International Workshop on Breakdown Science and High Gradient Technology
(April 19, 2012 in KEK)

Ignition of unipolar arcing on nanostructured tungsten

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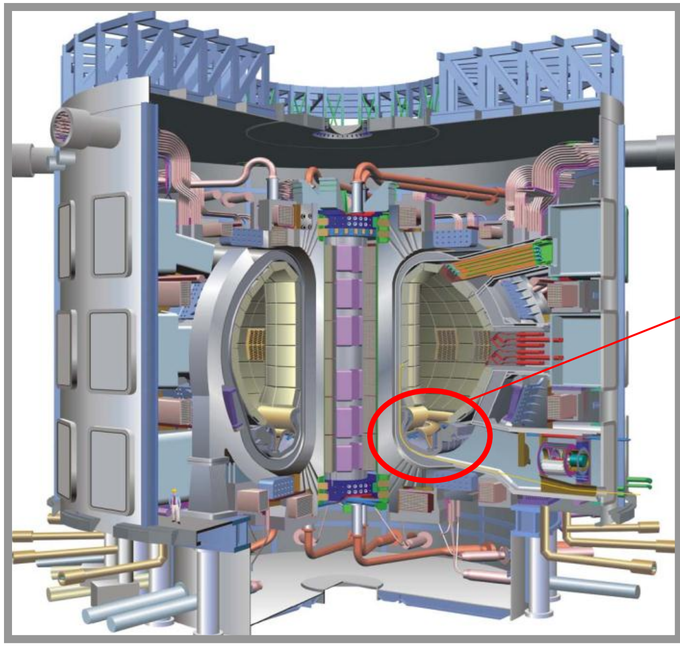
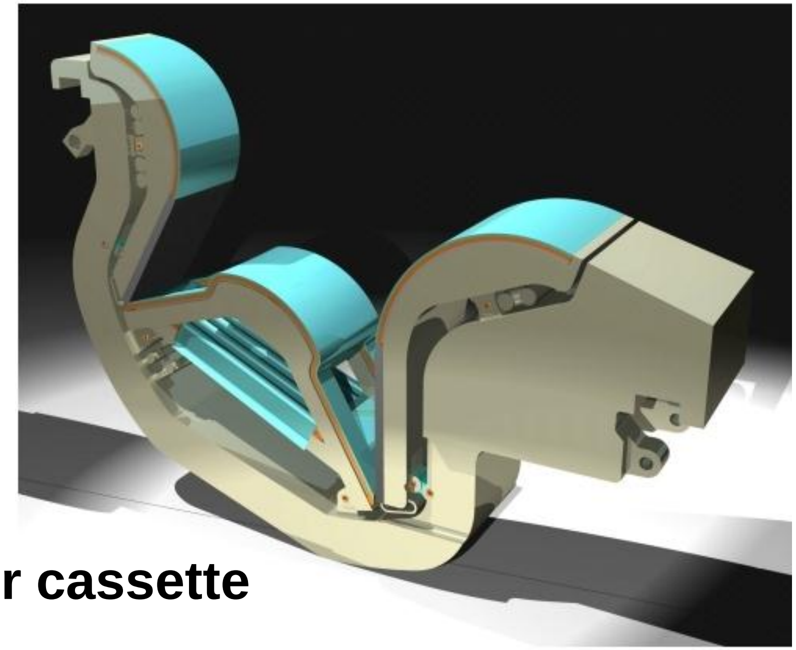
Nuclear Fusion Experiments: ITER



Divertor region



Divertor cassette

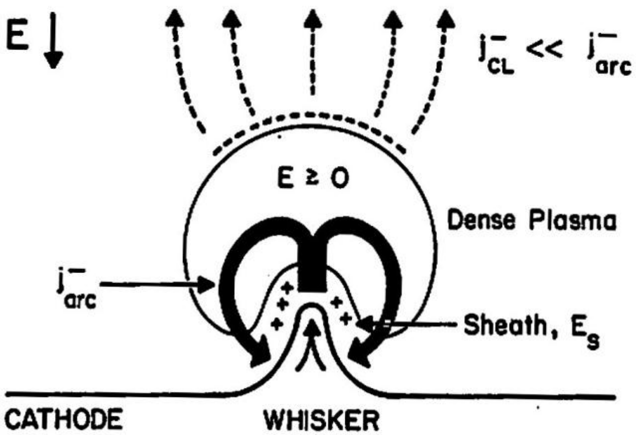
- **France, Cadarache**
- **EU, India, Japan, Korea, Russia, US**
- **First plasma will be produced in 2019.**

- **Material in fusion reactor are (tungsten) will be subjected to a high heat load, ~10 MW/m^2.**
- **And also exposed to the transient heat load. In ITER, ELMs (Edge Localized Modes) heat load is expected to be 0.5 MJ/m^2 for 0.1-1 ms.**

Arcing issue in fusion devices
- longstanding PSI issue -

•**Arcing has been extensively investigated in 1980s in tokamaks.**

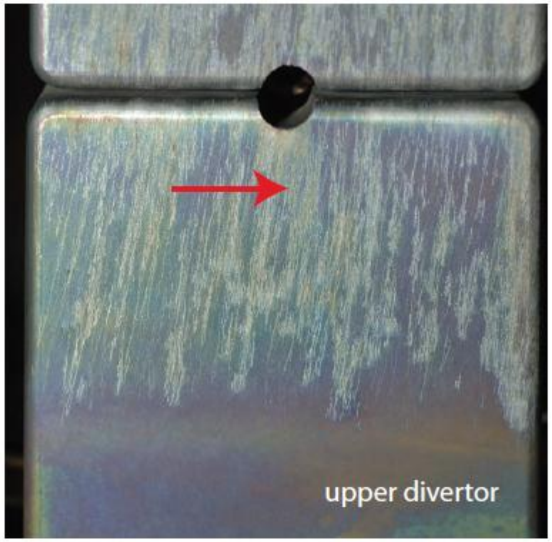
•**Mechanism: unipolar arcing**



Schwirzke, IEEE Trans. Plasma Sci. (1991)

•**Anode and cathode exist on a plate.**
•**Electron release from cathode spot**
•**Current loop is formed within one plate**

ASDEX-U



Rohde, 19th PSI conference, 2010, San Diego

•**Although, afterward, arcing was thought to be a minor issue, revival of arcing could be brought up from new aspects:**

-Pulsed heat load accompanied with ELMs

-Surface morphology change by plasma irradiation

The problem in fusion device:
Morphology change by fusion product helium

D-T nuclear fusion process

D + T ➔ He (3.5 MeV) + n (14.1 MeV)

Concentration will be up to 10% in divertor.

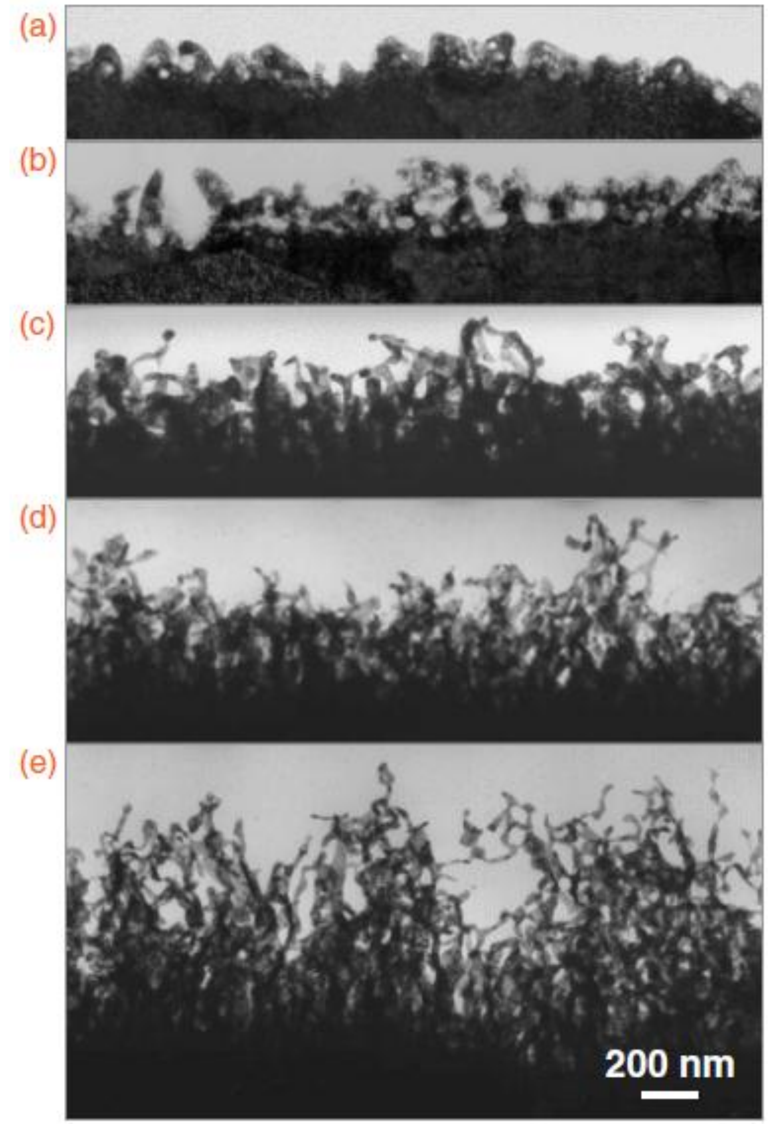
formation condition of the fiberform nanostructure *(fuzz)*
Temperature: 1000 K < T < 2000 K
Incident ion energy: >20 eV

By the nanostructure formation

•Field electron emission is enhanced.

•Thermal diffusivity is significantly decreased near the surface ➔ anomalous surface temperature increase in response to transient heat load.

S. Kajita, *et al.* Nucl. Fusion **47** (2007) 1358.
S. Kajita, *et al.* Nucl. Fusion **49** (2009) 095005.



S. Kajita, Appl. Phys. Exp. (2010)

Pulsed heat load and plasma irradiation to W

Damaged by the plasma irradiation + **Transient heat load** = ??

We performed laser irradiation experiments by using W exposed to helium plasma.

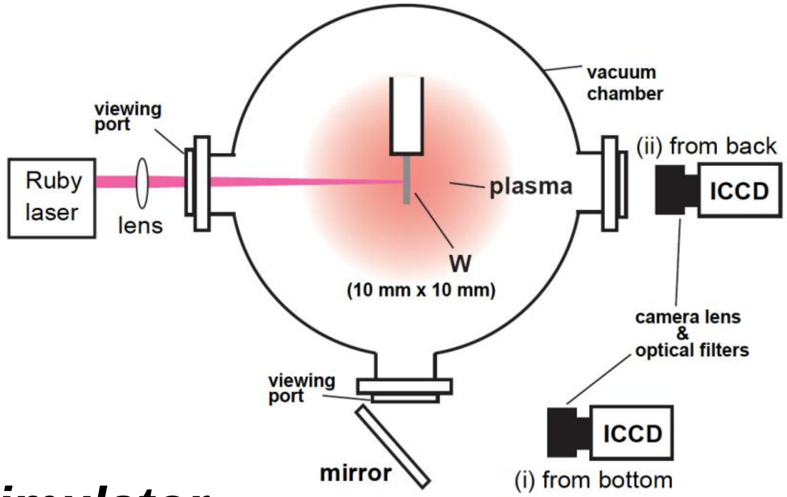
•Pre-irradiation of Helium

⇒formation of nanostructure

•Ruby laser irradiation

(0.6 ms, 5 MJm^{-2})

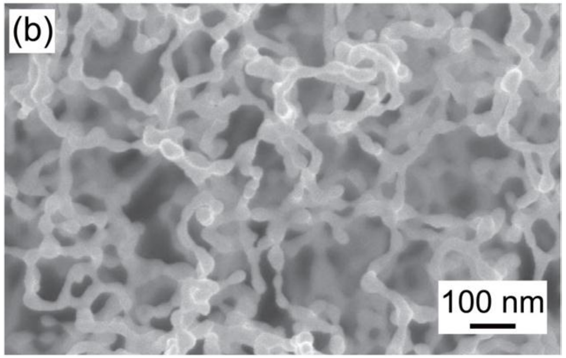
Similar as the type-I ELMs in ITER



Divertor simulator NAGDIS-II

n_e>10^{18}-10^{19} m^{-3}

T_e~5-15 eV



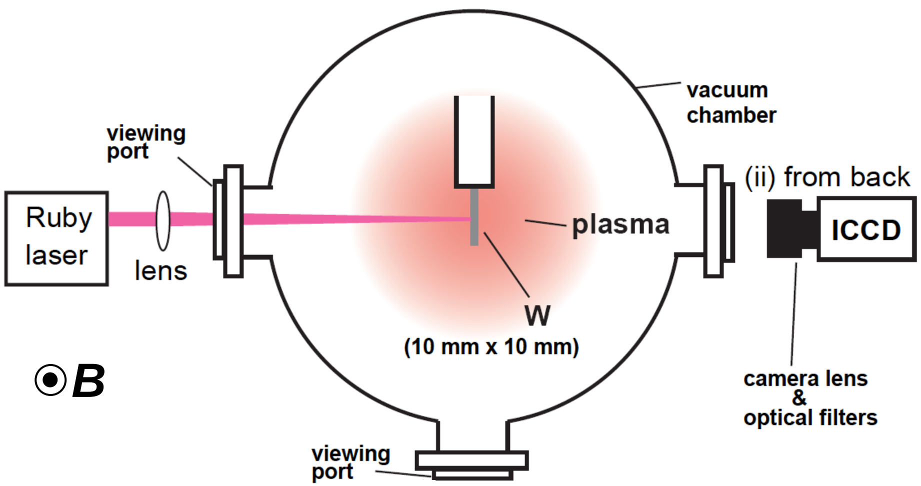
An arcing observed from backside

- **Arc spot moves freely in retrograde (-jxB) direction.**

From back

30 000 fps

(1 frame 33 μs)



Backside of the surface ➔

Arc trail was recorded clearly on the surface

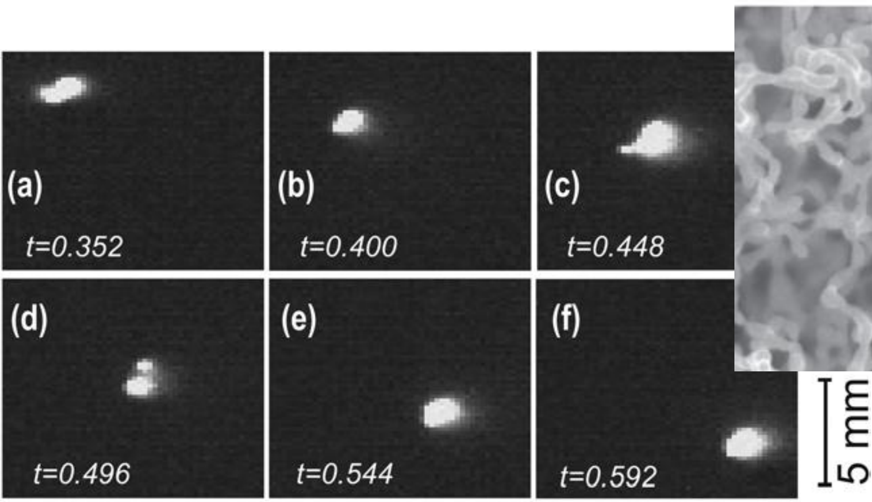
Note that the electrode is biased in this case.

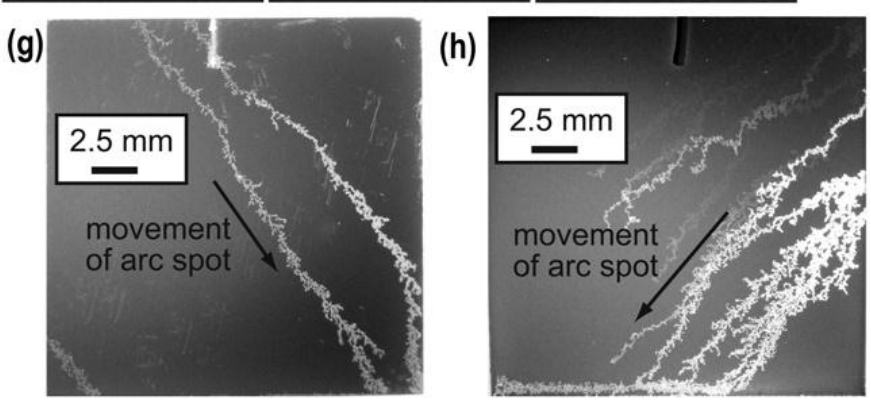
Observed from front side (laser irradiated side)

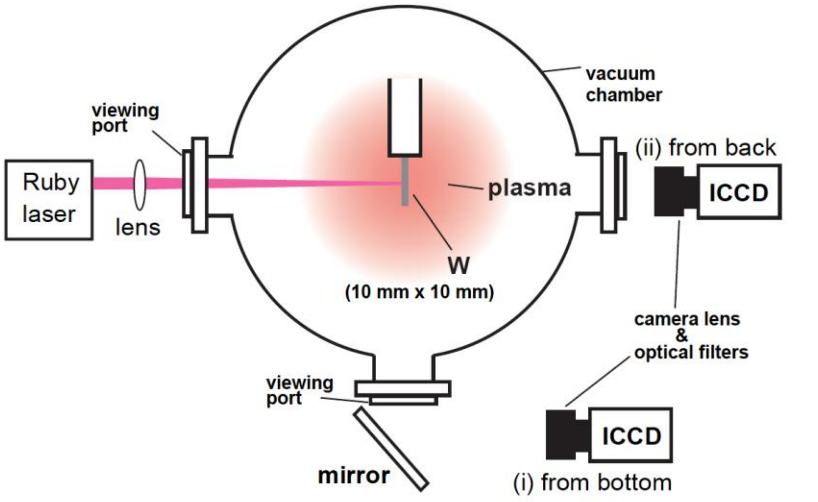
Arcing (biased). Frame rate: 1 000 000 fps

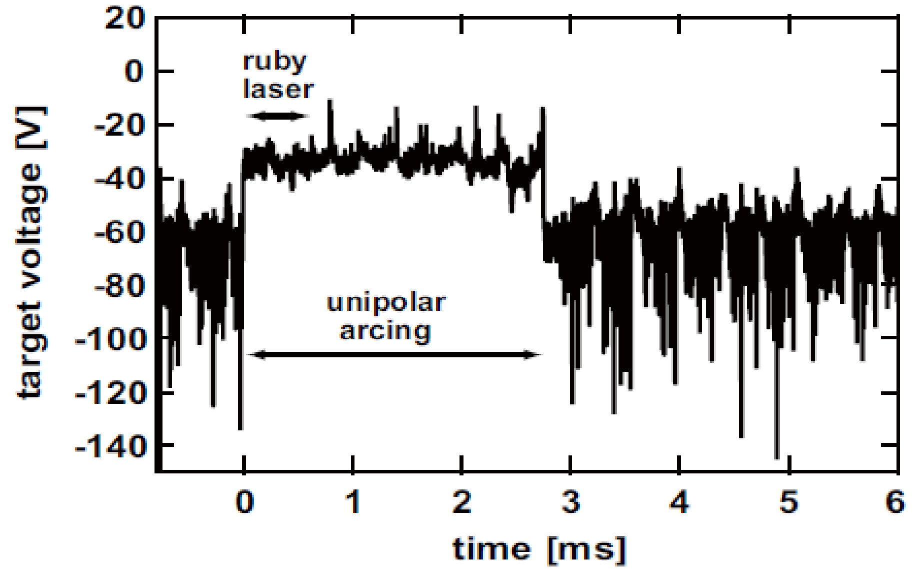
Critical evidence of unipolar arc (UA)

- Demonstration of ELMs on nanostructured W using laser.
- UA is confirmed from the jump of the floating potential.



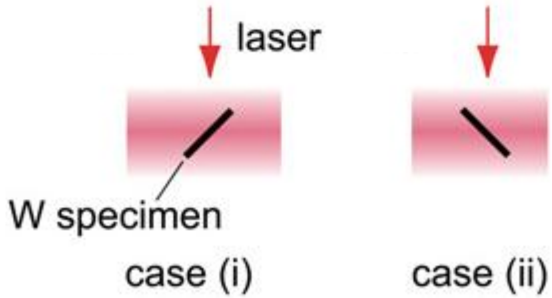




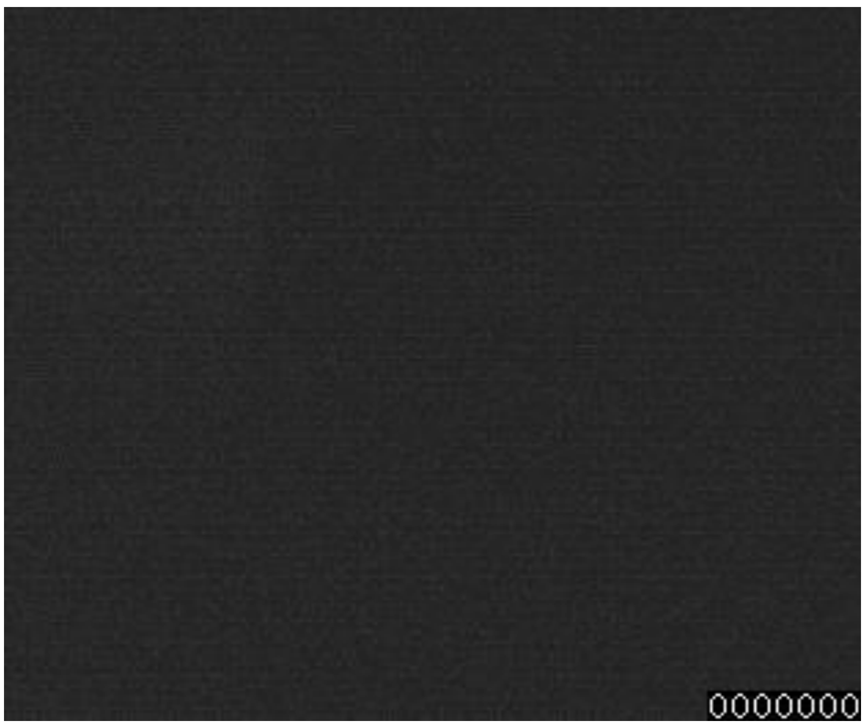


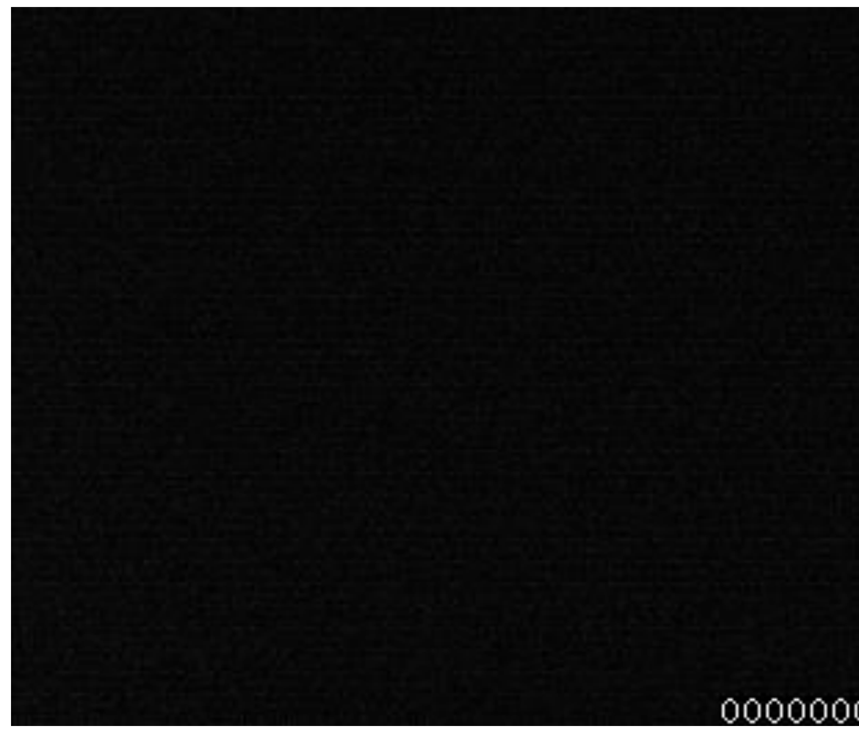
S. Kajita *et al.* Nucl. Fusion (Letter) (2009)

Arc spot motion in oblique magnetic field:
the arc spots rotate around the electrode



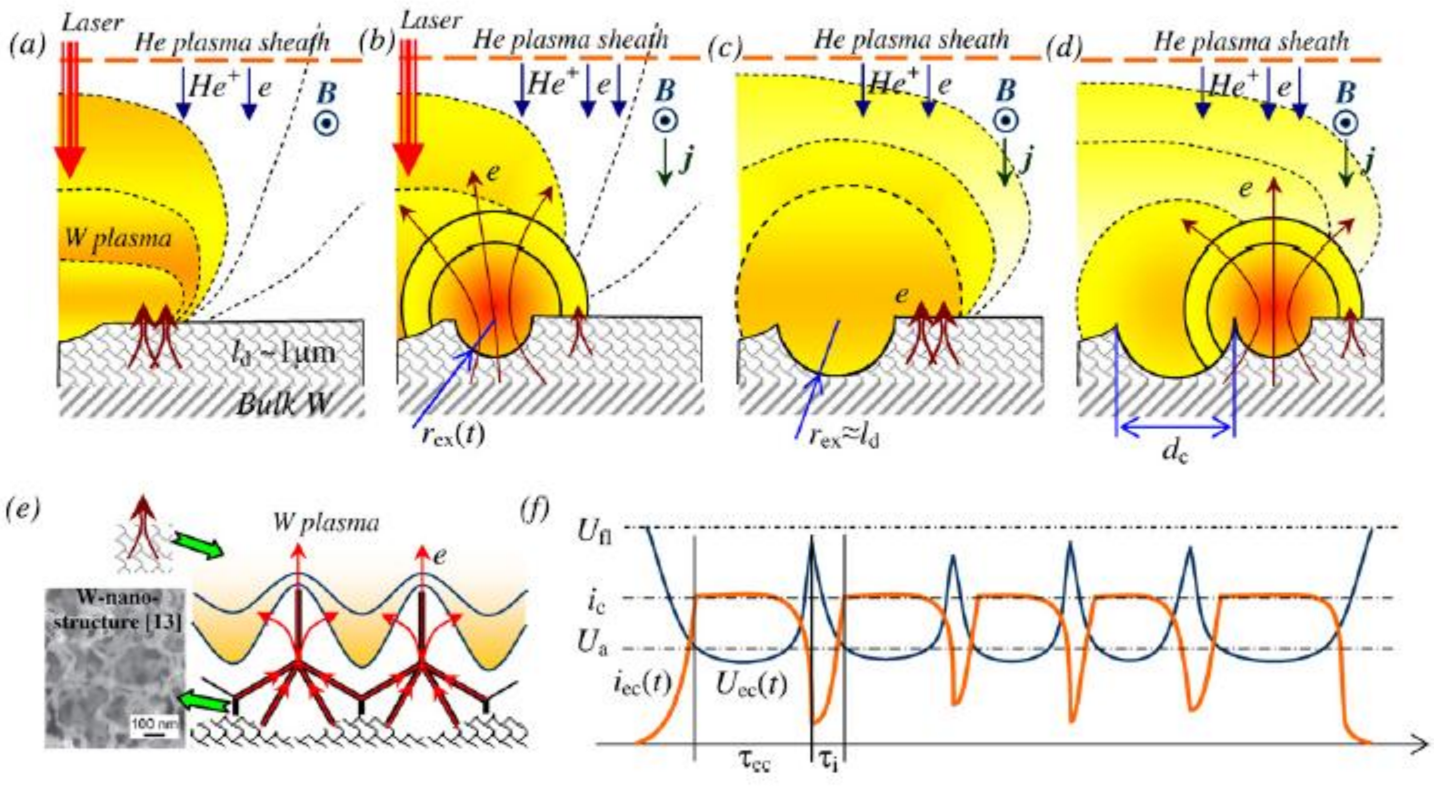
•**Arc spot moves globally to the direction determined by the axial and parallel magnetic fields.**





Ecton mechanism of unipolar arcing

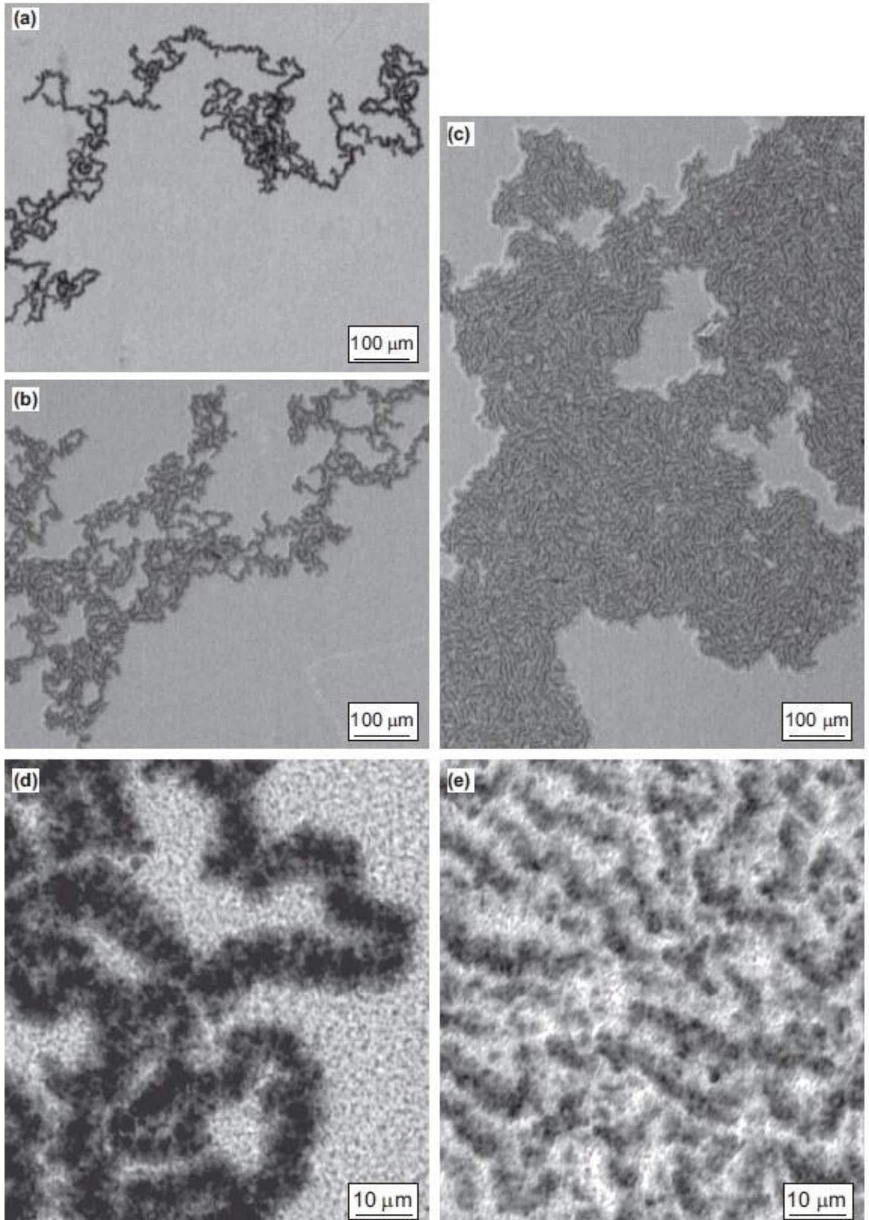
The unipolar arcing on the nanostructured W was explained using Ecton mechanism (Explosive electron emission process).

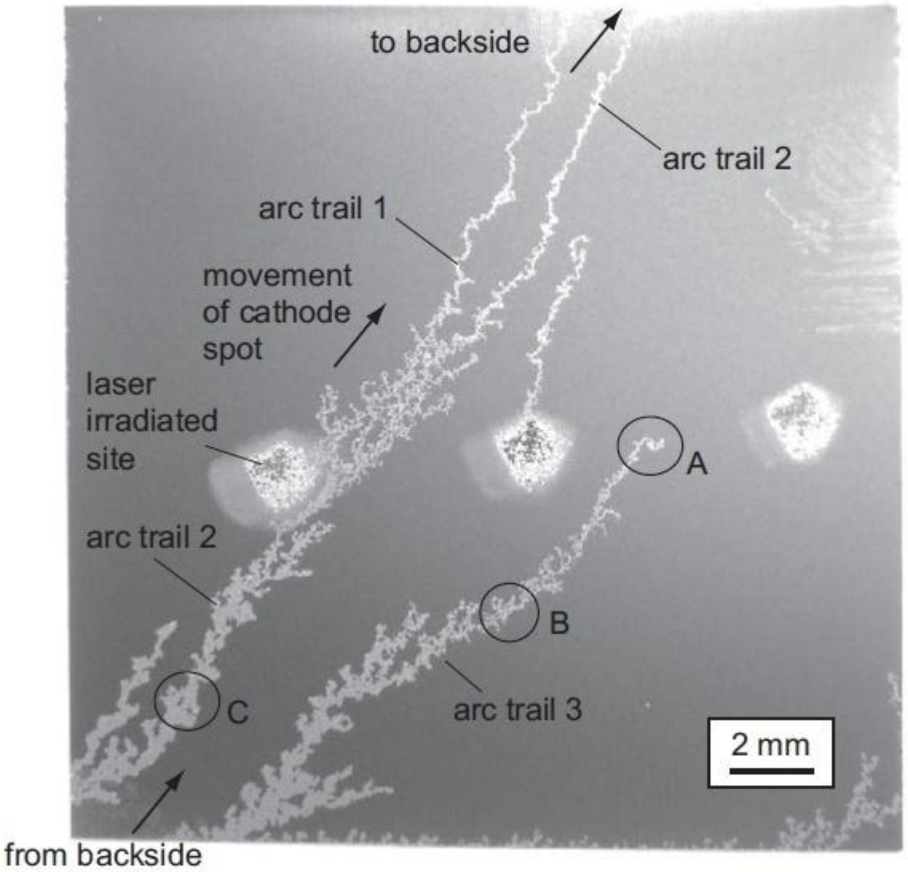


S.A. Barengolts[1], G.A. Mesyats[2] and M.M. Tsventoukh[2]

Nucl. Fusion **50** (2010) 125004 (6pp)

arc spots form a group and move together



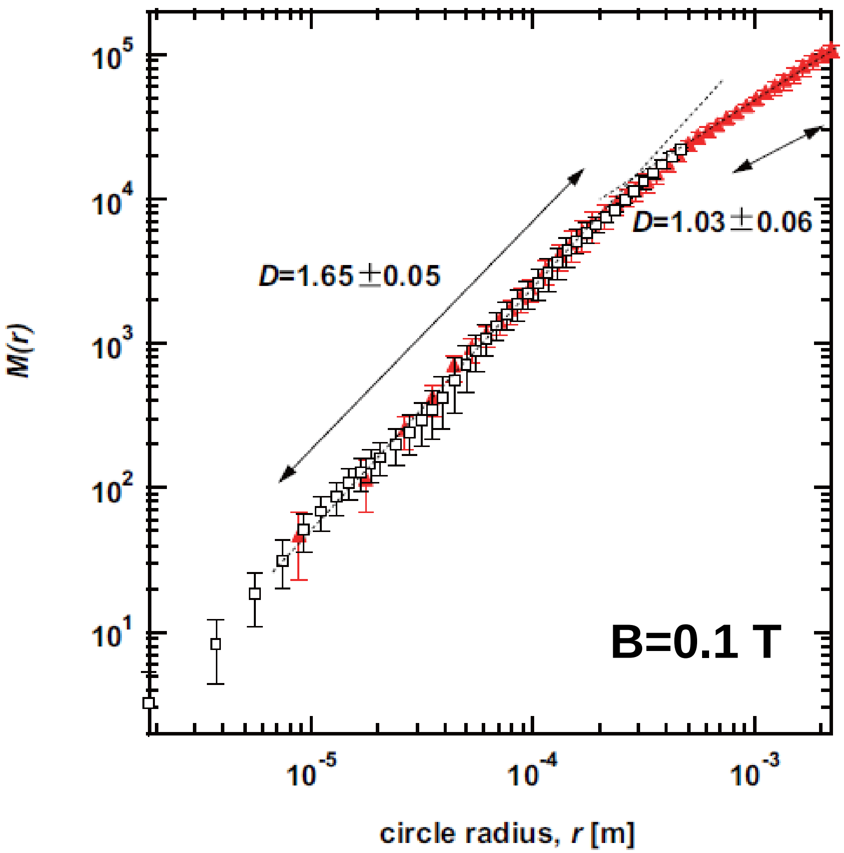


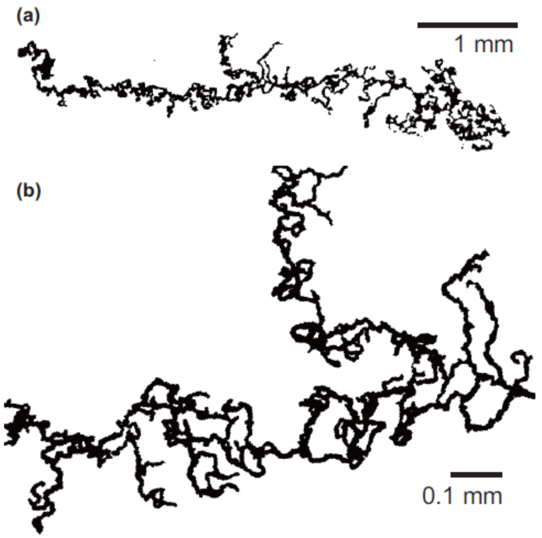
- **Arc spot moves along with retrograde direction + acute angle rule.**
- **Arc spot of ~10 μm moves with forming group.**

S. Kajita *et al.* Phys Letter A (2009)

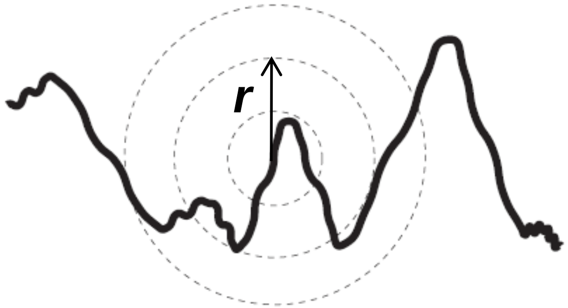
Fractality of trail under magnetized condition

- self-affine fractal (scale depends on direction) -





Digitized SEM micrographs of arc trail.



- **From the distribution of the dots in radius *r*, the number of dots represents fractality locally, but not globally.**

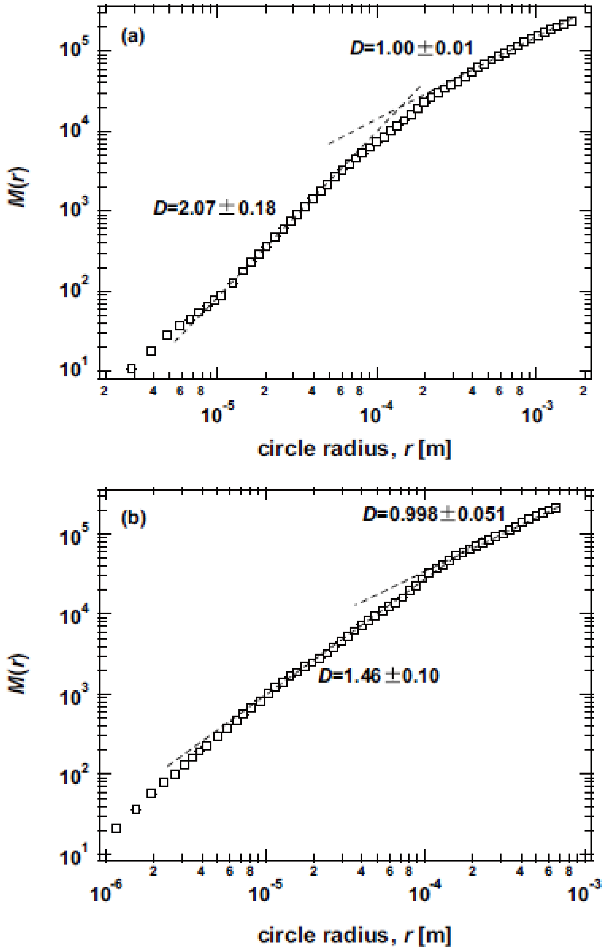
➔ self-affine fractality

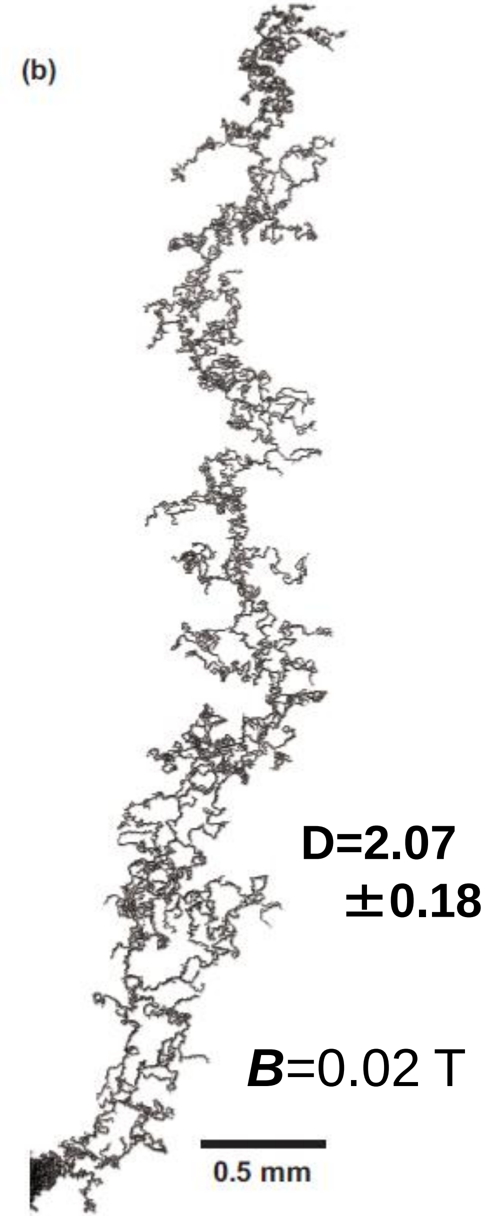
Locally: random motion

Globally: linear motion due to magnetic field

S. Kajita *et al.* J. Phys. Soc. Jpn. (2010)

Fractality decreases with *B*

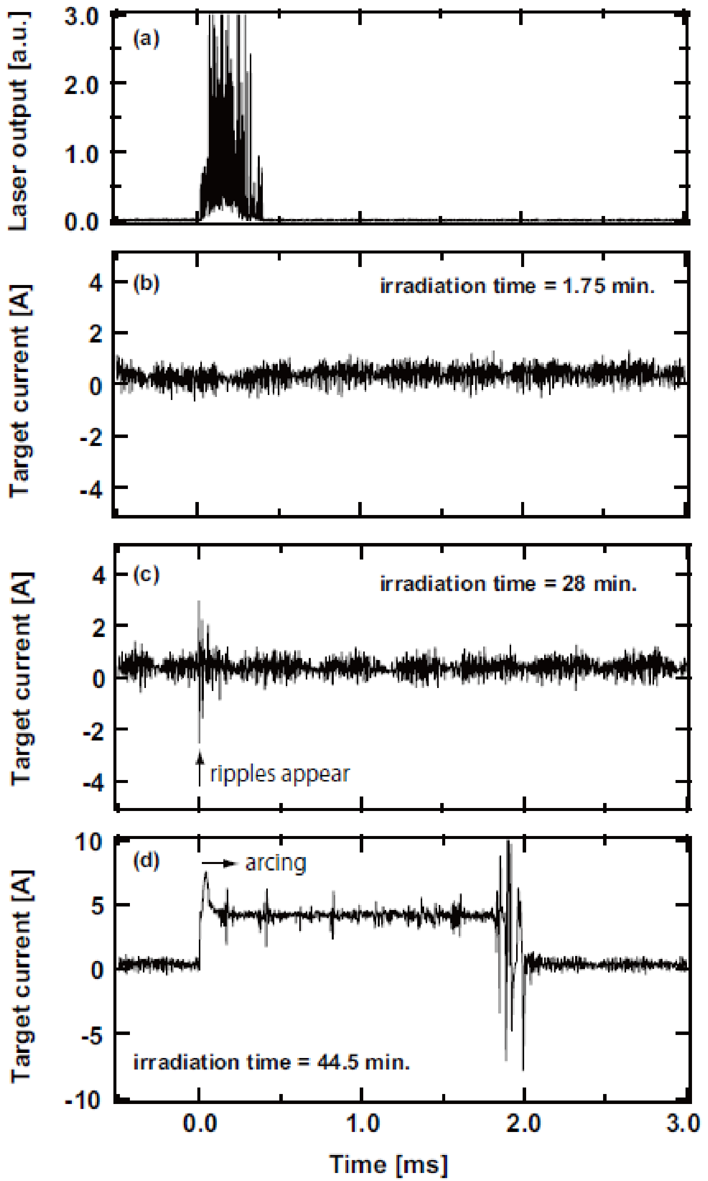


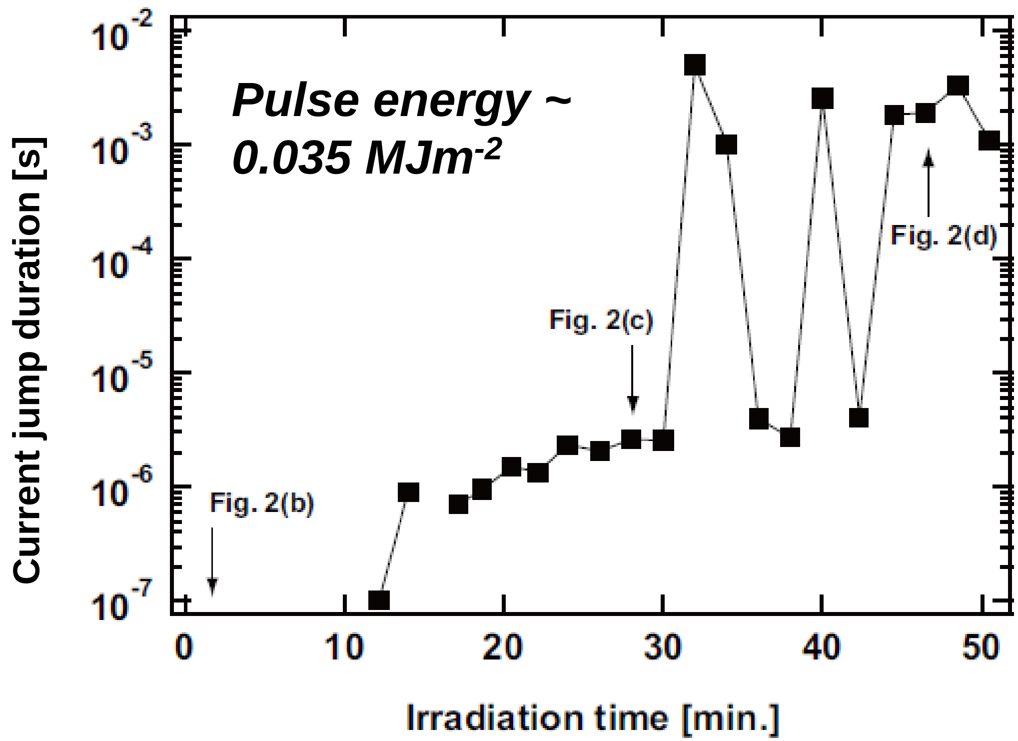


- **Local fractal dimension *D* was 2.07±0.18 at B=0.02 T, but decreases to 1.46±0.10 at 0.2 T.**

S. Kajita *et al.* Plasma Phys. Cotrol. Fusion (2011)

Ignition condition I: He Fluence dependence





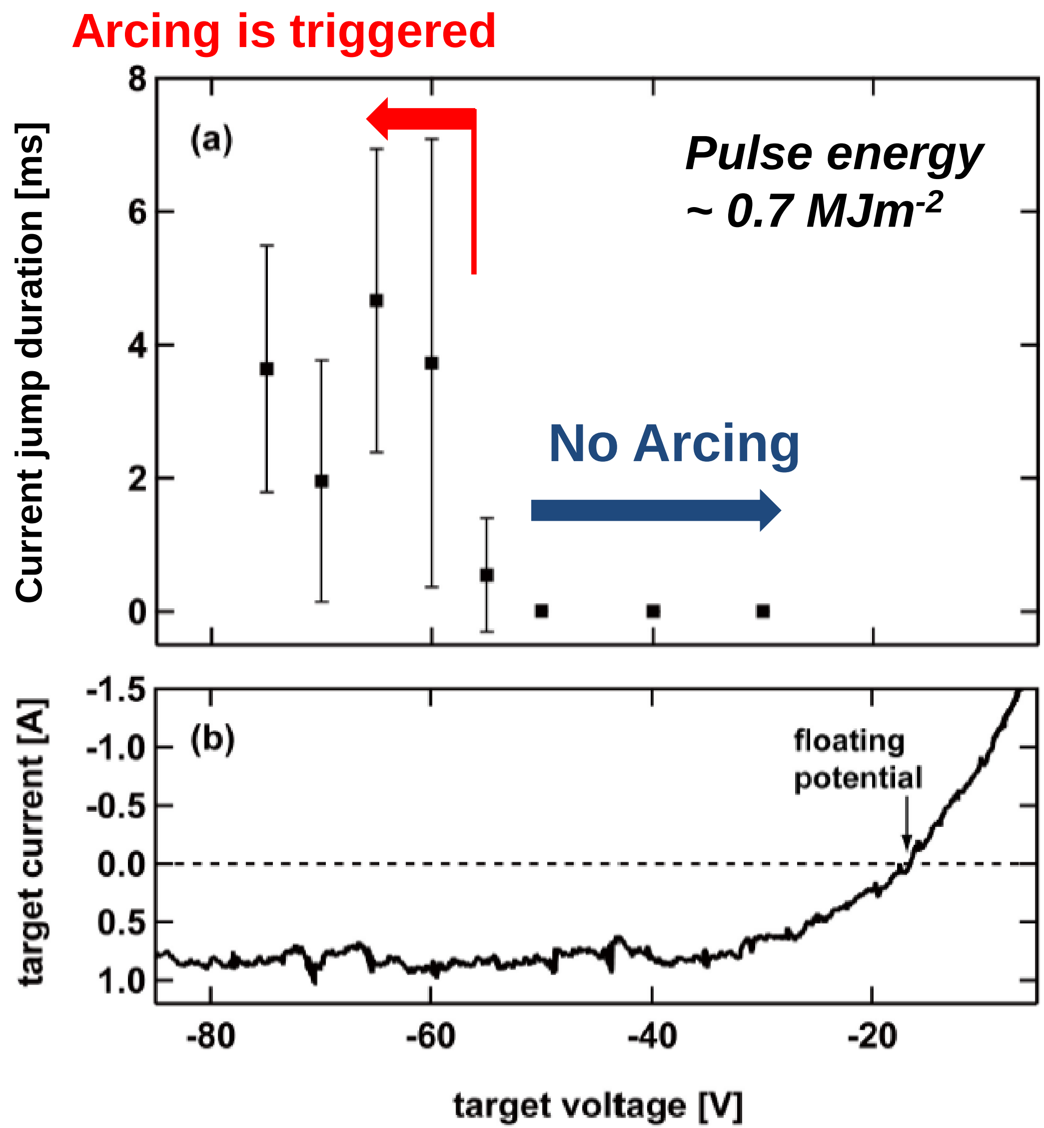
- ***Laser position is changed shot-by-shot.***
- **Current jump duration increases with helium fluence, and arc was initiated when >3x10^{25} m^{-2}.**

From additional exp: necessary fluence decreased as increasing the laser pulse energy.

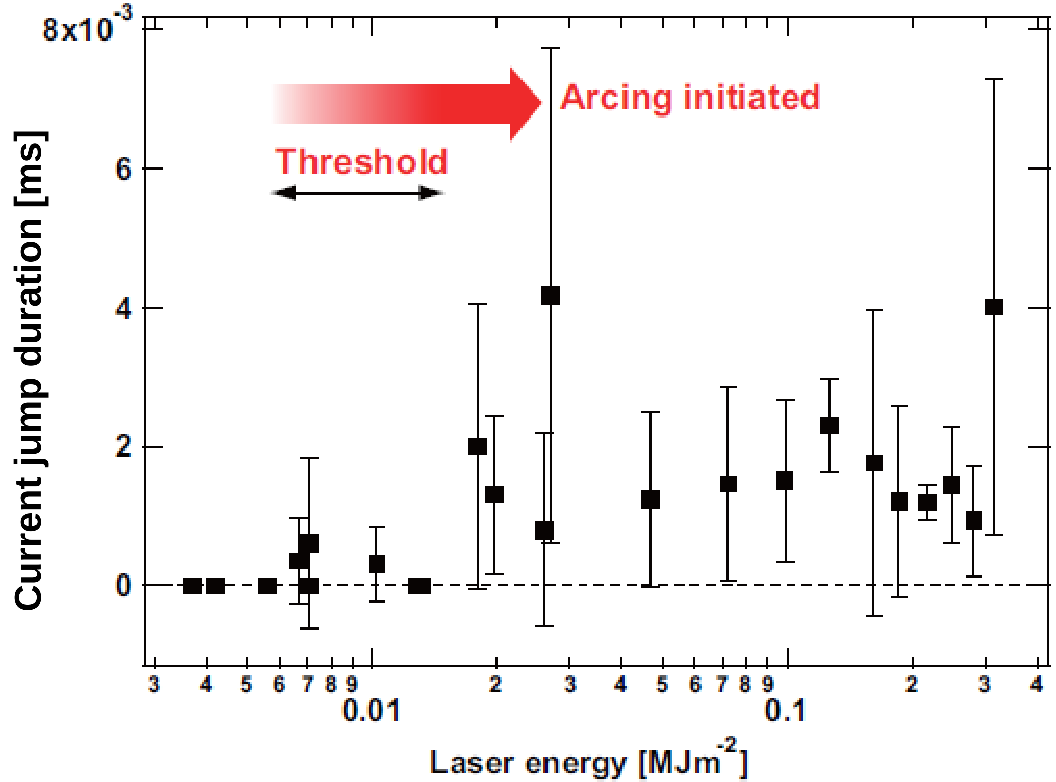
Ignition condition II: Target potential is important factor to trigger arcing

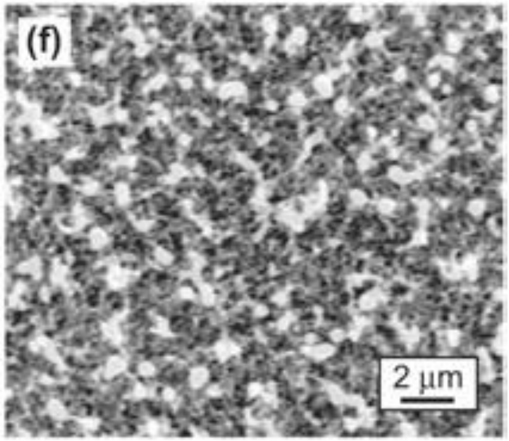
•Arcing is never triggered when the target voltage is higher than -55 V, but constantly triggered when the biasing voltage is sufficiently low (here, -60 V, **which is sufficiently lower than the floating potential of -18 V!**).

•Arcing might be suppressed if we could control the target potential.



Ignition condition III : laser power dependence Threshold is VERY LOW on nanostructured W





Nanostructure can melt even at 0.1 MJm^{-2} because the thermal diffusivity significantly decreased. (Kajita, NF(2007))

・When the nanostructure is formed on the surface, arcing is initiated with very a low power pulse.

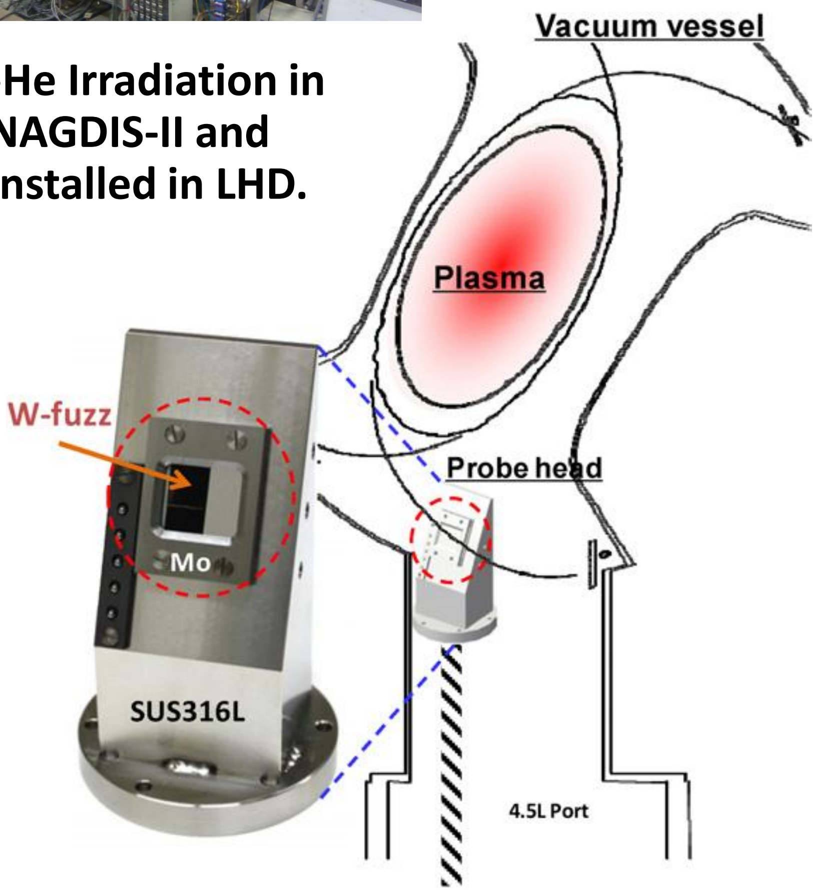
・The threshold power is ~0.01-0.02 MJm^{-2}, which is much lower than the typical TYPE-I ELMs in ITER (~1 MJm^{-2}).

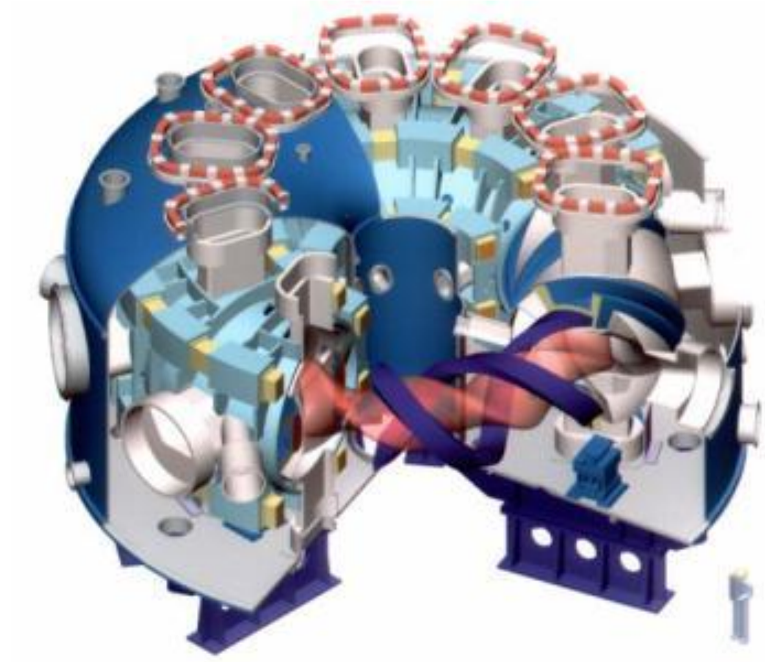
S. Kajita, et al., Plasma Phys. Control. Fusion **54** (2012) 035009.

Fuzz-W exposed to the LHD plasma

T : 1460K
Γ : 1.2×10^{22} /m²s
Fluence : 2.2×10^{25} /m²
Energy : 57eV

-He Irradiation in NAGDIS-II and installed in LHD.

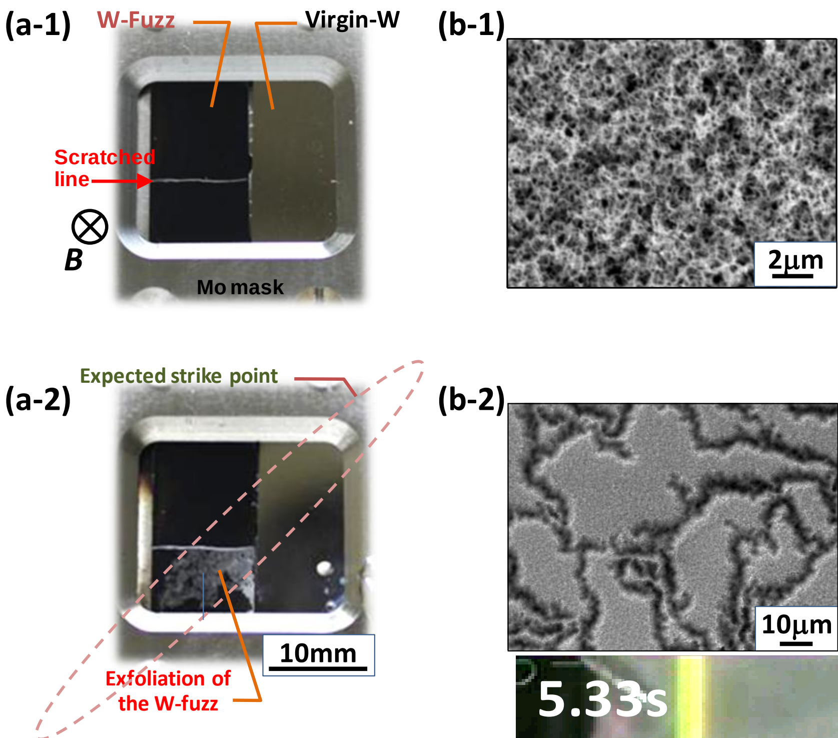


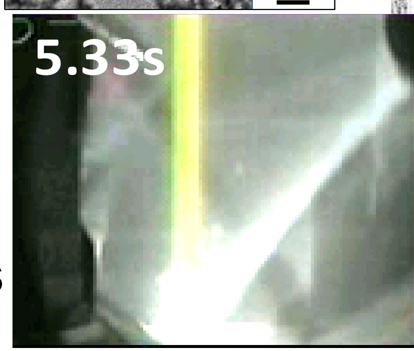


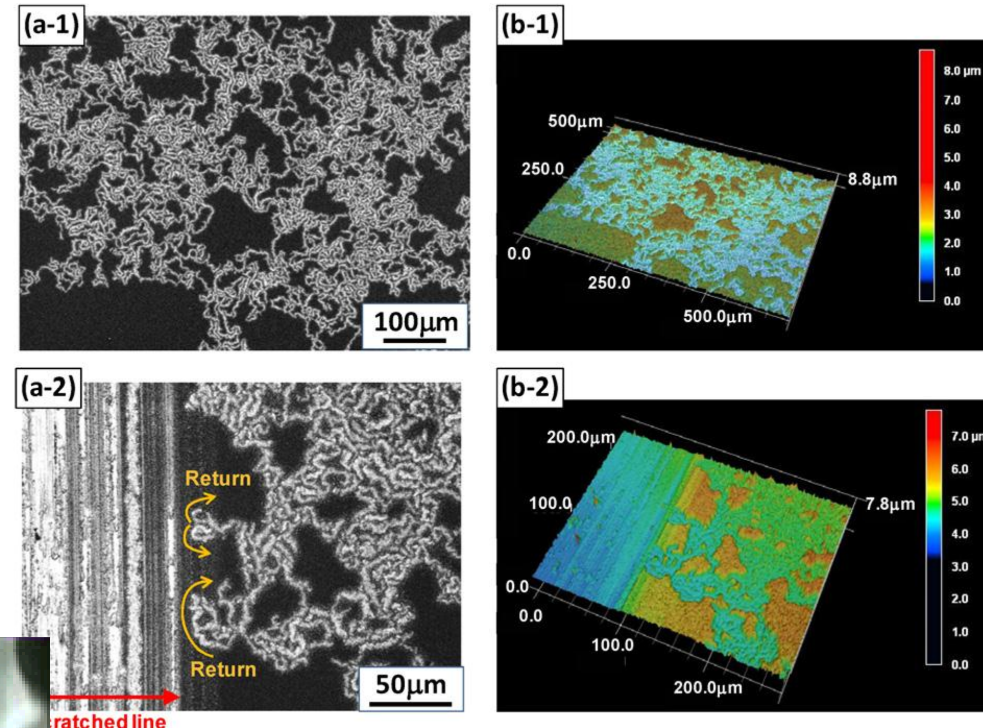
LHD : Large Helical Device
(@Gifu, Japan)

Outer diameter of the machine	13.5m
Toroidal plasma diameter	Approx. 8m
Poloidal plasma diameter	1.0 to 1.2m
Magnetic field Bo/Bmax	3/6.6T

Arc trail analysis: Brownian like motion of arc spots was observed







-Exposed to the LHD plasma for 2s.

-bright emission was observed.

-Nanostructure disappeared in some part. Arc trail was clearly recoded on the surface.

-This results strongly suggest that arcing can be easily initiated when the nanostructure is formed on the surface even without transients.

M. Tokitani *et al.* Nucl. Fusion 51 (2011) 102001.

conclusion

- Unipolar arc was initiated on the nanostructured W surface in steady state plasma environment.

- From fundamental arc experiments, it is found that arcing can be initiated under the fusion relevant conditions when the surface is covered with nanostructures. The ignition conditions were investigated in terms of the helium fluence, laser power, (plasma density, target potential).

- The initiation of arcing on the nanostructured W has been demonstrated in LHD. Arcing was initiated without transients.

- Arcing could be an important issue in future fusion devices. It is important to reveal the initiation process and mechanism and find avoidance or mitigation strategies.