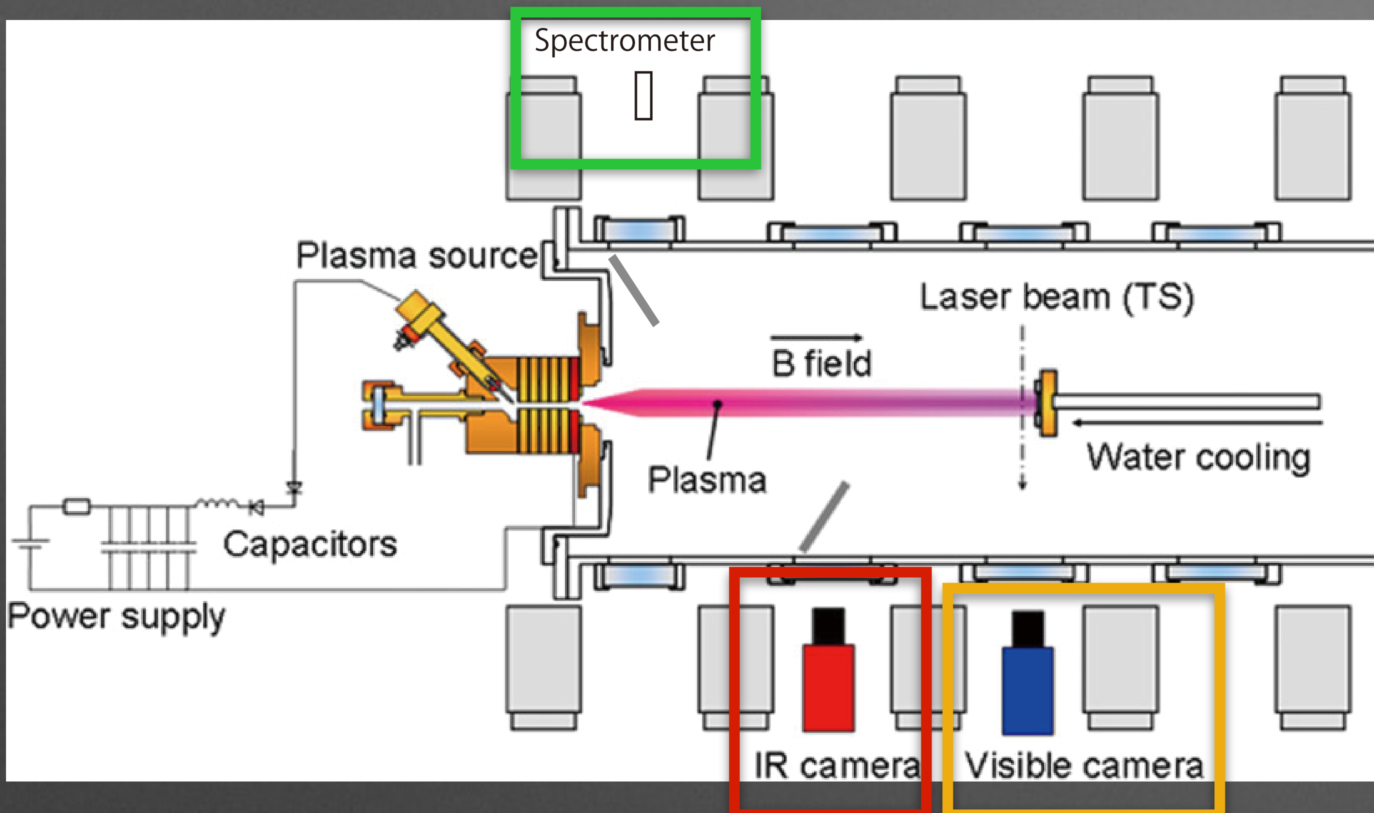
  詳細はポスター発表にて

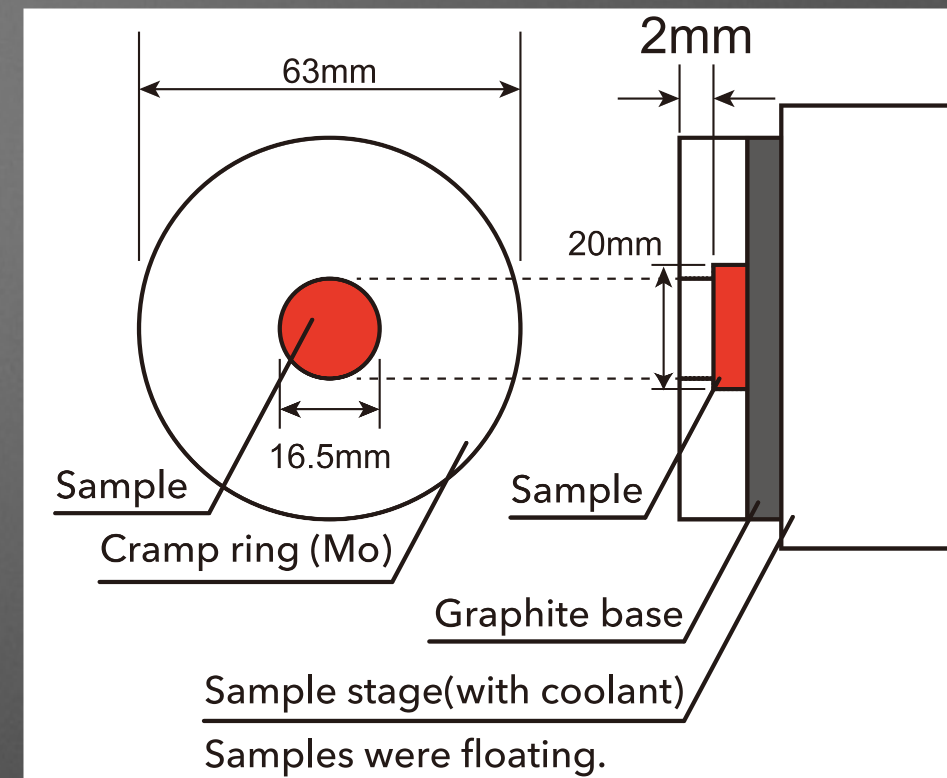


Schematic view of Pilot-PSI device

- Discharge parameter
  - DC source
    - I: 160 A, B: 1.6 T
  - Pulse source
    - V: 1500 V(169J each), Frequency: 10 Hz, Pulse number: 25
  - Plasma gas: H

Diagnostics





Sample holder

- Instruments
  - IR camera(FLIR SC7500B):Surface measurements
    - Waveband: 1.5–5.1 μm, Frame rate: 5 kHz
  - Spectrometer(Avantes 2048):Surface measurements
    - Wavelength range: 299-579 nm, Resolution: ~0.07 nm/pixel
    - Integration time: 2 ms, Frame rate: ~20 Hz
  - Visible high speed camera(Phantom v12): Radial direction in front of the surface
    - Frame rate: 10 kHz
    - Band path filter(Al I): 394 nm, FWHM: 10 nm
  - Thomson scattering (Only steady-state)

Samples

- Common size
  - Diameter : 20 [mm]
  - Base thickness: 1 [mm]
- Aluminum on Tungsten base(Al on W)
  - Al thickness: 1 and 3 [μm]
- Bulk W
  - Thickness: 1 [mm]

Al on W (1μm)

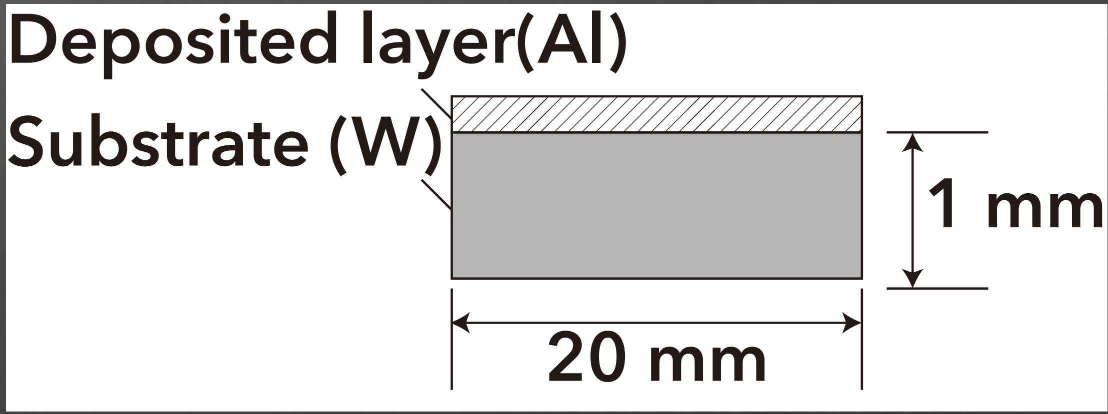
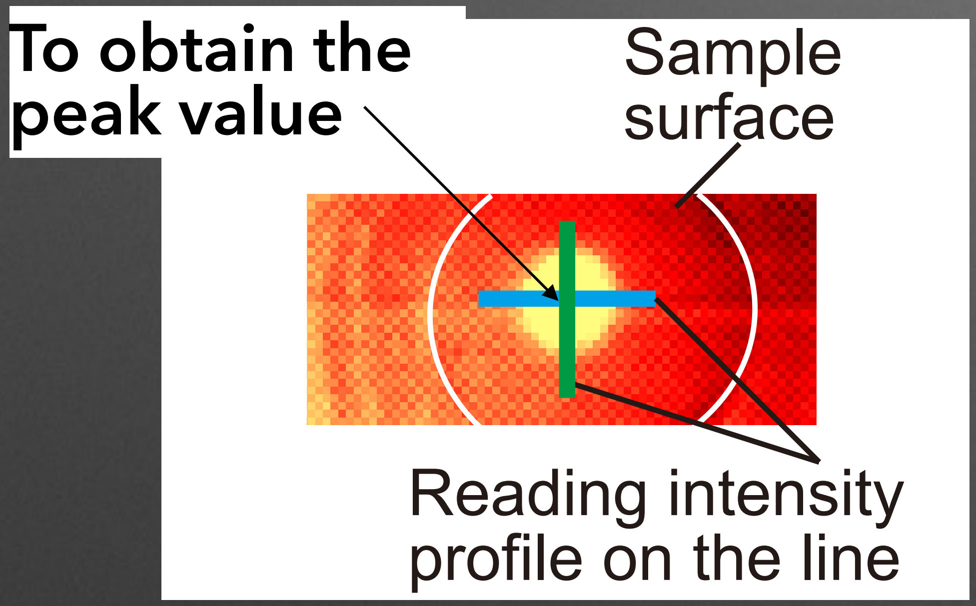


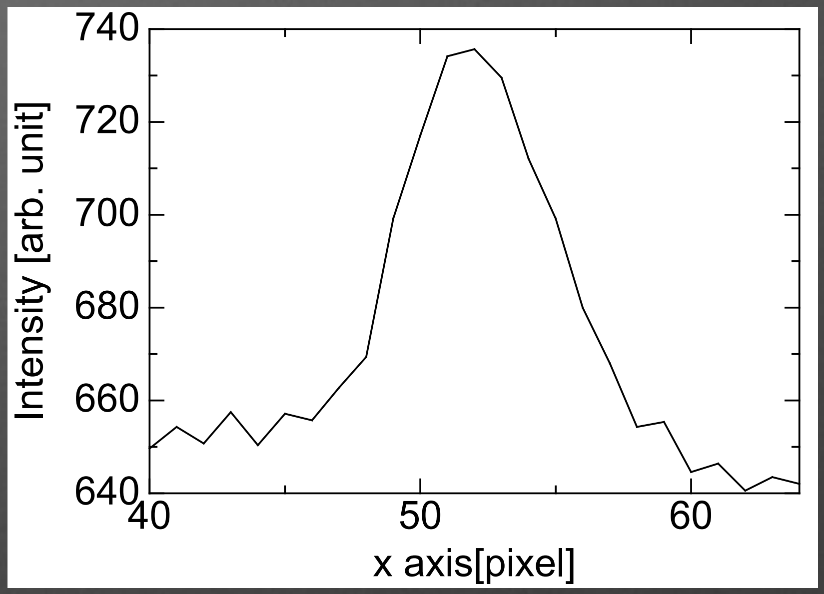
Image of sample structure

→ The films were deposited by using a magnetron sputtering device in Osaka University.

IR camera measurement

- Measuring IR emission from the surface
  - Surface temperature is obtained by Measuring IR emissions
  - Wavelength range: 1.5-5.1μm

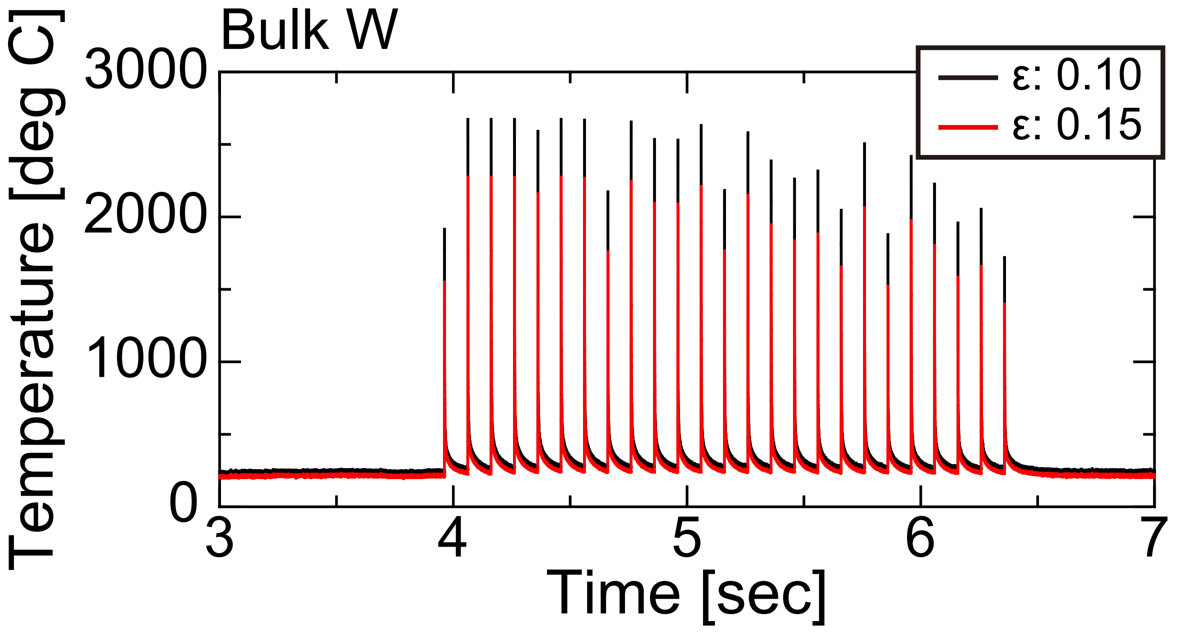


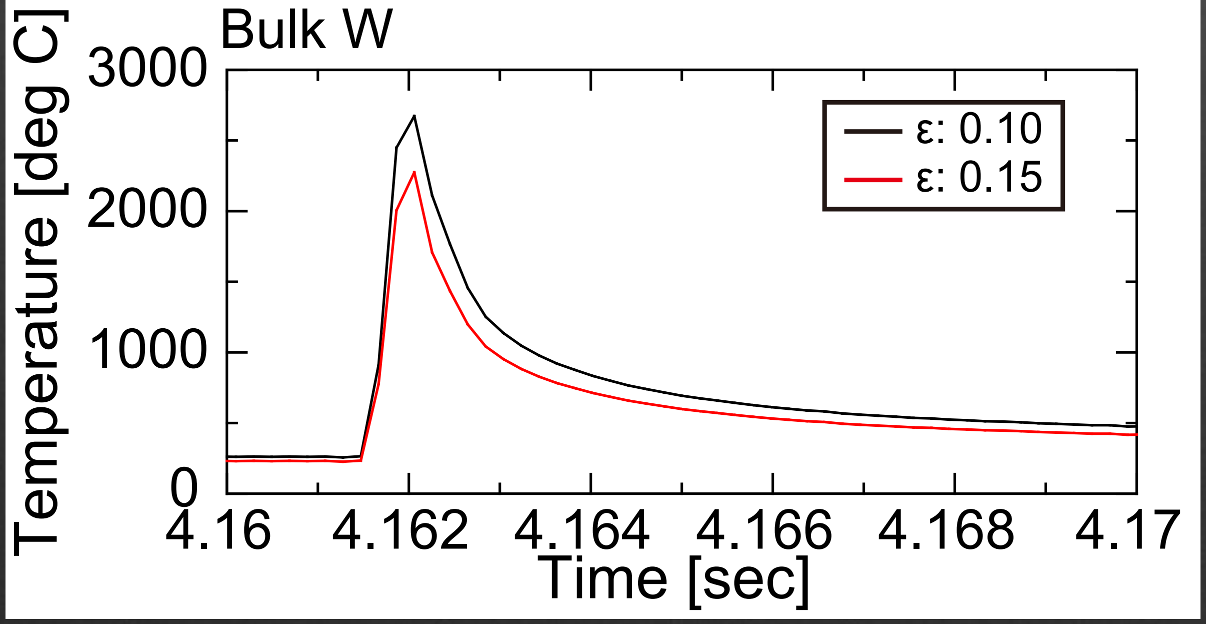


- Reading hot spot data on two crossed line
- Normally, the profile has a peak distribution

IR camera measurement

- Time evolution of IR temperature on a bulk W sample



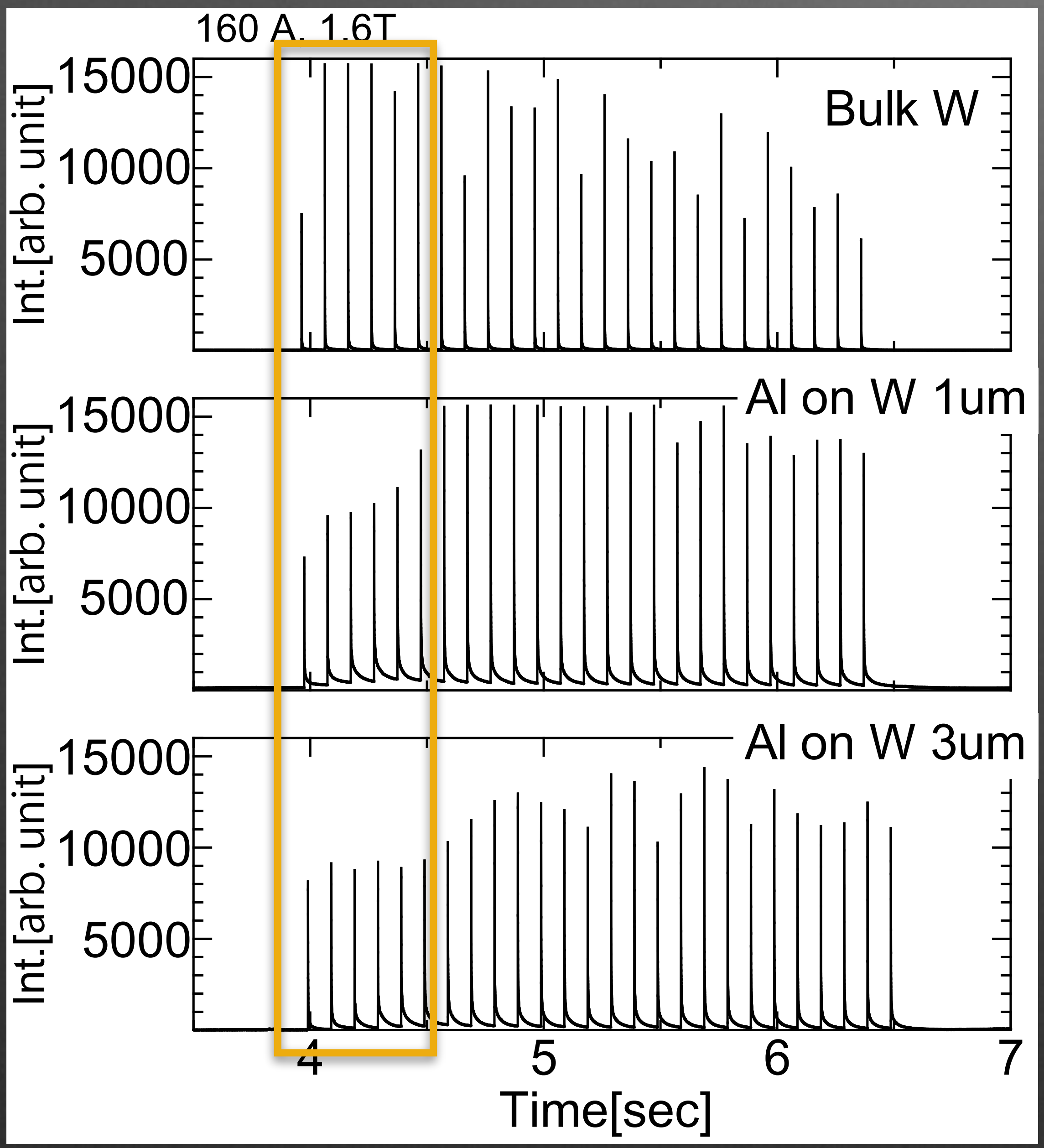


- Steady-state temperature:
  - ~300 deg C
- The Peak temperature:
  - ~2200 deg C (ε: 0.15)
  - ~2700 deg C (ε: 0.10)

- 2nd pulse
  - Rise time: ~500 μs
  - 1/e decay time: ~1300μs

IR emission : Al on W

- Time evolution of IR emissions on a Al on W sample



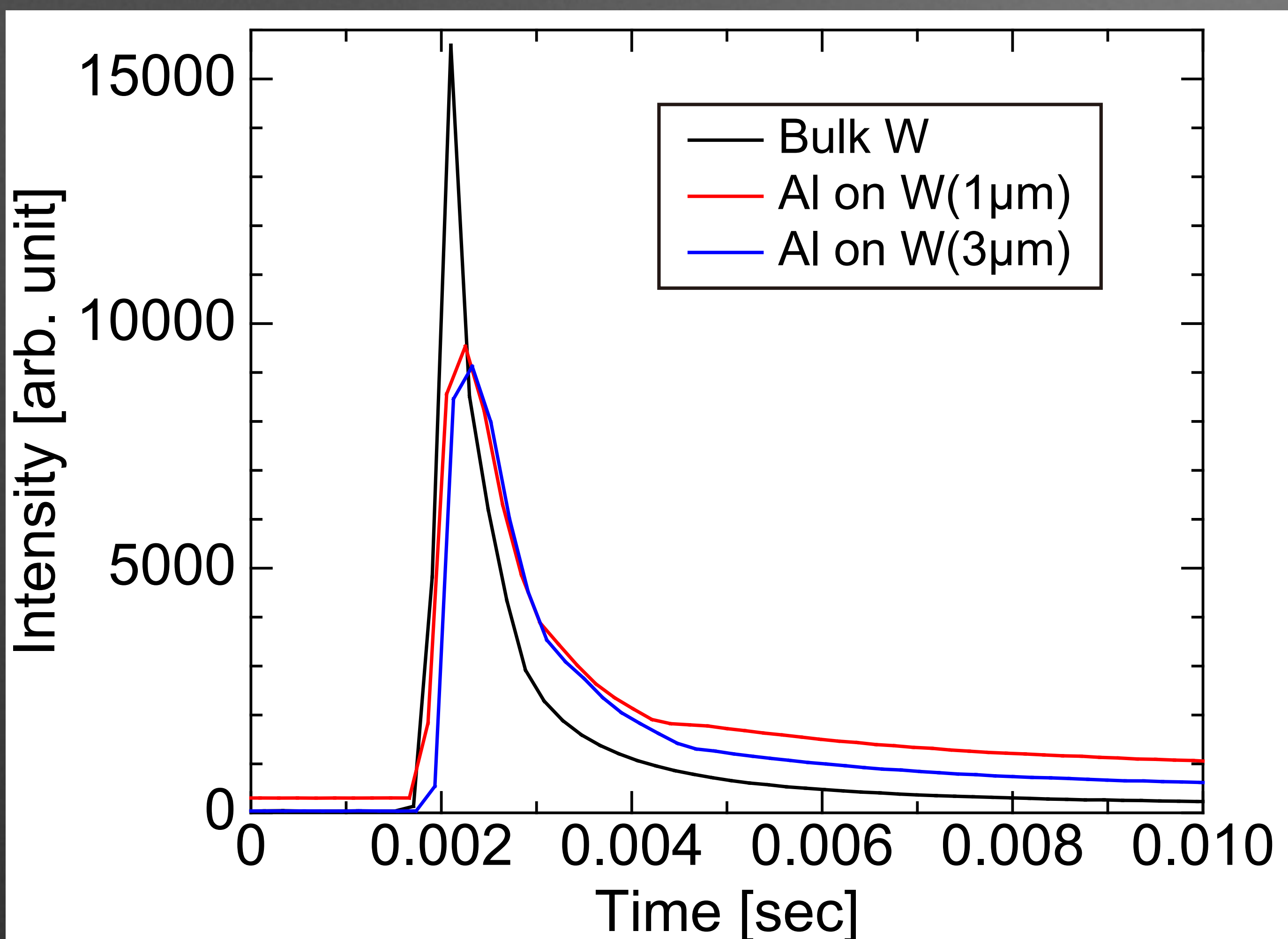
- In first 5 pulses, intensities of Al on W samples are **weaker** than that of bulk W sample.
- Steady-state intensities of Al on W were stronger than that of bulk W.

⬇

Focusing 2nd pulse

IR emission : Al on W

- Focusing 2nd pulse of each sample IR emission



- Decay time of Al on W samples are longer than that of Bulk W.
- After 0.004 sec, the decay time of Al on W samples are different from each other.

➡ Al layers were likely to have low thermal conductivity due to thermal resistance at interface of the sample.

Visible camera: Al on W

- High-speed visible camera
  - Al I filter: 394 nm, FWHM: 10 nm, Diameter: 25 mm

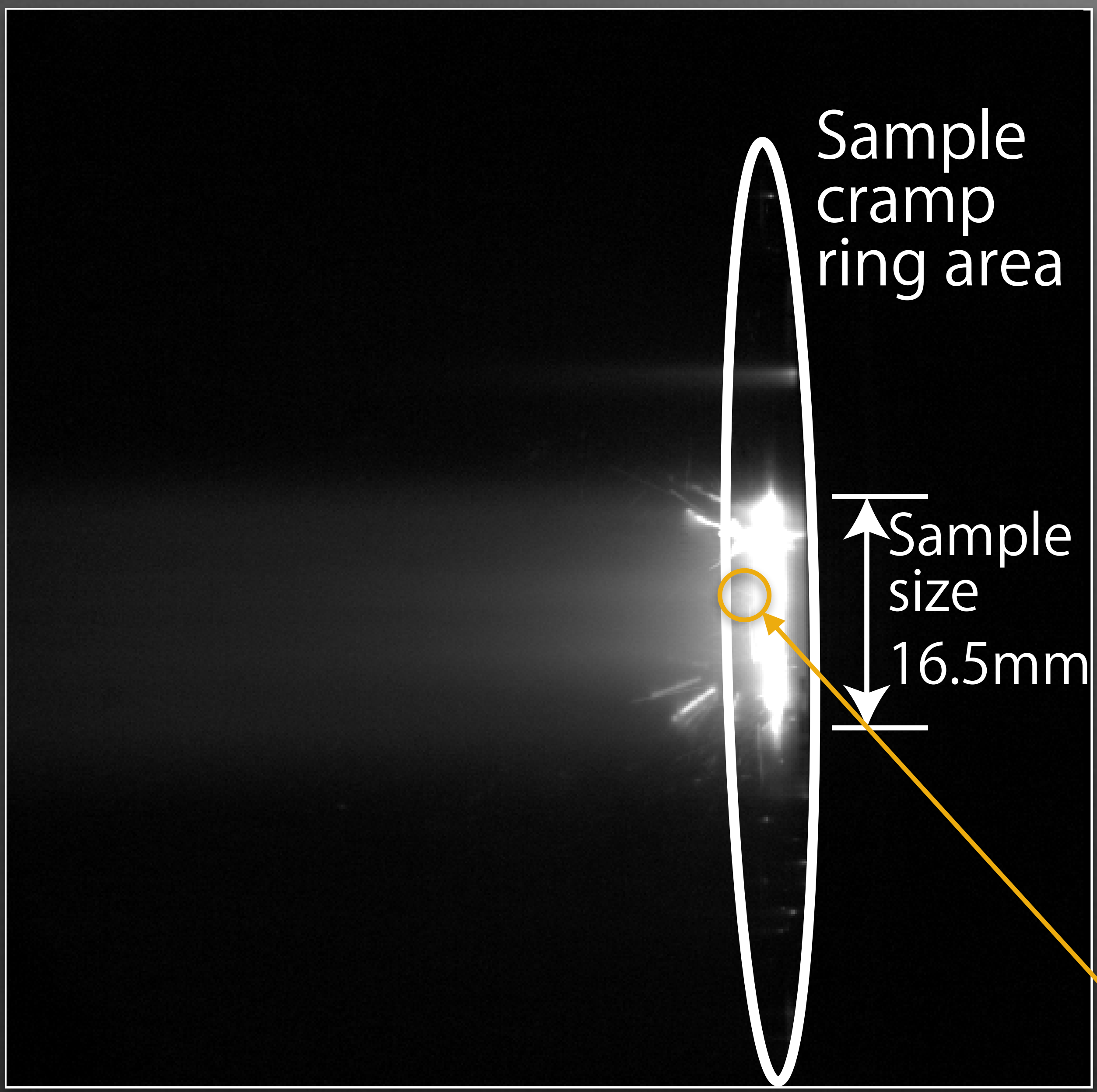


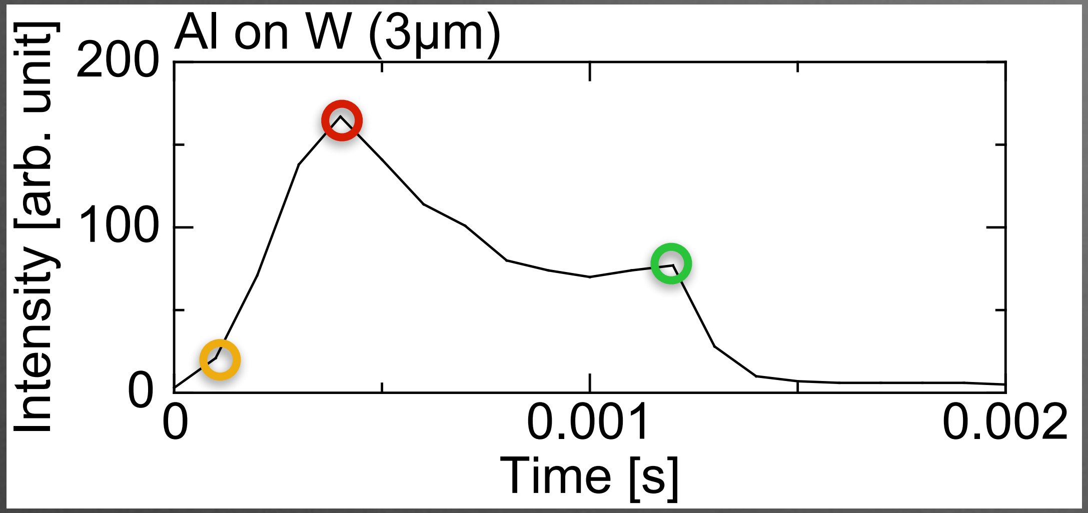
Photo image through the interference filter

- Hydrogen emissions were also observed because of wide FWHM of the Al I filter.
- The center of the sample was mainly irradiated because of focusing to 10mm FWHM.
- However, the emissions were observed wider area due to existence of lower energy plasma wider area.

Focusing a bright spot to investigate numerical data

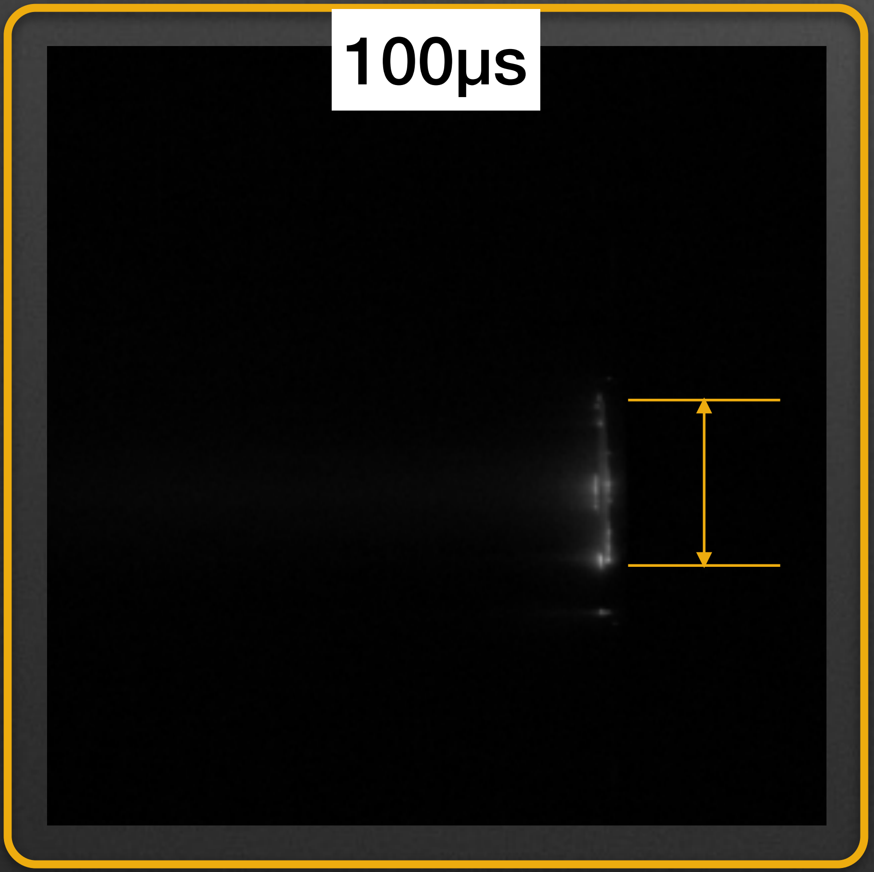
Visible camera: Al on W

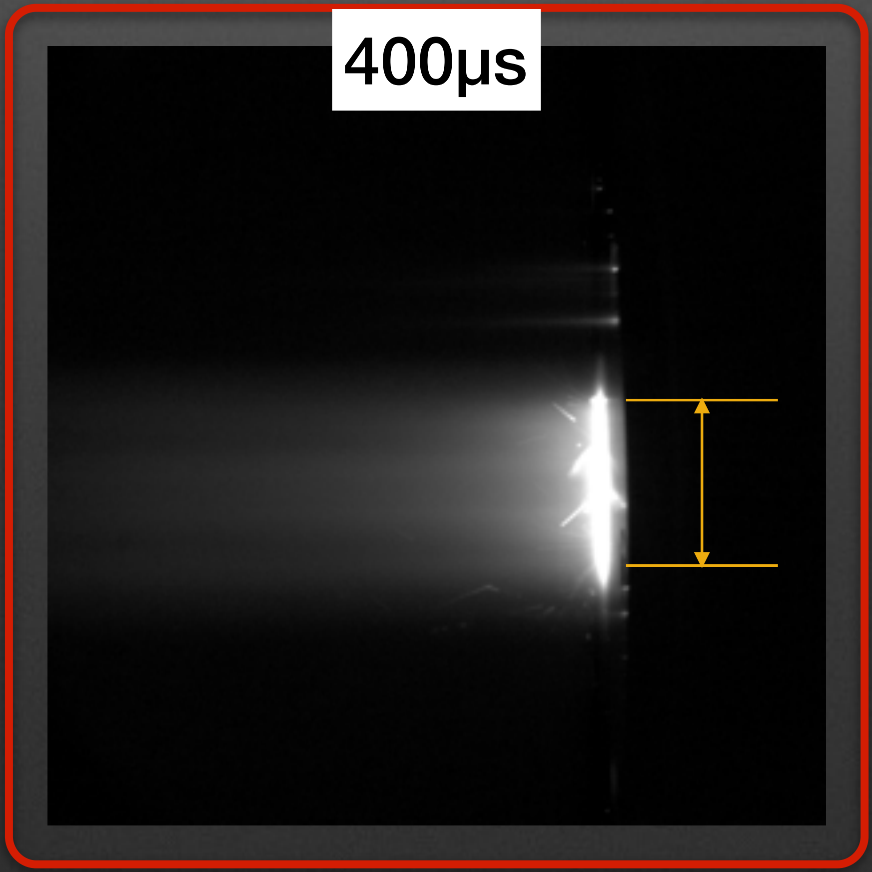
- Time evolution of photo image on a Al on W sample

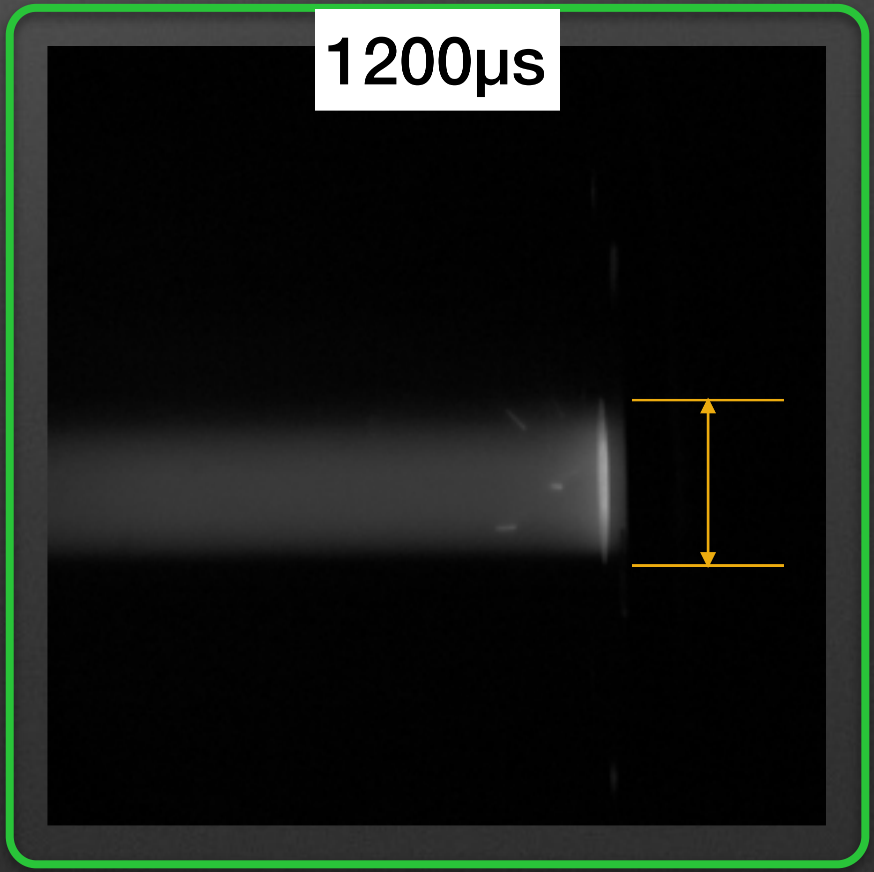


- 2nd pulse photo images of 3μm Al on W sample

➡ Emission was originated from the sample surface.

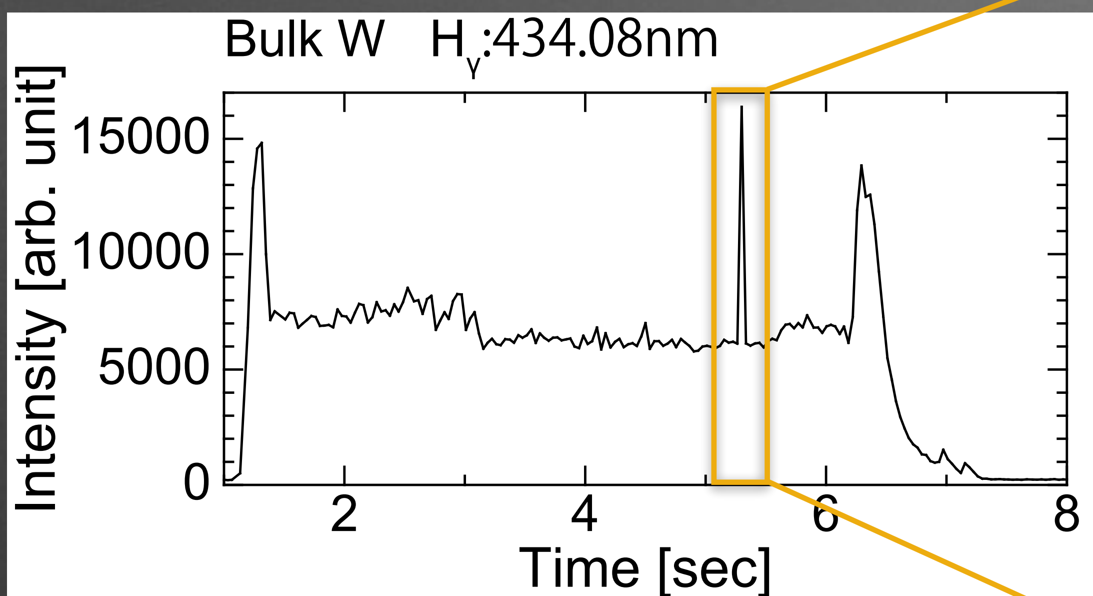




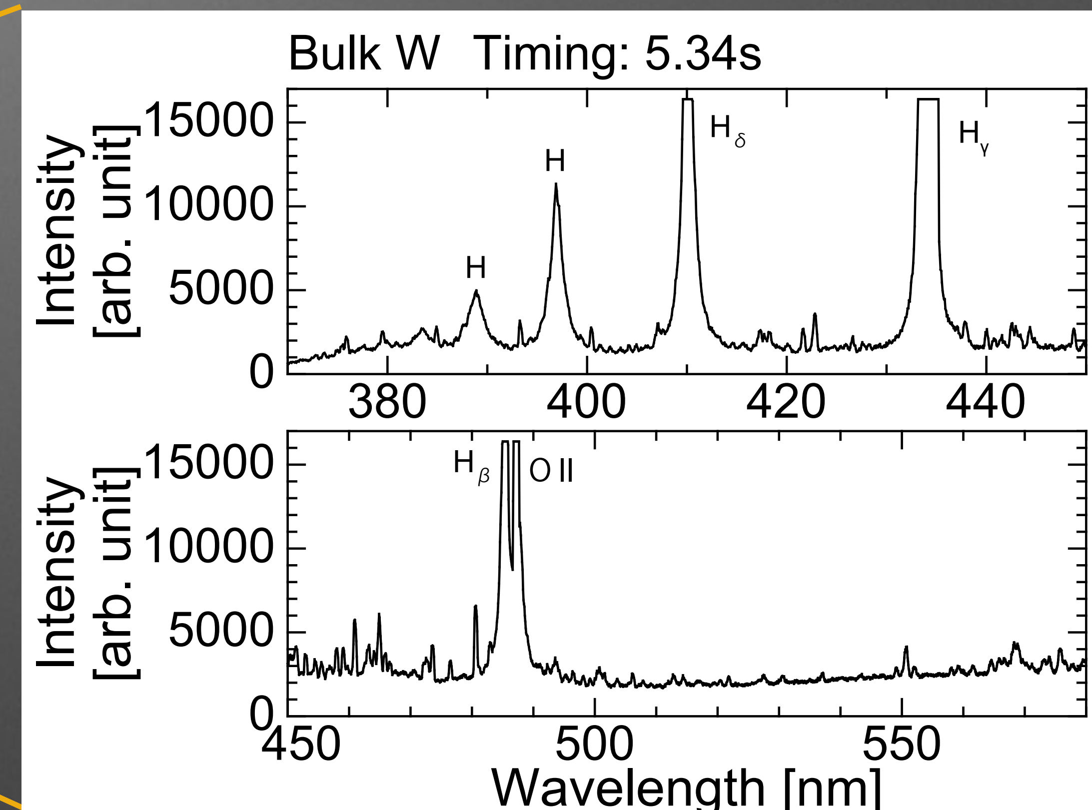


Spectra: Bulk W

- Optical emission spectroscopy
  - Integration time: 2ms, Frame rate: ~20 Hz



Time evolution of H_γ

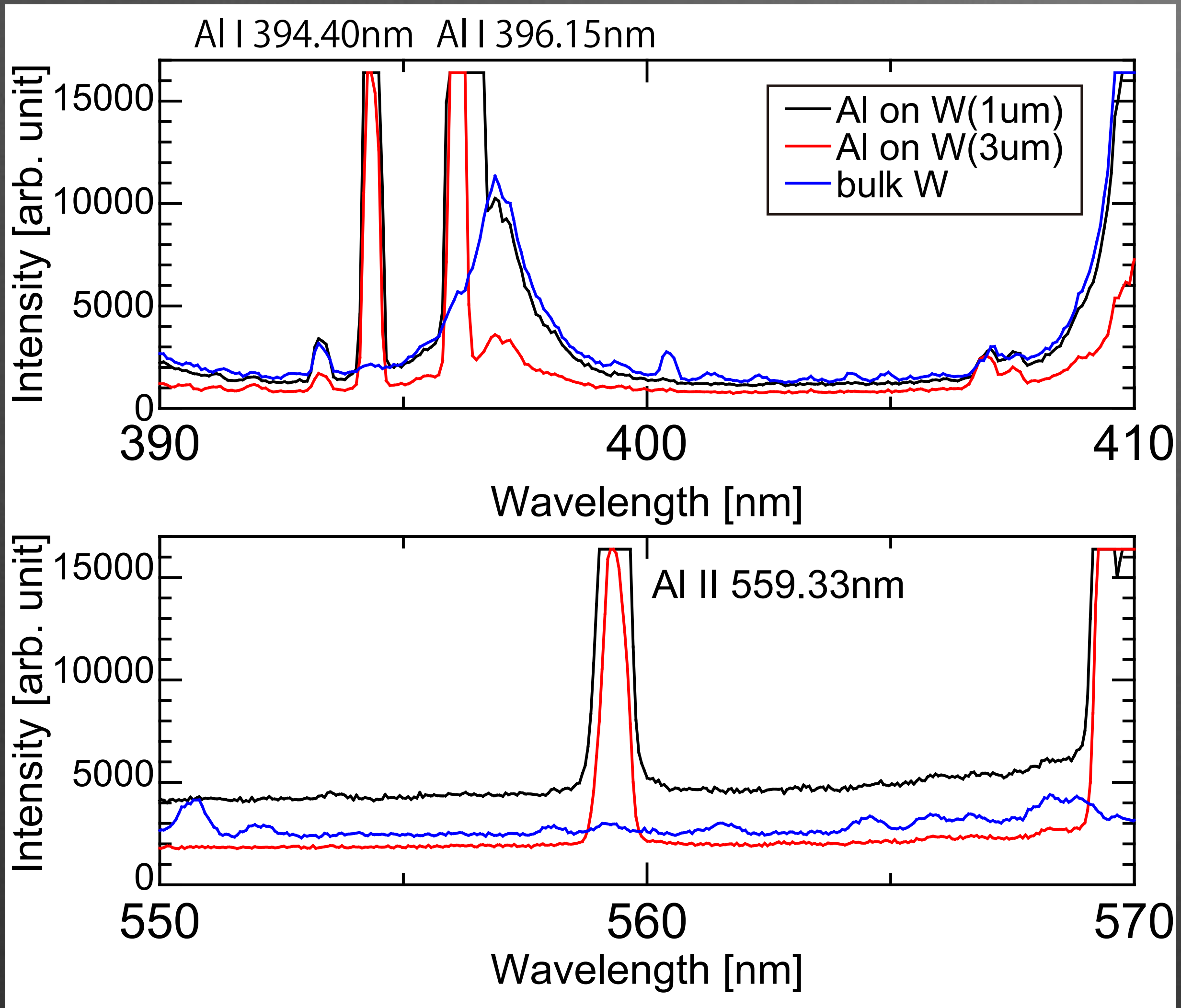


Spectra(370-580nm) during pulse

- There is **no W I emission**.
- In the recoded pulse spectra:
  - Strong spectra are mainly hydrogen spectra.

Spectra: Al on W

- Optical emission spectroscopy
  - Integration time: 2ms, Sample rate: ~20 Hz



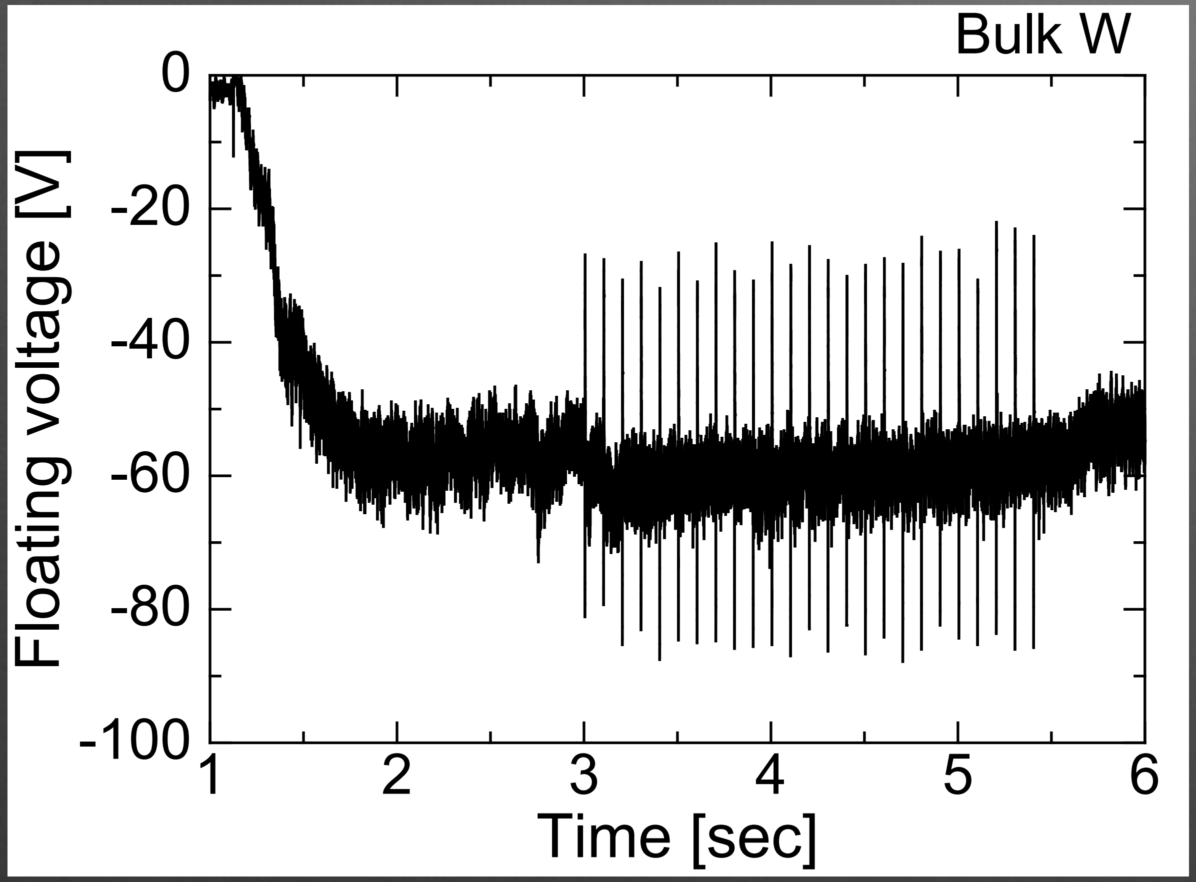
There are some spectra of Al I and Al II emission.

Vapor of the materials was formed.

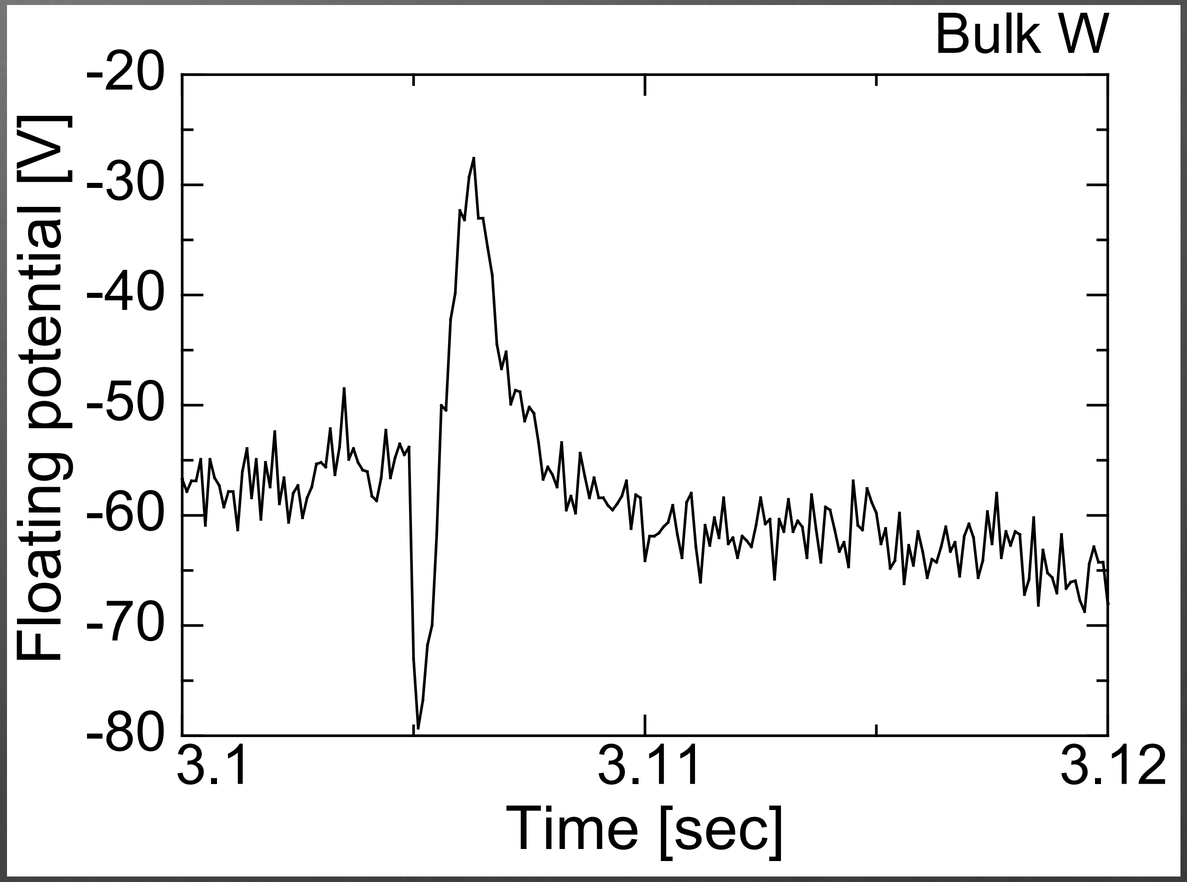
- The effect of the vapor formation was investigated by measuring target floating potential.

Floating potential: Bulk W

- Floating target voltage measurement
  - Sampling rate: 10 kHz



Time evolution of the voltage

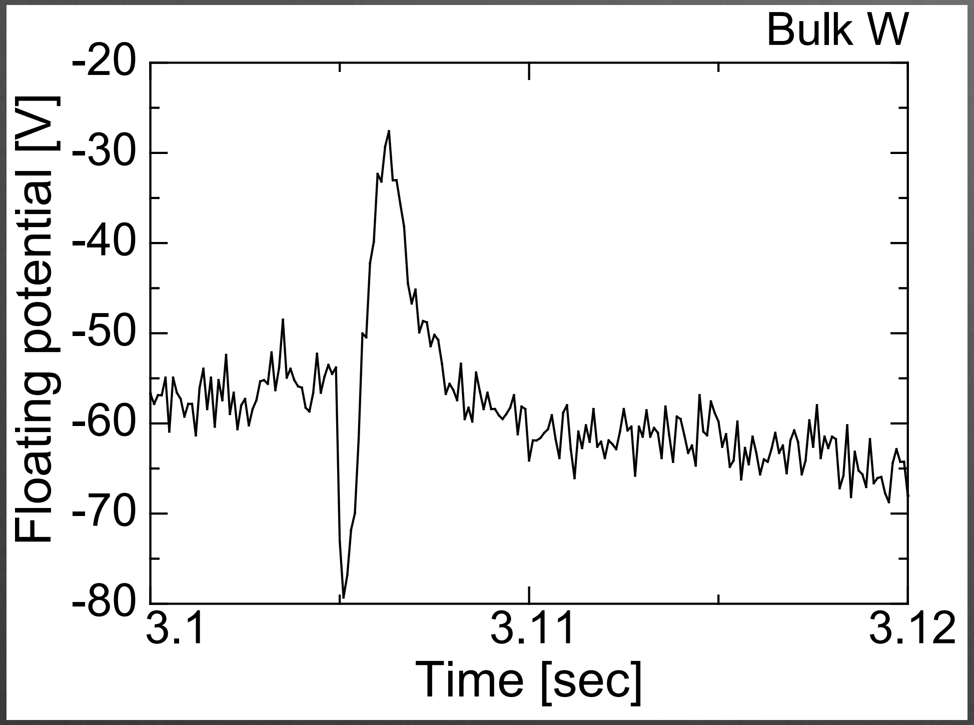


Voltage during 2nd pulse

- Steady-state voltage : ~-60 V

Floating potential: Bulk W

- Time-resolved voltage show the details
  - Sample rate: 10 kHz

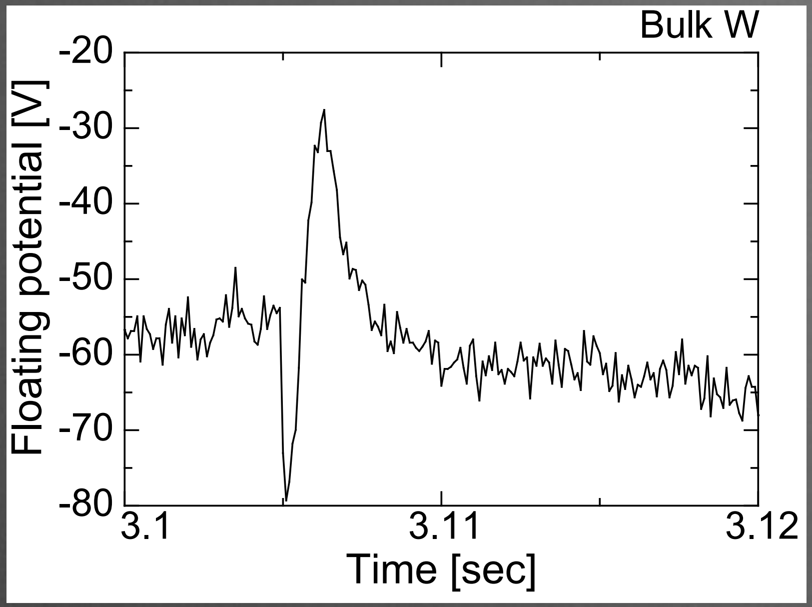


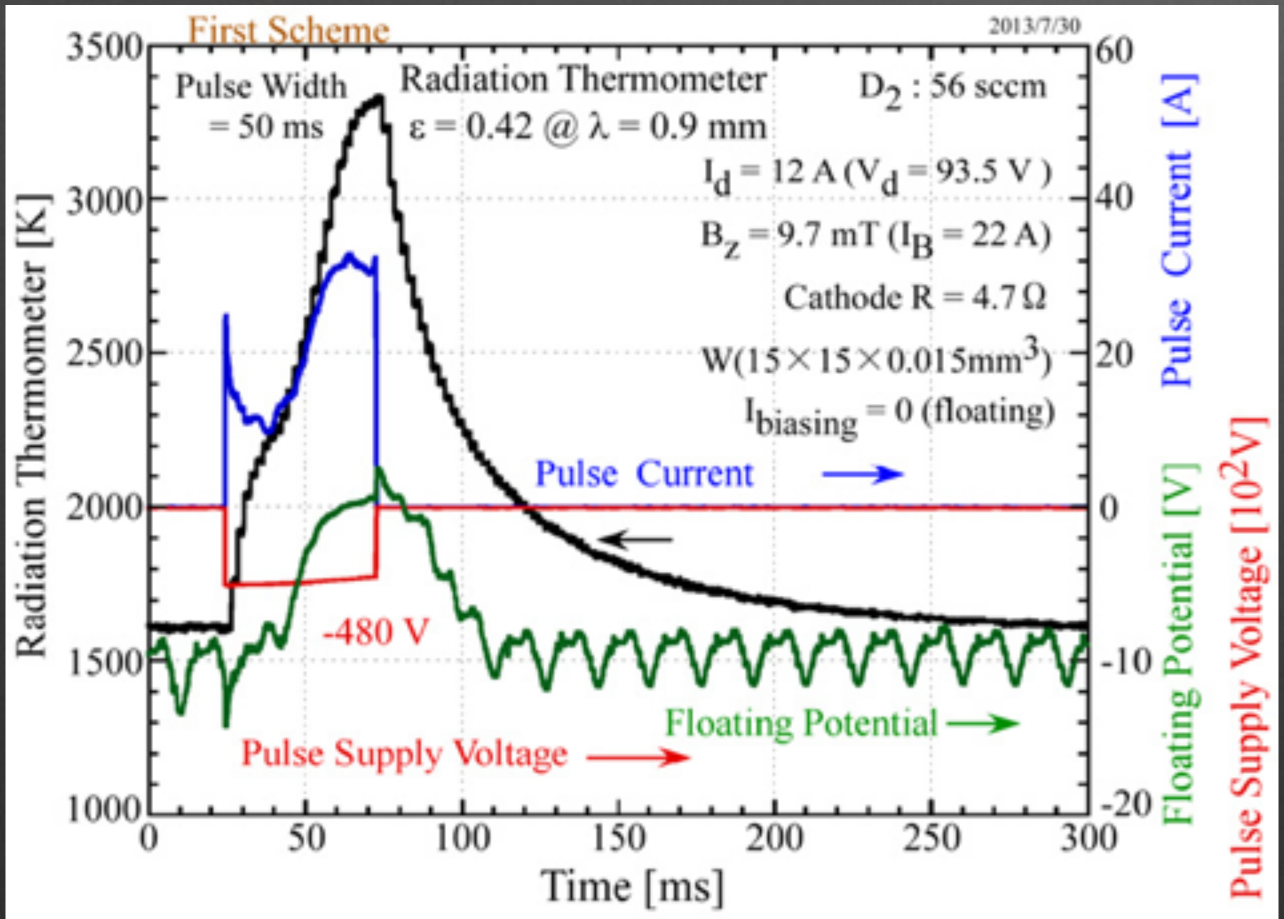
Time evolution of 2nd pulse floating potential

- Firstly, the voltage was decreased owing to fast electron incidence.
- Secondly, the voltage began to recover to steady-state level, however, it exceeded the level.

- It was considered that <u>electron emissions</u> such as thermo-electron emission may decrease the sheath voltage.

Change of the floating potential





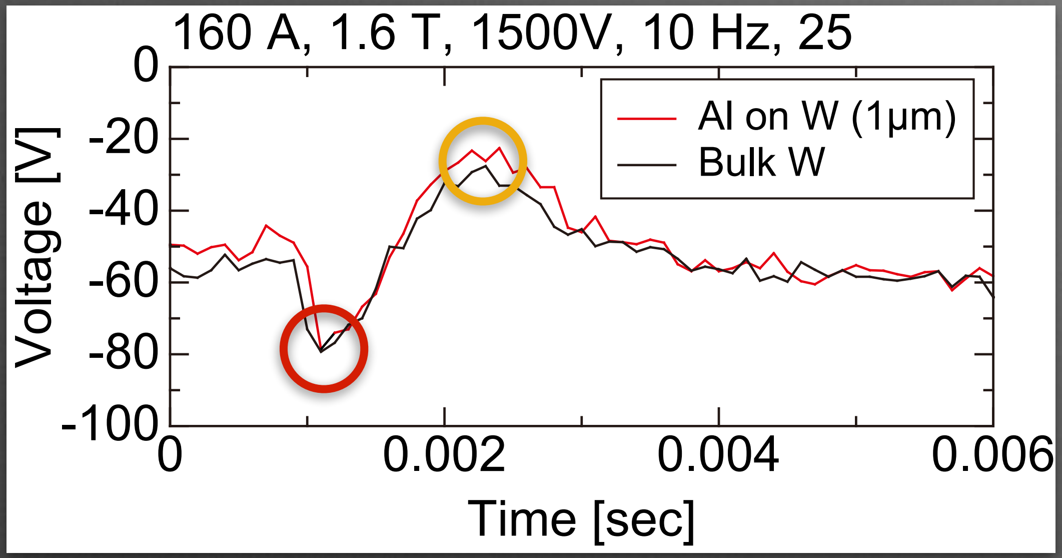
Ref.: S Takamura et al Nucl. Fusion (2015)

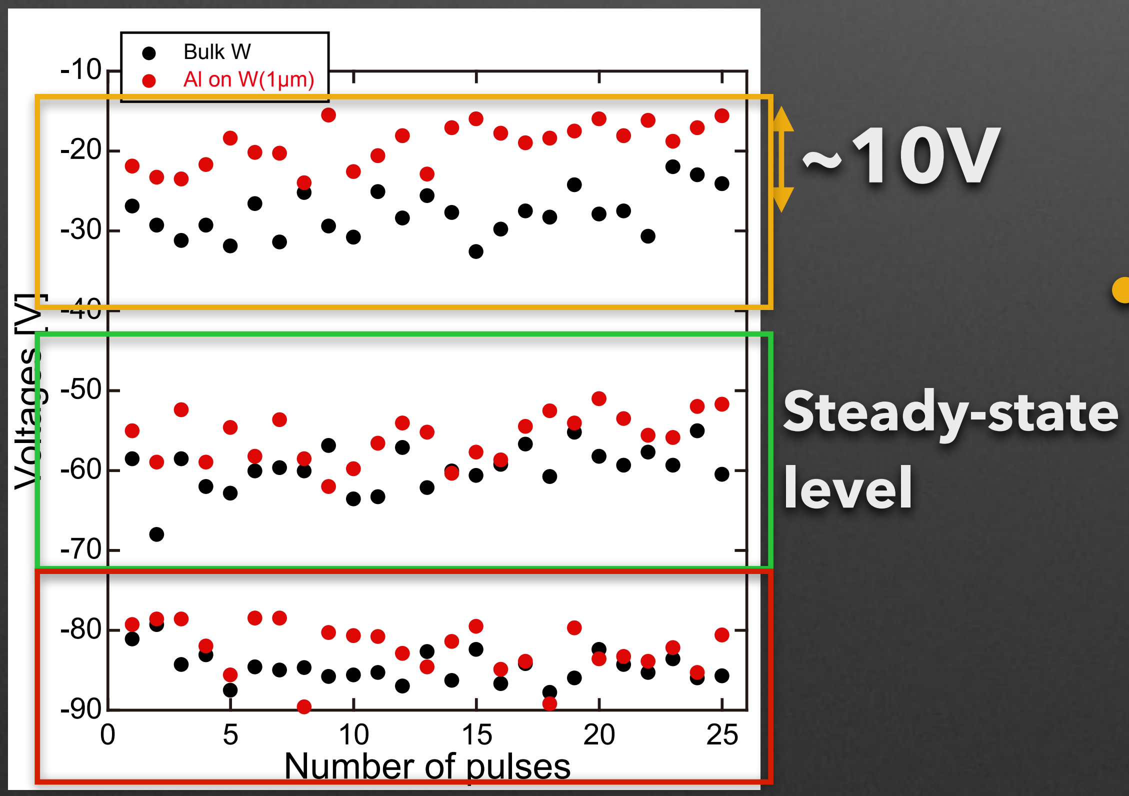
- In this reference, these changes of the sheath voltage may be caused by electron emissions.
  - Thermo-electron emission
  - Secondary electron emission
- Reduction in sheath voltage due to electron emissions brings an increase in plasma heat flux.

(Ref.: S Takamura et al Nucl. Fusion(2015))

Discussion of the sheath voltage change

- Difference between Al no W and Bulk W





3 different timing voltages of each pulse plasma

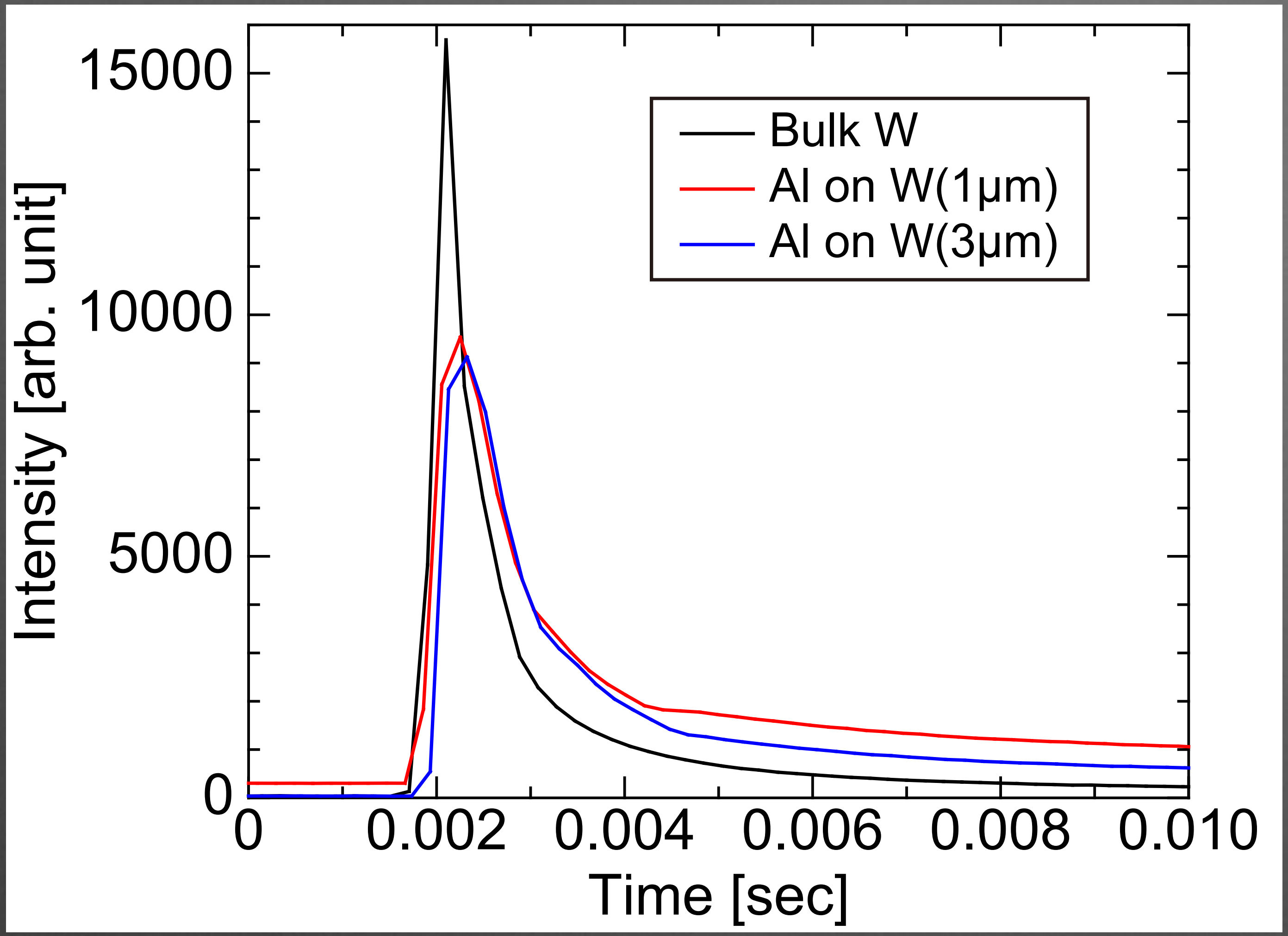
- Plot each 3 different timing voltage every pulse.
- There are approximately 10 V difference in peak voltages.
- It is under analyzed that these potential differences were caused by melting or evaporation of the deposited Al layer.

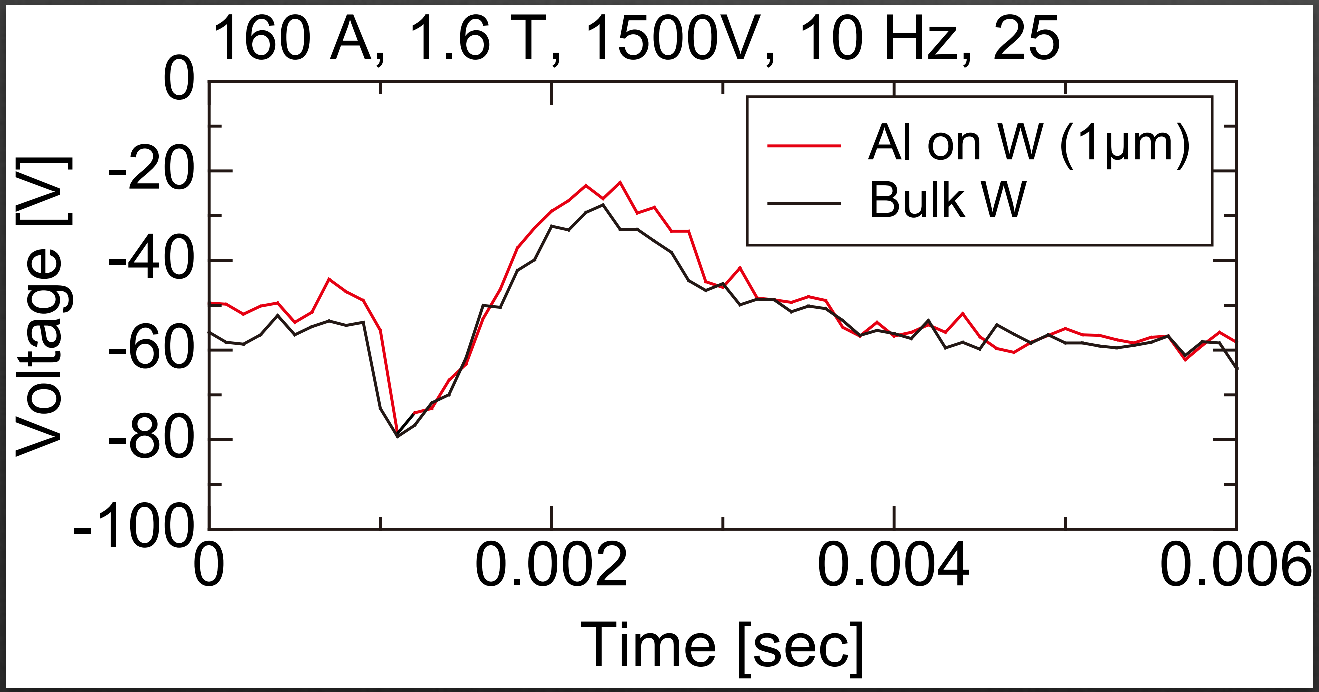
Summary

- Carried out steady-state/ pulse combined plasma irradiation experiment in Pilot-PSI
  - The generation of the vapor was measured by a high speed camera and a spectrometer.
  - IR intensity ($\propto T^{1/4}$) was suppressed in first 5 pulses on Al film deposited W samples.

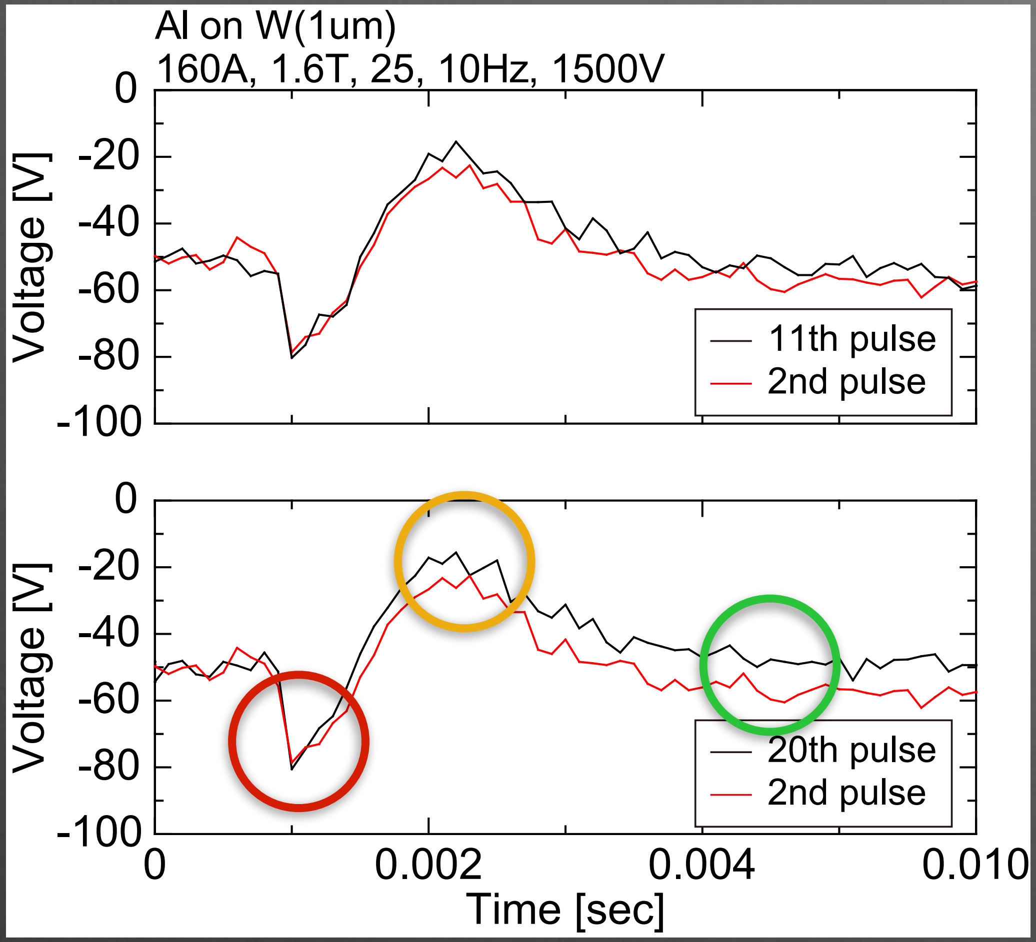
- Measuring the floating potential of the samples.
  - The floating potential decreased exceed the steady-state voltage.
    - In tungsten sample, this is likely caused by the thermo-electorn emission.
  - The floating potential differed from each surface material.

➡ It has been investigated the effect of evaporation or melting of the Al layer in Al on W sample.


15000
10000
5000
0
Intensity [arb. unit]
0
0.002
0.004
0.006
0.008
0.010
Time [sec]
Bulk W
Al on W(1μm)
Al on W(3μm)

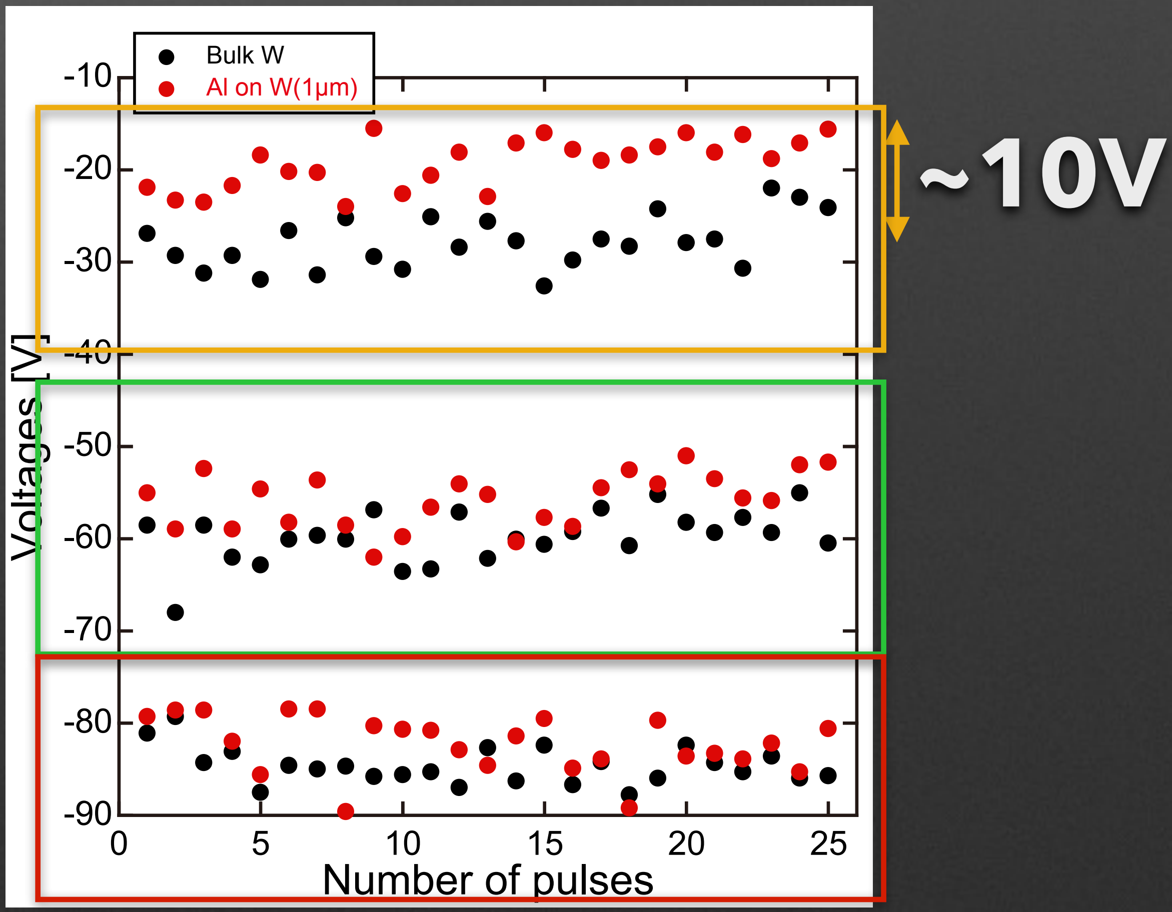

160 A, 1.6 T, 1500V, 10 Hz, 25
0
-20
-40
-60
-80
-100
Voltage [V]
0
0.002
0.004
0.006
Time [sec]
Al on W (1μm)
Bulk W

Target voltage: Al on W



- Comparing pulses in Al on W (1μm), subsequent pulse voltages were shallower than 2nd pulse voltage.
- The difference of surface temperature (≈ IR emission) likely to relate the difference of the voltage.

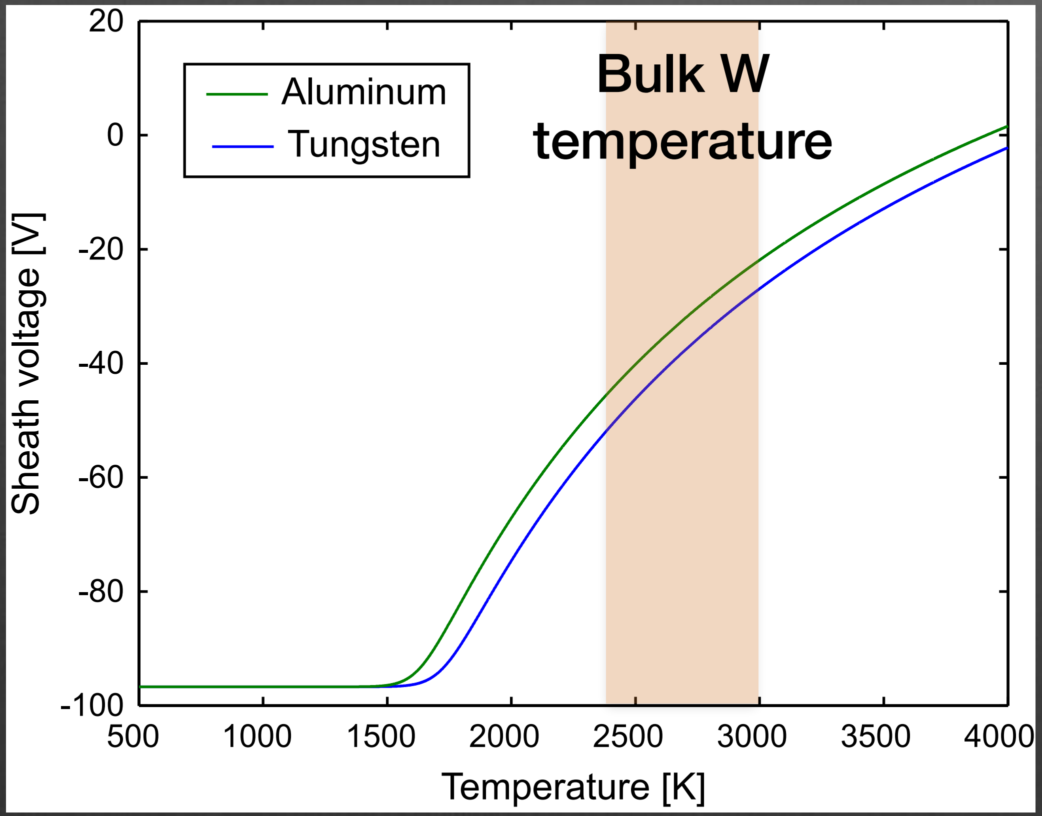
- This figure indicates voltages at each timings. Bottom, peak and after the pulse discharge.
- In peak values, there are differences in these materials.



Discussion of the sheath voltage change

- Calculation of sheath voltage
- Thermo-electron emission depends on work function and temperature of each material

$$e\phi_f = kT_e \ln\left\{ M\sqrt{\frac{2m_e}{m_i}} + \frac{j_{em}^-}{(en_{se}/4)\sqrt{8kT_e/\pi m_e}} \right\}$$



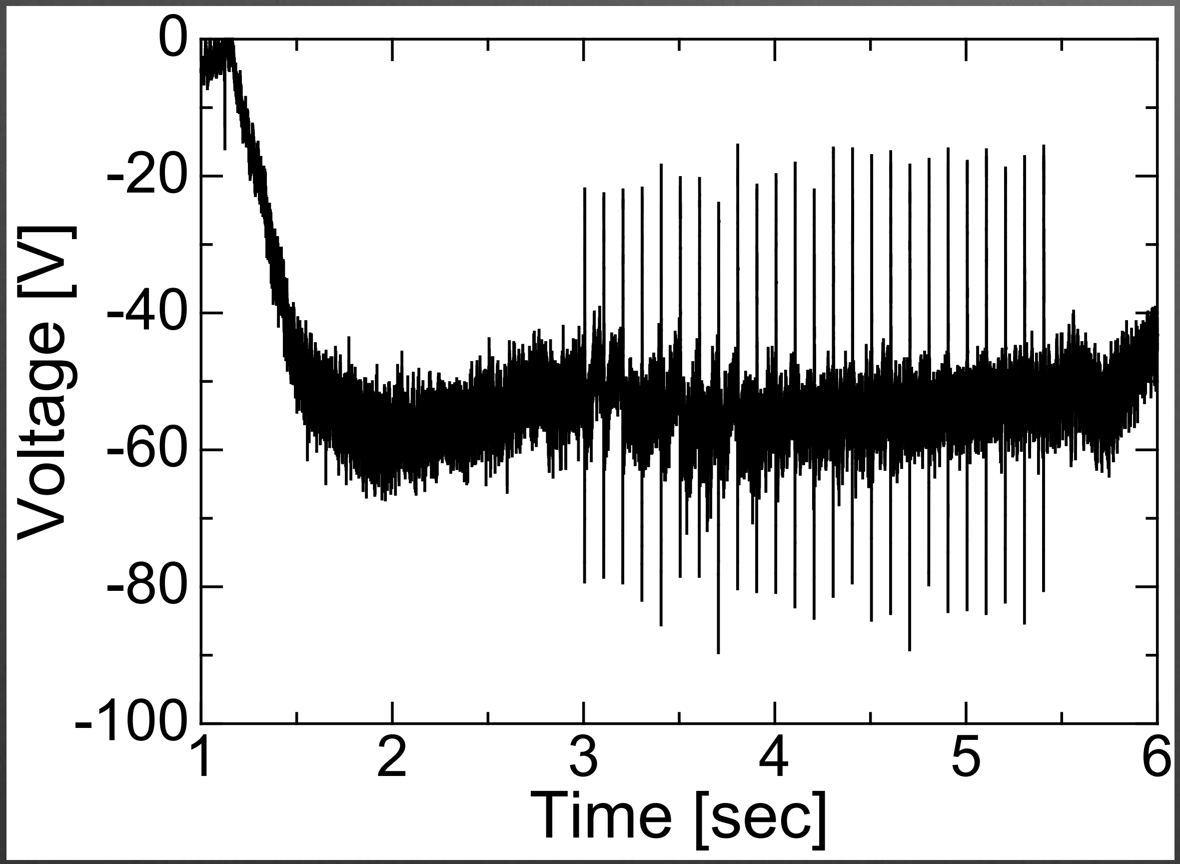
- In the equation, emission current density was assumed only coming from thermo-electron emission.

- Results
  - Aluminum
    - -20 V: 3060 K(2787 deg C)
  - Tungsten
    - -30 V: 2907 K (2634 deg C)

➡ In tungsten, the voltage is good agree with experimental data(2473K~2973K)

Target floating potential: Al on W

- Target voltage (floating) measurement
  - Sample rate: 10 kHz

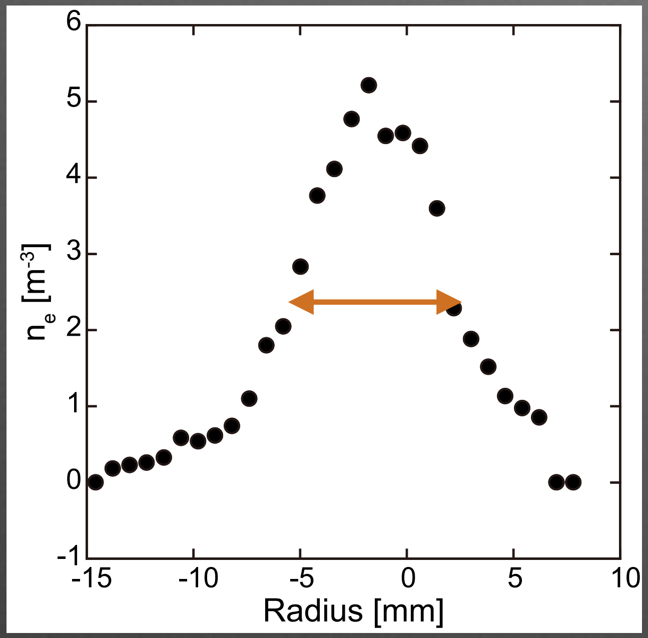


- Figure shows the target voltage of Al on W (1μm) sample.
- Firstly, the sheath was formed by steady-state plasma irradiation.
- These spikes indicate each pulse plasma irradiation.

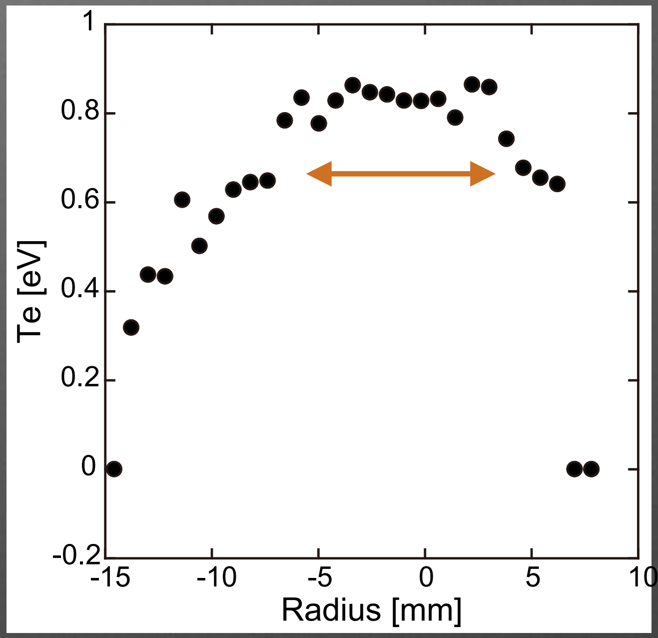
➡ There are 2 way peaks, deeper and shallower

Plasma parameter

- Steady-state plasma parameter
  - Thomson scattering (Source current I: 160A)



FWHM: ~10mm



Stable at the top

➡ Plasma main diameter was smaller than the irradiation area of the samples.

These parameter were measured in this experiment.

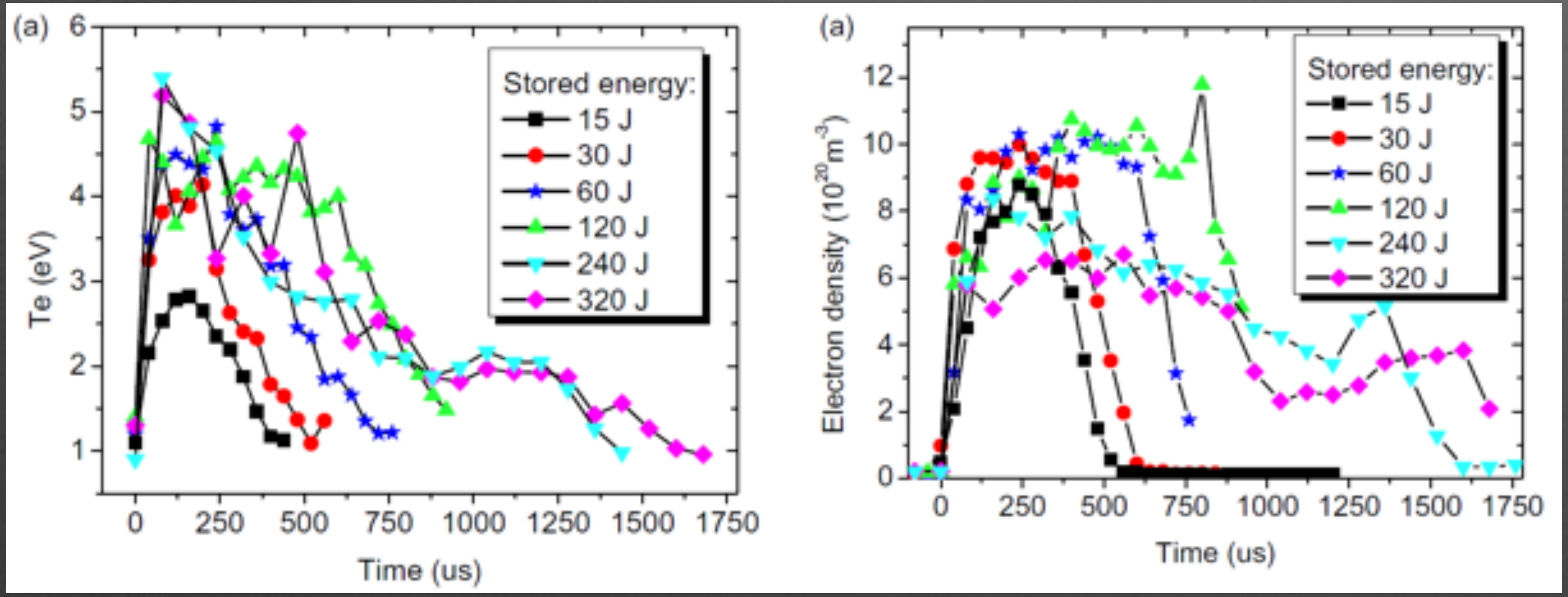
- T_e: 0.6 [eV]
- n_e: 0.79 [$\times 10^{20}$ m^{-3}]

Plasma parameter

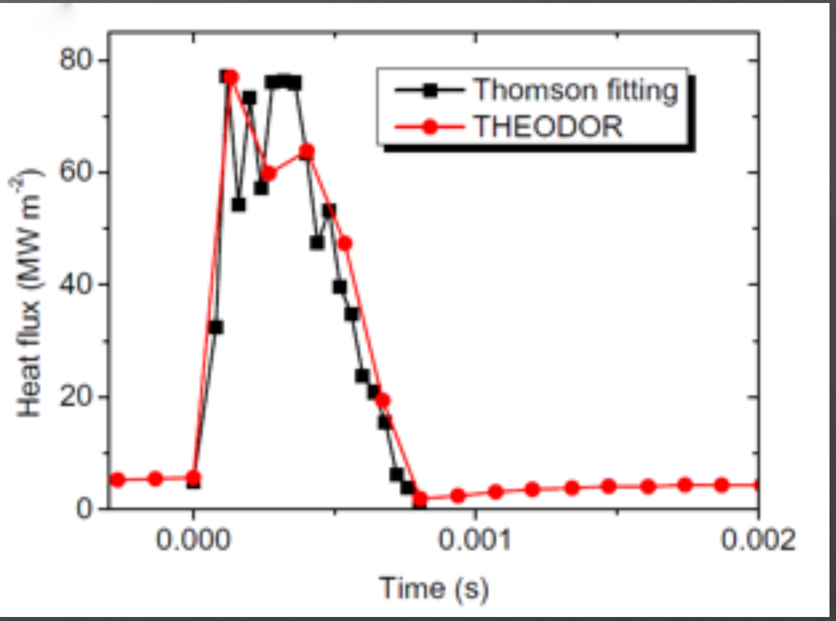
- Pulse plasma parameter (Reference)

➡ Referred by measurement results of Magnum-PSI

Ref.: T W Morgan et al Plasma Phys. Control. Fusion (2014)



These were measured in Magnum-PSI



Comparing plasma heat flux and numerically solved surface heat flux

- Pulse plasma parameter
  - T_e: ~5 [eV]
  - n_e: 10 [$\times 10^{20}$ m^{-3}]
  - Pulse length: ~1 [ms]

$$q = \gamma k_B T_e \Gamma_{se} \approx \left(\frac{2}{3m_i}\right)^{1/2} \gamma n_e (k_B T_e)^{3/2}, \qquad (8)$$

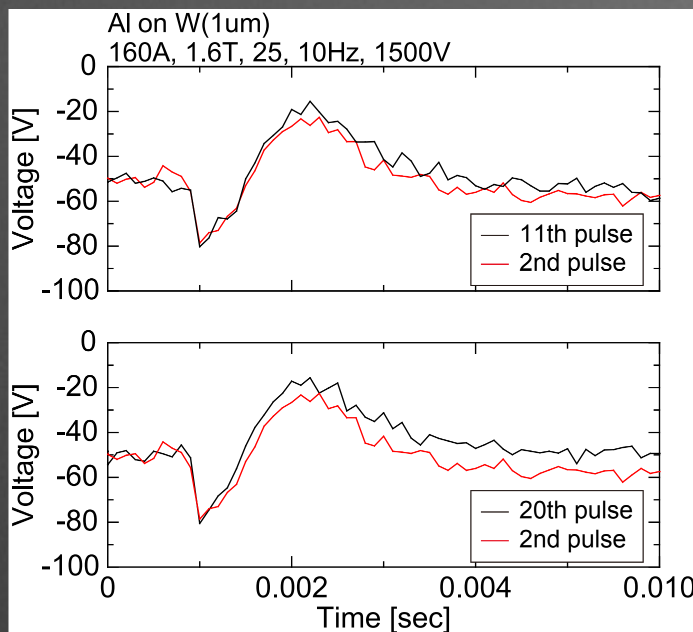
- Heat flux: 110 MW/m^2(γ:7.7)

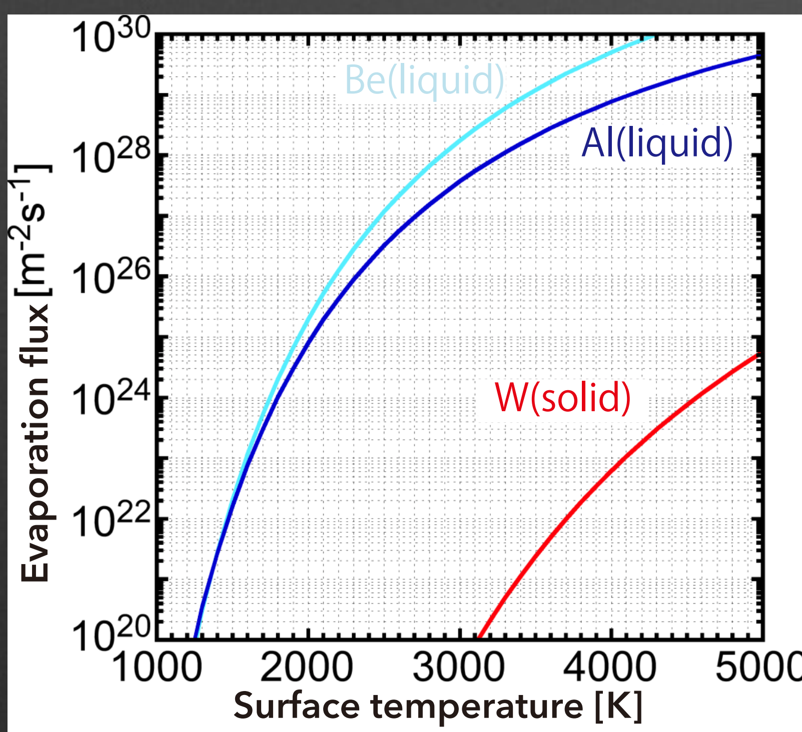
Future work

- Measuring surface temperature/heat flux of film deposited samples
  - To measure surface temperature and to compare each other, lower energy plasma irradiation (peak temperature doesn't reach melting point) is required.
- Measuring the vapor motion by using narrower band pass filter such as 1 nm for Al I: 394.40 nm emission.

Discussion of the sheath voltage change

- Voltage change in subsequent pulse



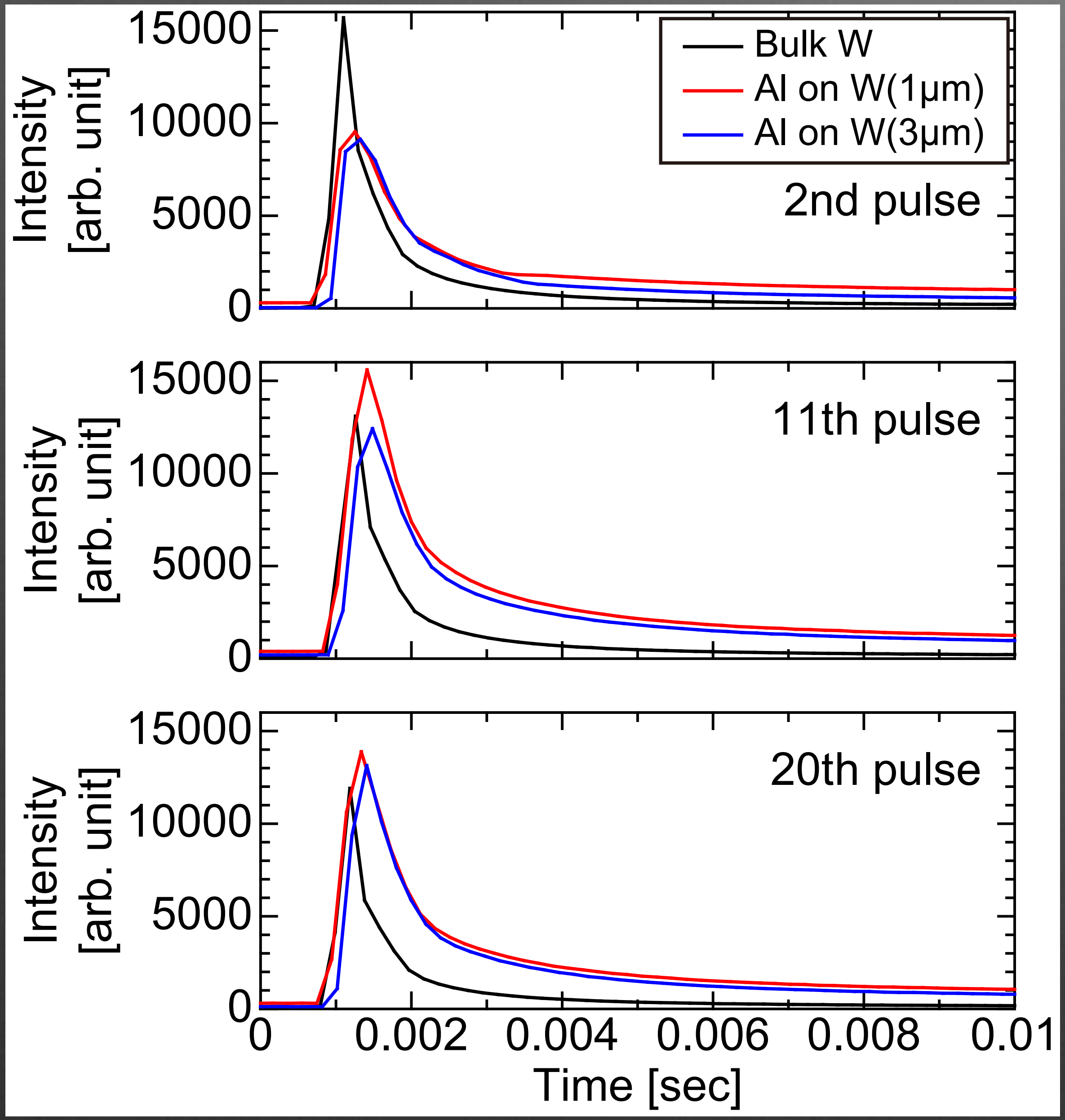


Evaporation flux

- Aluminum has large evaporation flux comparing tungsten around 2000 [K].
- Latent heat or vapor shielding of aluminum may cause the difference.
- In subsequent pulse, the aluminum layer at the irradiation spot had been removed by previous pulse heat load. Therefore, the surface temperature likely to increase and the thermo-electron emission will occur.

IR emission : Al on W

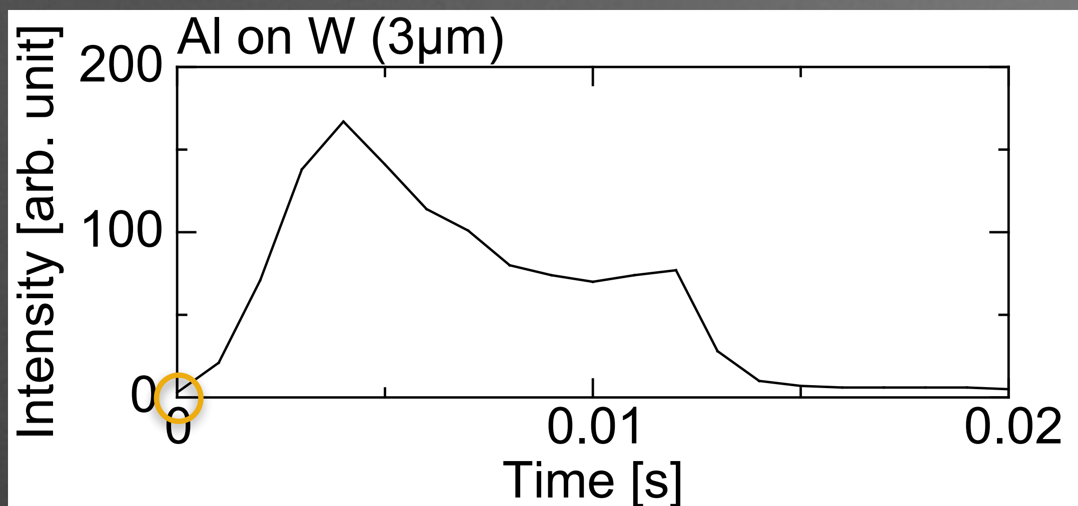
- Compare with 2nd, 11th and 20th pulses

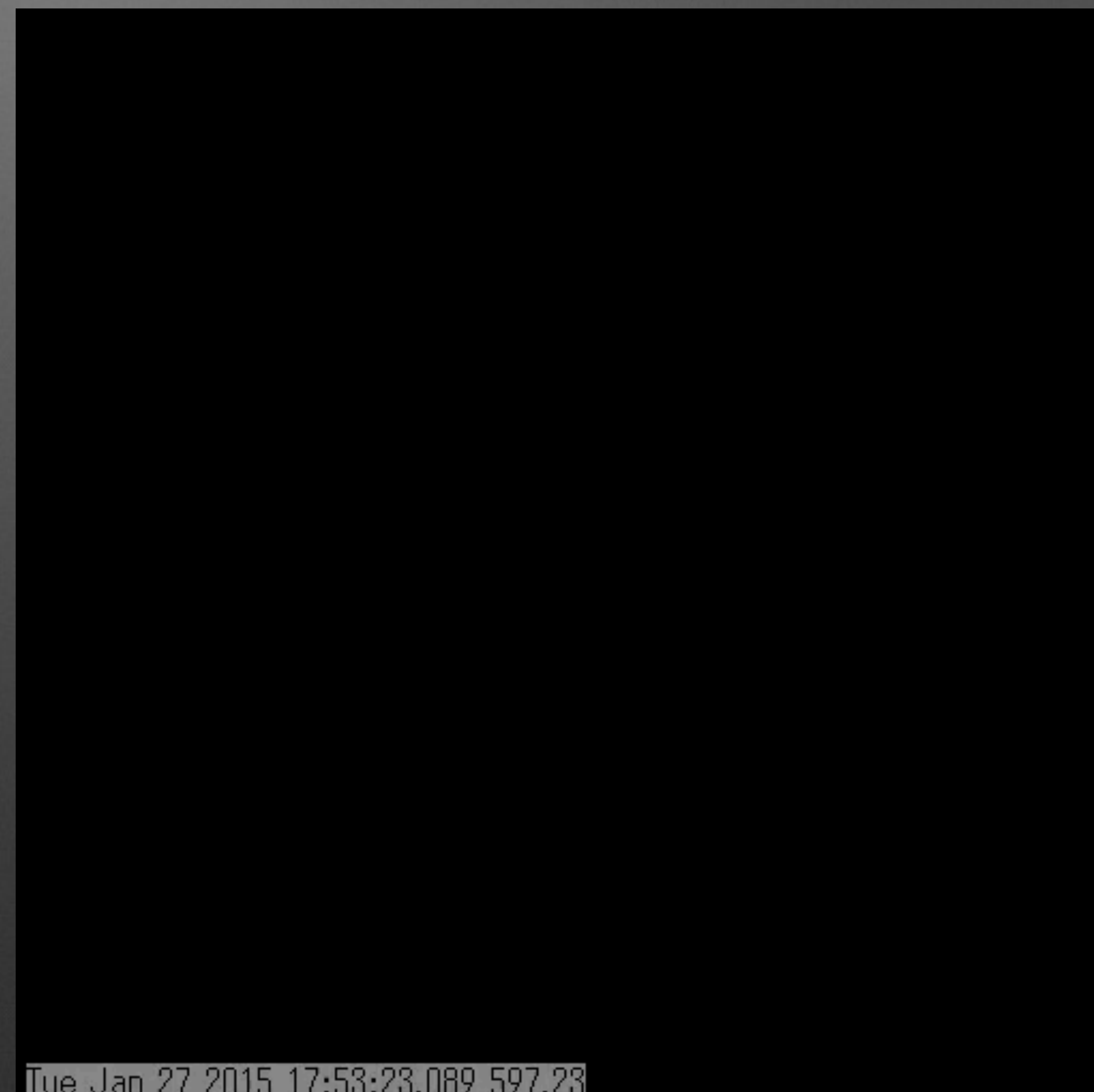


➡ Comparing with other 11th and 20th pulses

Visible camera : Al on W

- Time evolution of photo image on a Al on W sample





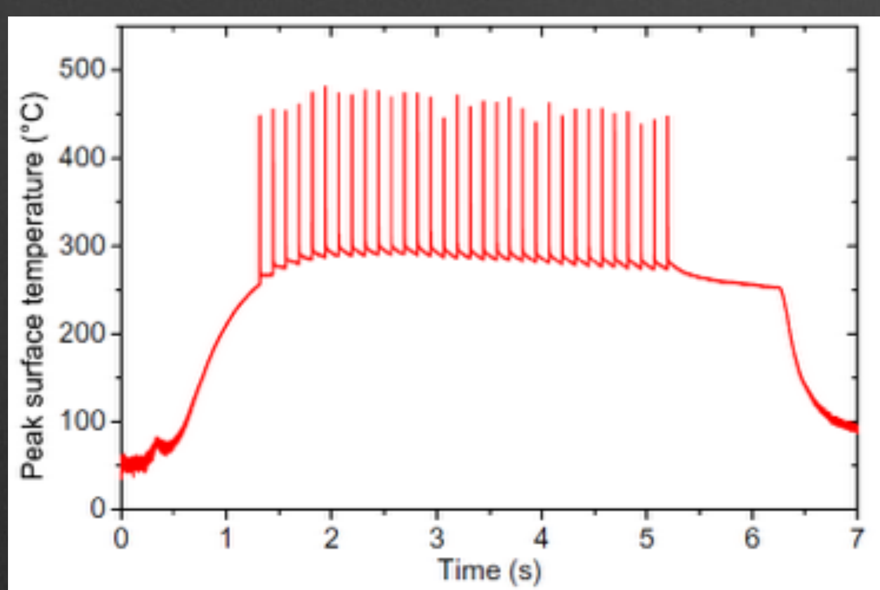
Introduction

- Vapor shielding effect

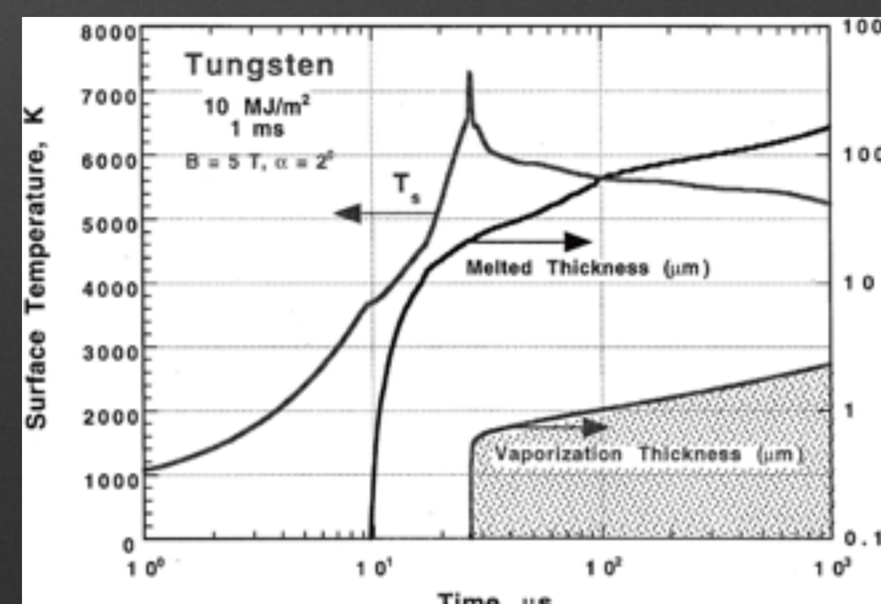
核融合炉において，高温のパルス熱負荷によって炉壁材料が溶融・損耗することが懸念されている．一方で，溶融・蒸発した材料蒸気が後続の熱負荷を緩和する蒸気遮蔽効果がシミュレーション研究等で予想されており，実験的な検証が求められている．

- Necessity of combined plasma irradiation experiment

本研究グループでは，これまで主にパルス熱負荷に着目して核融合炉壁の健全性評価としてプラズマ照射実験を行ってきたが，本来の核融合炉の状況を加味すると，定常負荷がある状態での実験的検証が求められる．



Ref.: T W Morgan et al Plasma Phys. Control. Fusion (2014)



Ref.: A Hassanein at el J. Nucl. Mater. (1999)