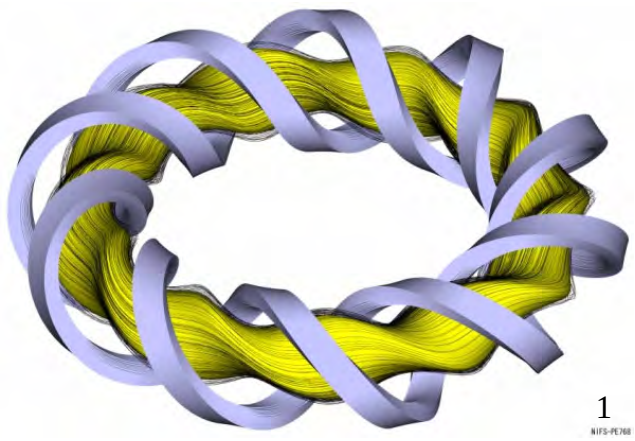
IAEA Technical Meeting on Long-Pulse Operation of Fusion Devices, Nov. 14, 2022, Vienna, Austria

Challenges on Long Pulse Operation in LHD

Tomohiro Morisaki

National Institute for Fusion Science



Introduction - *the way to the fusion reactor* -

Fusion reactor

Fusion engineering

- should establish or develop
  - energy extraction (blanket)
  - tritium handling
  - material science (low activation)
  - maintenance (remote handling)

To maintain Steady-state operation,

- it is necessary
  - to clarify PWIs
  - to remove heat and particle from vv
  - to keep plasma current (tokamak)
  - to establish data acquisition system

High performance plasma

- should be
  - burnable (Lawson criterion)
  - economical (high beta)
  - stable (MHD)
  - well-confined (turbulence, flow)

Tomohiro Morisaki, IAEA-TM LPO

Various limits preventing high performance and long pulse duration

Machine/engineering limits

1. Limit in available flux
2. Limit in energy or forces for the coils
3. Limit in injected power and/or Energy
   1. Max energy limit that can be exhausted by the cooling system
   2. Max. power (limit in performance)
   3. Max duration (energy) of injected power
4. Limit in energy and/or temperature for PFC
   1. Limit on wall or divertor temperature
   2. Limit on heating systems: RF guard limiter or antenna, beam dump (NB shine through)
5. Limits in measurements in control system

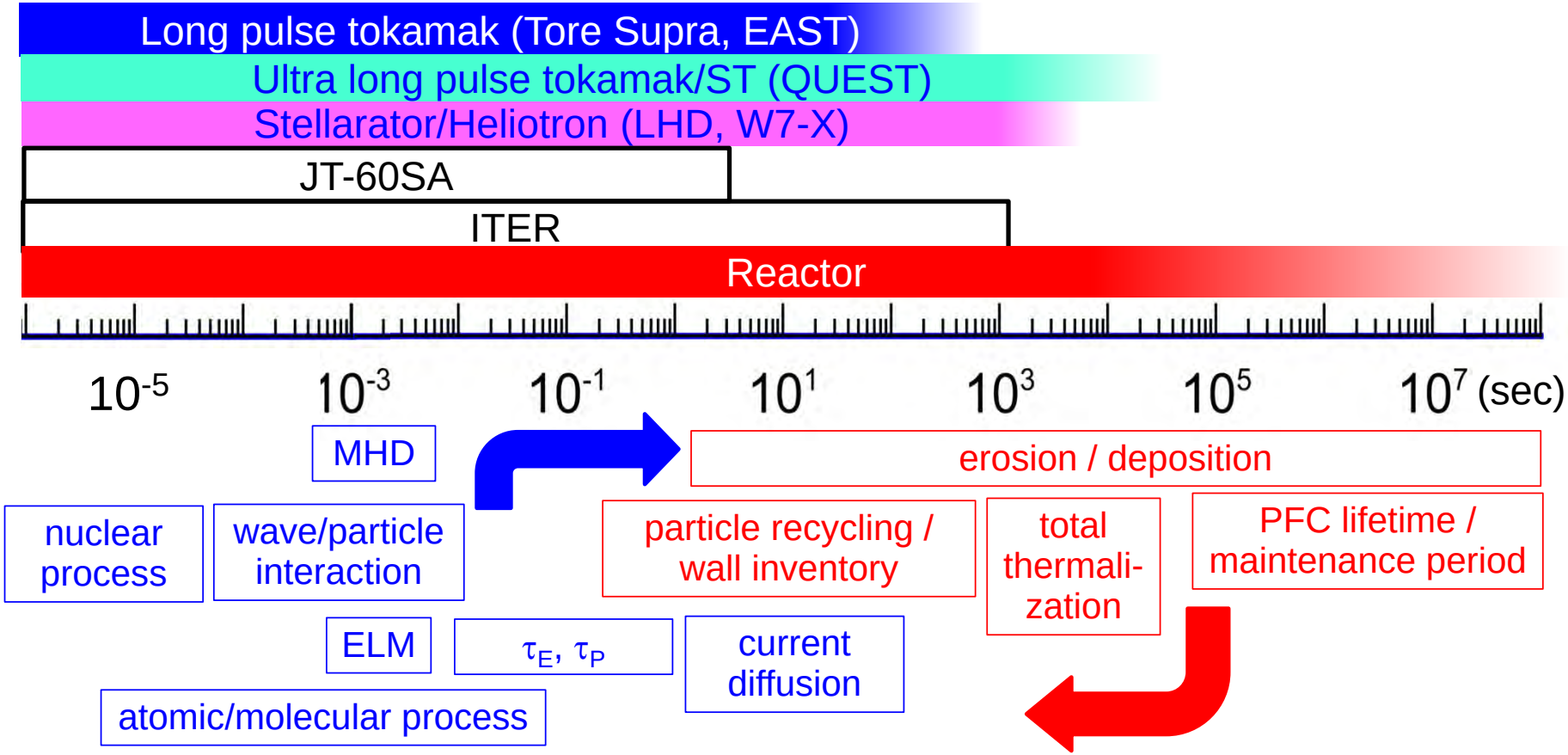
Plasma physics limits

1. Limit in MHD stability (current and pressure)
   1. Pressure/Beta, current instability limits
2. Limit in core/pedestal confinement
   1. Ion temperature clamping in dominant electron heating regimes
   2. Limits in pedestal pressure
3. Limit in plasma radiations
   1. Core impurity, e.g. W, accumulations
   2. UFO, Be-flakes resulting from erosion
4. Limit in density
   1. Uncontrolled density evolution
   2. Stability limit approaching density limits
5. Limit in wall/divertor erosion, migration
   1. Flake or dust production

Items: related to this talk

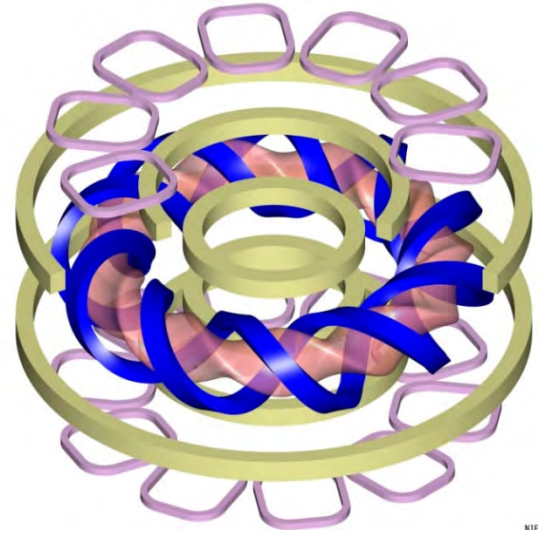
Complex physical system – *we are struggling* –

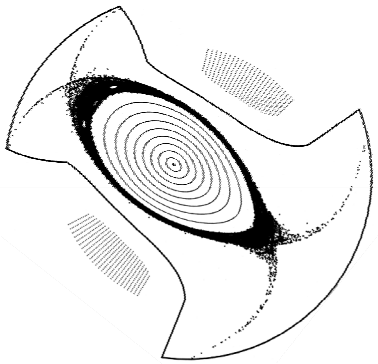
Steady-state devices should be involved phenomena/issues with **various time constant**



LHD - *a superconducting heliotron* -

One of the main missions of the LHD project is "steady-state operation with divertor"



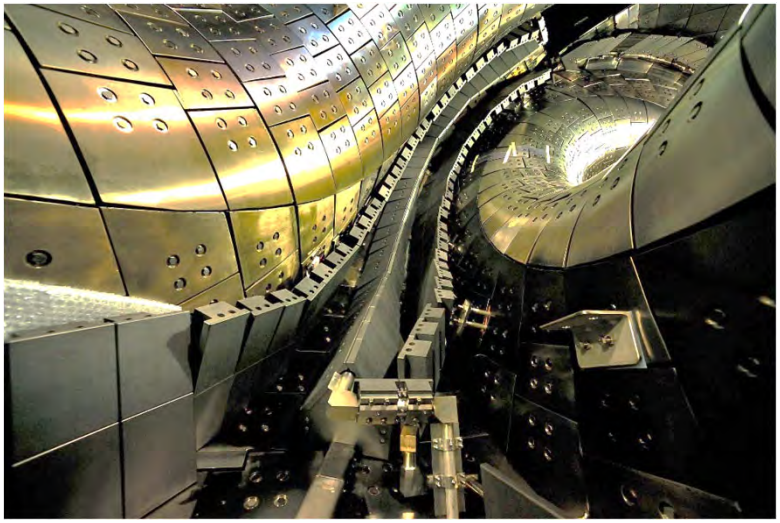


Specification

- helical mode numbers: *l/m*=2/10
- plasma major radius: 3.42-4.1 / 0.63 m
- plasma volume: 30 m^3
- toroidal field strength: 3 T
- edge modification: 20 NC RMP coils
- edge plasma/neutral control: closed helical divertor

In-vessel materials

- divertor tile: carbon, tungsten (partially)
- first wall: stainless steel, molybdenum (partially)

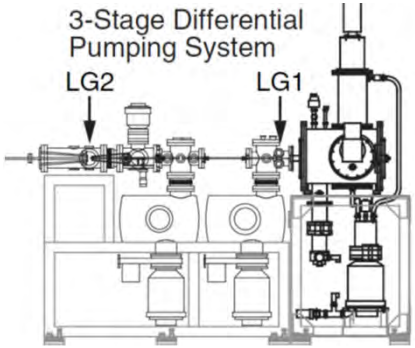


Heating Systems

- negative-NBI x 3 (180-190keV): H16MW, D8MW
- positive-NBI x 2 (40-80keV): H6MW, D18MW
- ICH (20 – 100MHz) x 6 3 MW
- ECH (77GHz x 3, 154 x 2, 82.7, 84) 5.5MW

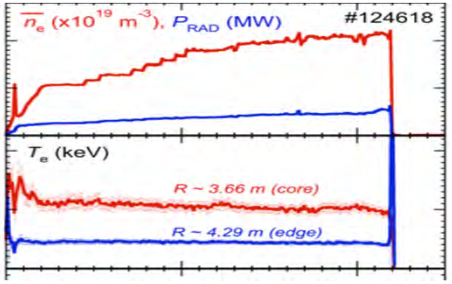
Peripheral equipment to sustain long pulse discharges

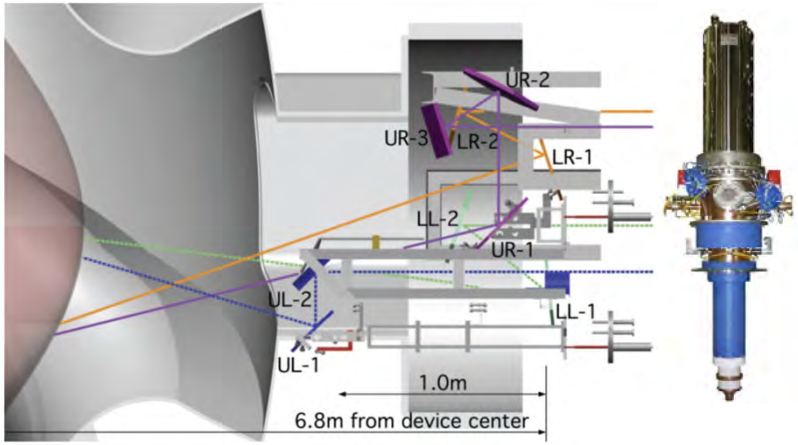
Repetitive pellet injector and gas puff



Diagnostics

n_e, T_e





Gyrotron and beam steering launcher

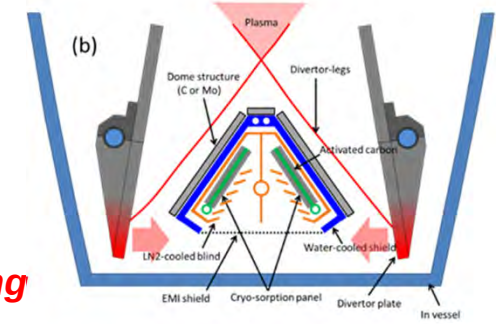
Integrated real time feedback control system
- booster heating
- fuelling
- interlock

Kasahara
Tue. afternoon

HAS antenna
Field-aligned,
large k

FAIT antenna
Field-aligned,
Imp. transformer

Cryogenic pump

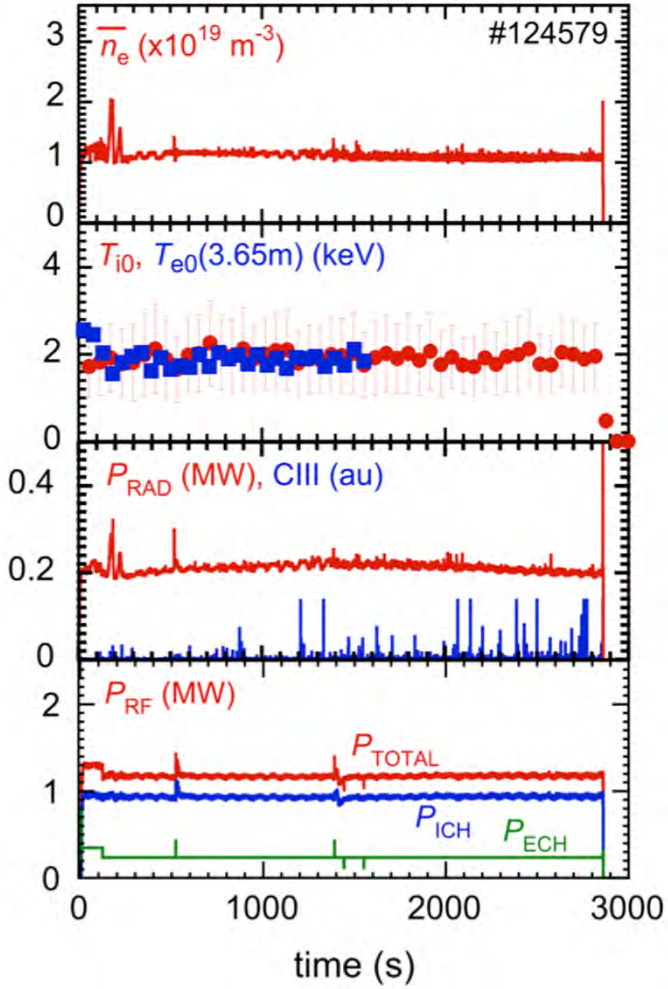


~ 70 m^3/s
(total 260 m^3/s)

Motojima
Wed. morning

Steady-state operation in LHD

48min. 3.36GJ discharge

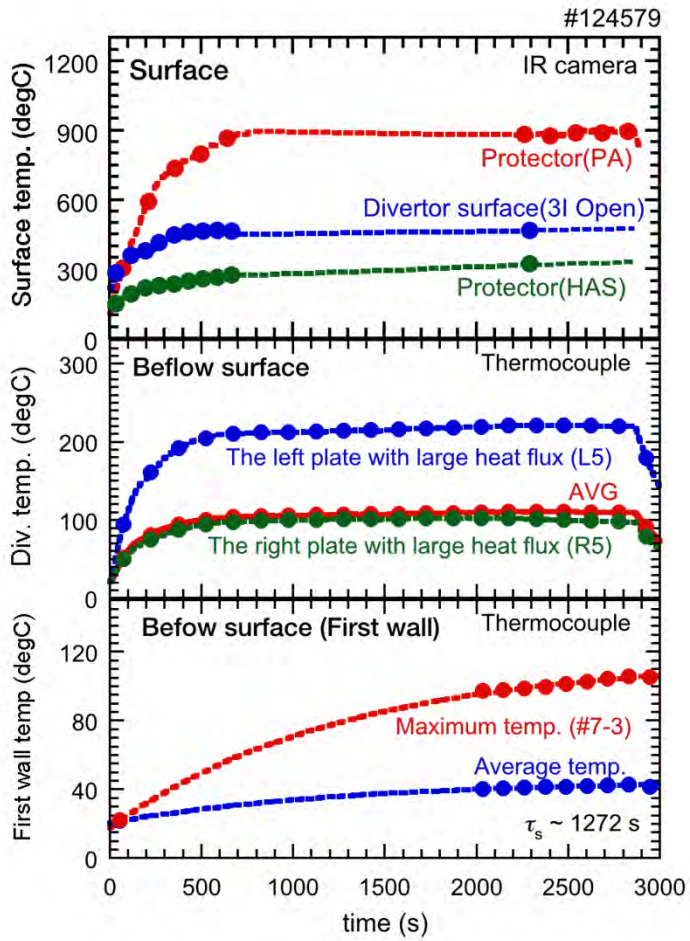


- Real time feedback control kept stable electron density and radiation despite evolving the PWI effect
- By boosting RF power, plasma temperature $T_e \sim T_i$ was quickly recovered just after the events of density rising

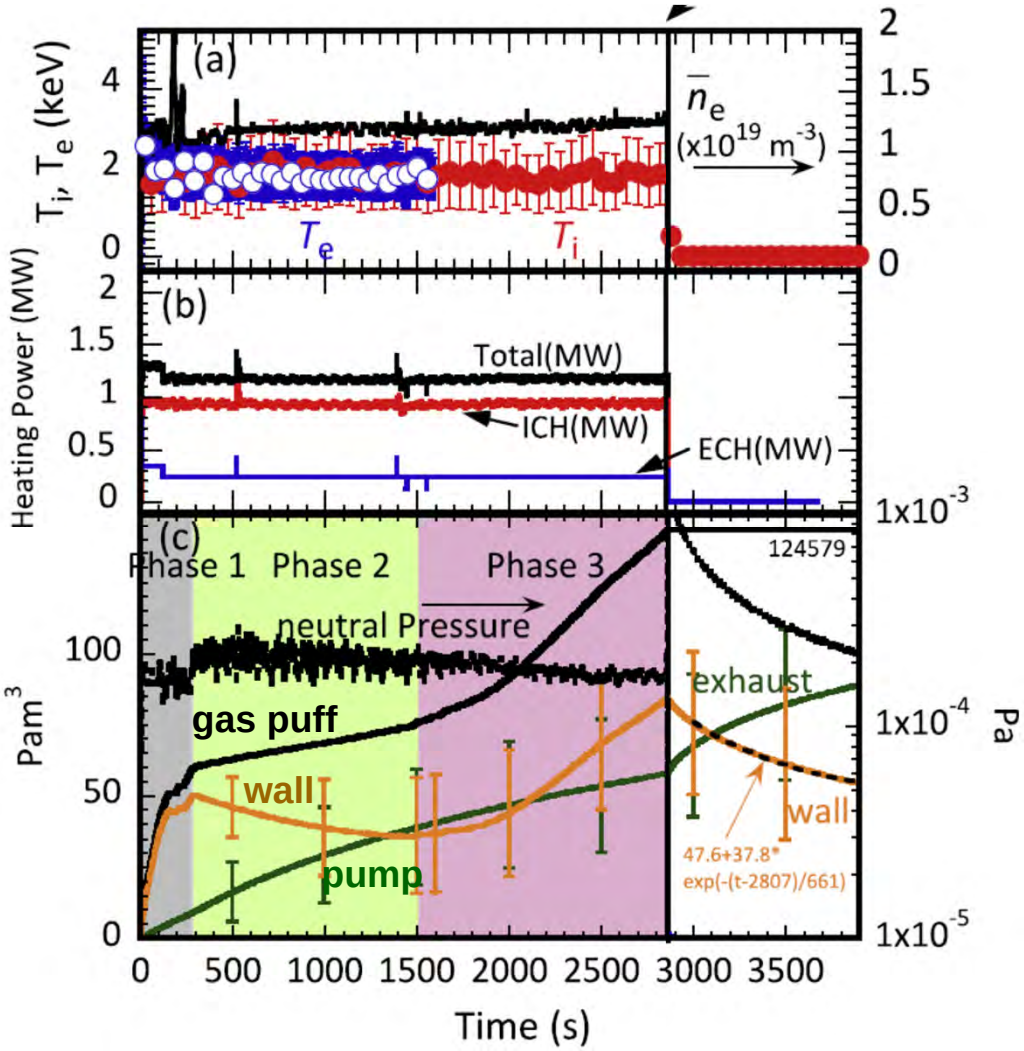
Time constant (saturation time)

- divertor plate: ~ 700 s

  ==> really saturated?
- first wall: > 3000 s



Dynamic wall retention



G. Motojima, J. Nucl. Mat. **463** (2015) 1080.

Although plasma parameters seem steady-state, property of VV surface dynamically changes

- Vacuum vessel wall (divertor plates) acts as sink (pump) or source, depending on its temperature and surface conditions
  - Phase 1: Fresh C absorbs gas (sink)
  - Phase 2: Heated C desorbs gas (source)
  - Phase 3: Co-deposition of C and H/He makes substantial wall pumping effect (sink)
- Dynamic wall retention makes continuous wall pumping effect

	Phase 1 (sink)	Phase 2 (source)	Phase 3 (sink)
Γ_{wall}	1.0×10^{20} He/s	-3.5×10^{18} He/s	1.4×10^{19} He/s

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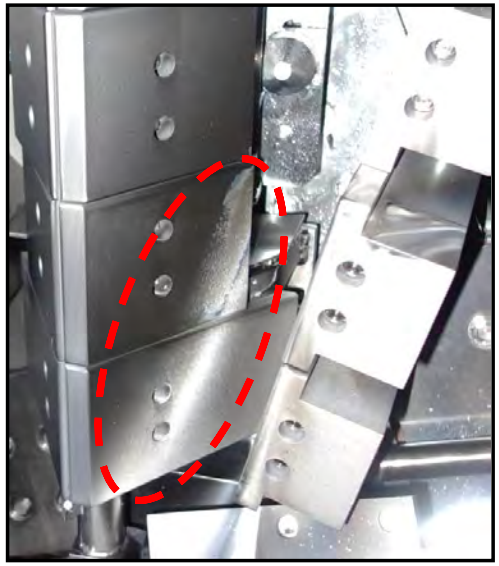
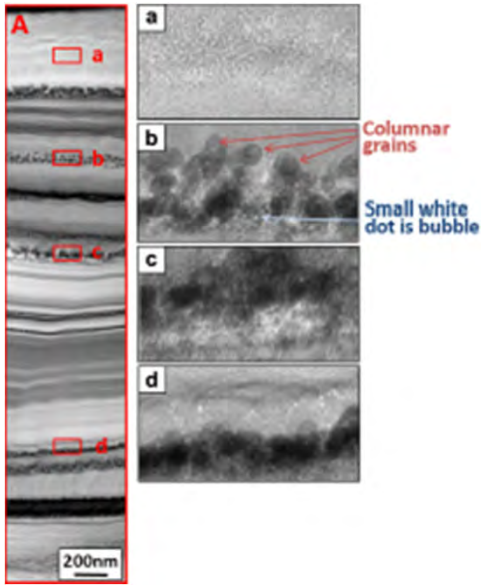
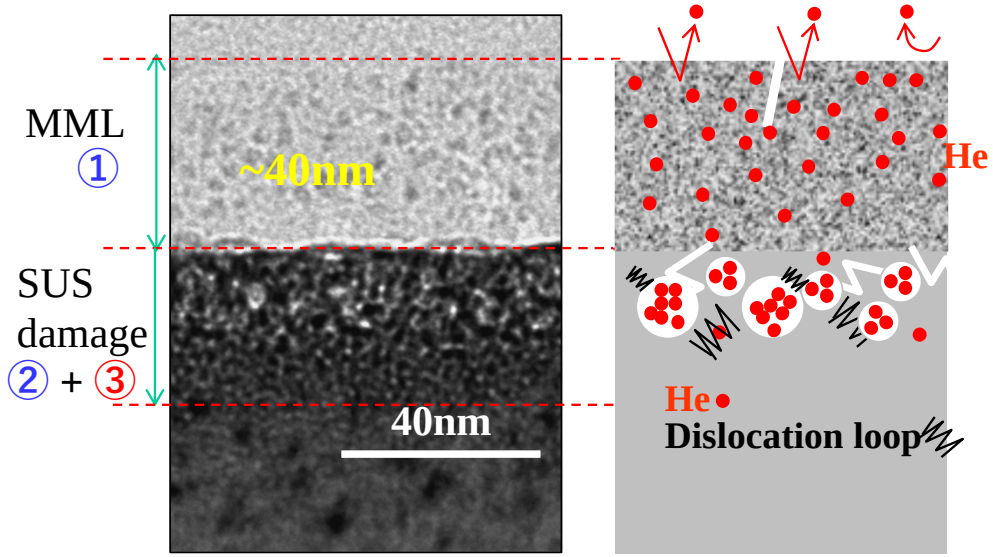
Mixed material layer (MML)

M. Tokitani *J. Nucl. Mater.* **438** (2013) S818.





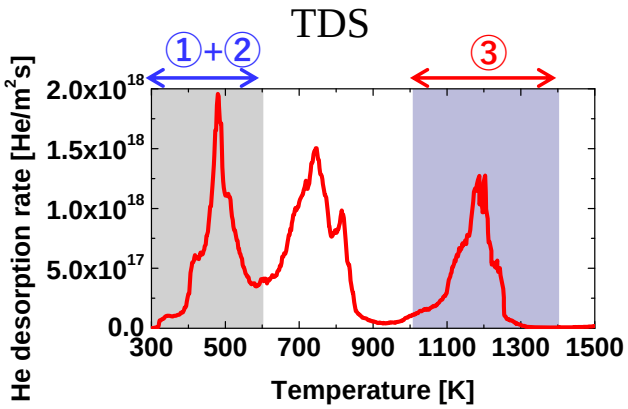


MML is formed and accumulating, sputtered C (>90%), Fe (~a few %), O, etc., analyzed with SEM/EDX

- hard, brittle

MML is a main reservoir of neutrals

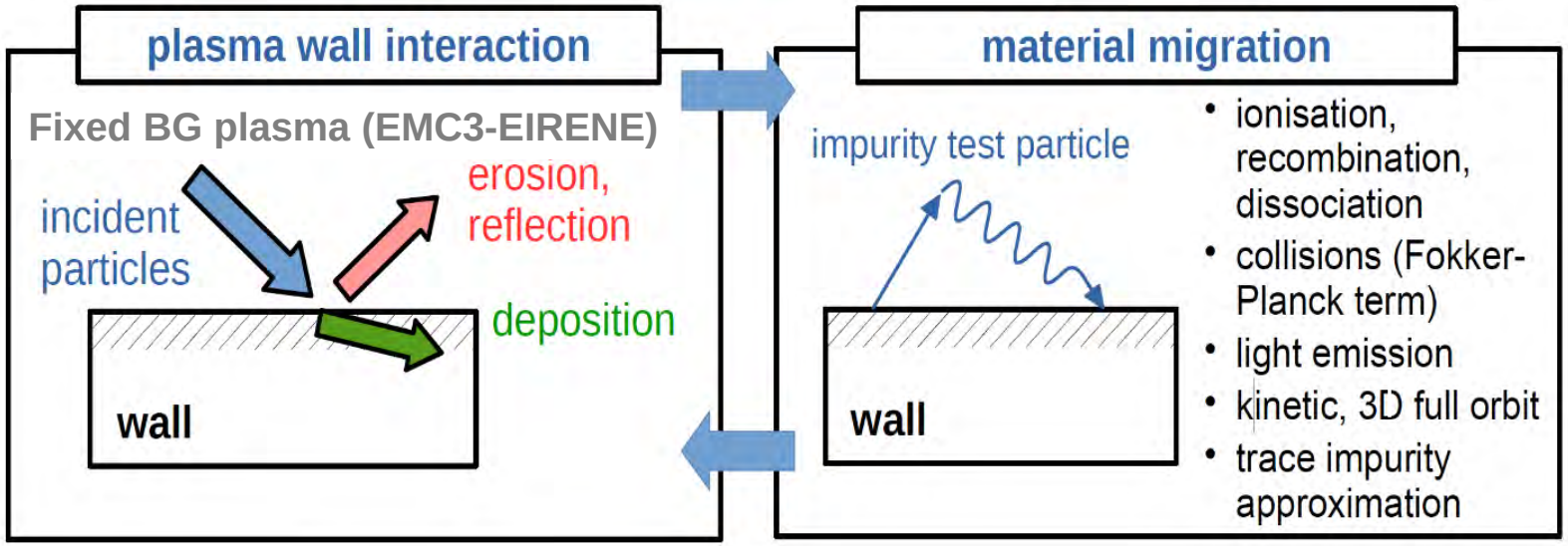
- ☐ **Low temperature: ~ 300-600K**
  - **① MML**
  - **② Weak trapping site in the SUS matrix**
- ☐ **High temperature: ~ 1000-1400K**
  - **③ He bubble deep inside**



Where the carbon is migrated from, and to …

Carbon deposition (origin of flakes) on VV wall was simulated by ERO2.0

3-d PWI Monte-Carlo code ERO2.0 (Time dependent code)



Major code upgrade ERO2.0:

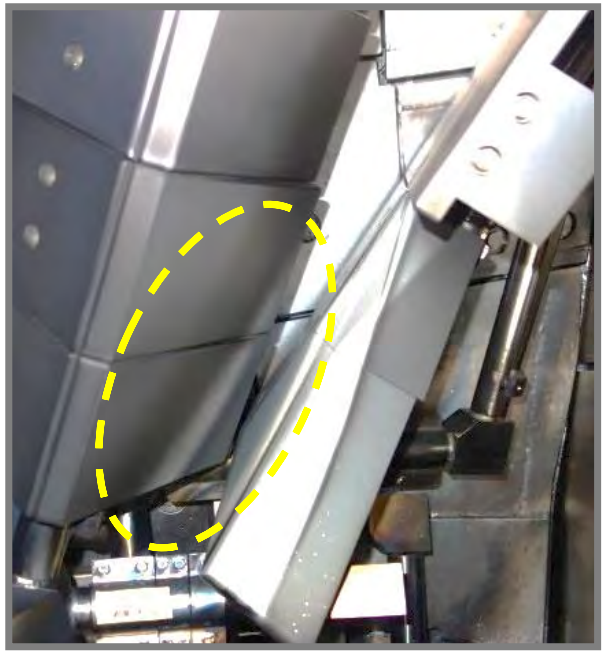
Based on same principles as ERO, but allows extending the simulation volume significantly

Ref. J. Romazanov et al., Nucl. Mat. and Energy 18 (2019) 331.

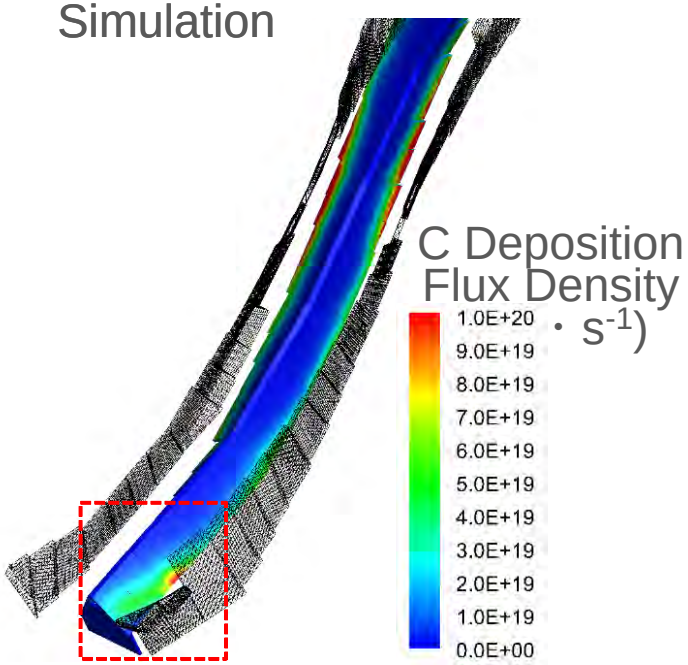
ERO2.0 could reproduce C deposition on dome plates

Shoji, Nucl. Mat.Energy (2020)

Observation

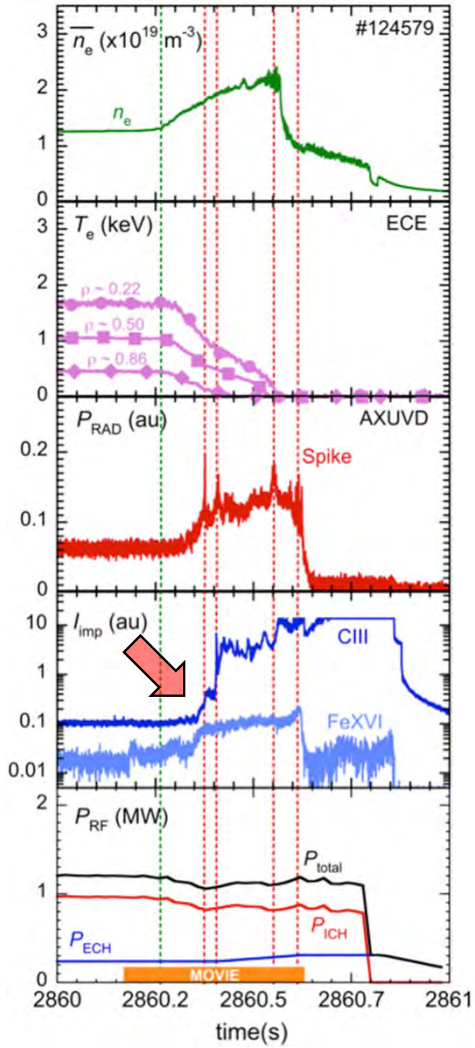


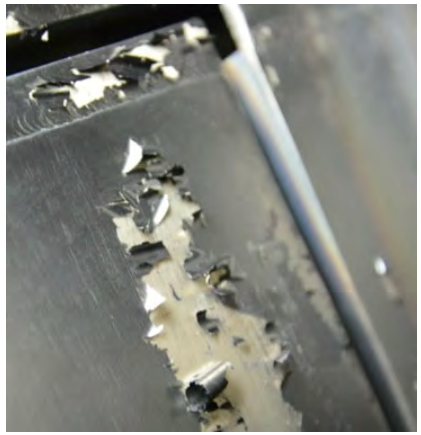
Simulation

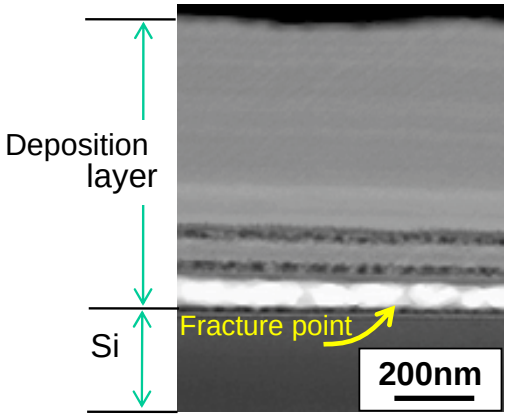


ERO2.0 simulation shows the highest carbon deposition area is originated from where the higher heat flux comes.

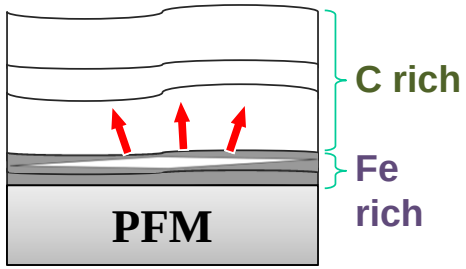
Discharge terminates by abrupt increase of C impurity (flake exfoliation)

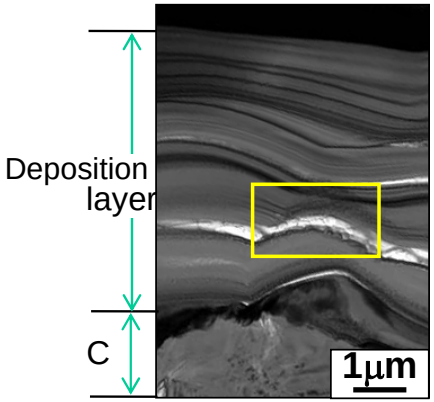




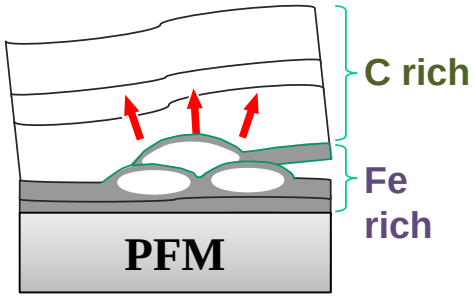


Stress release
"Fracture at Fe layer"





Blistering growth
"Fracture at Fe layer"



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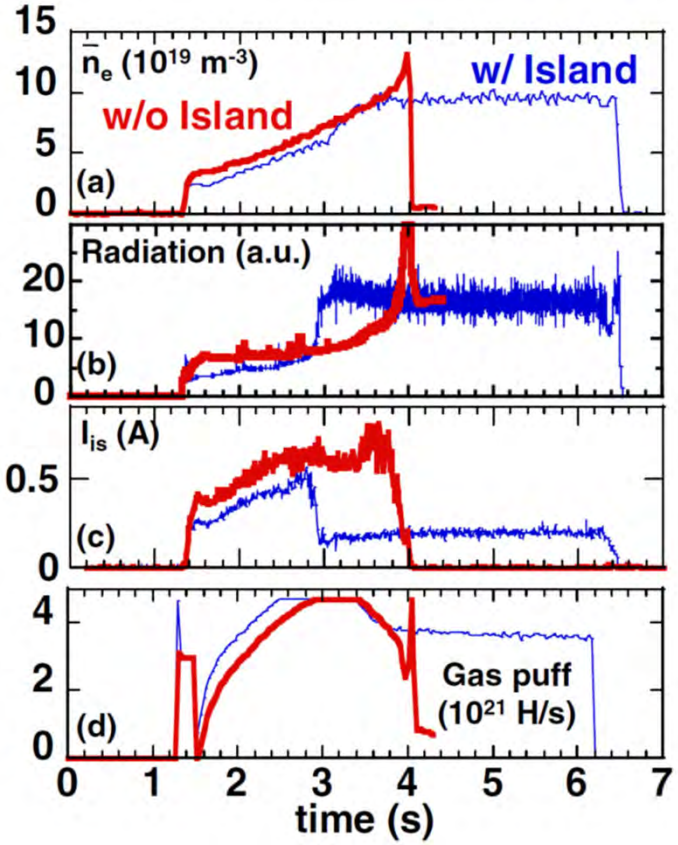
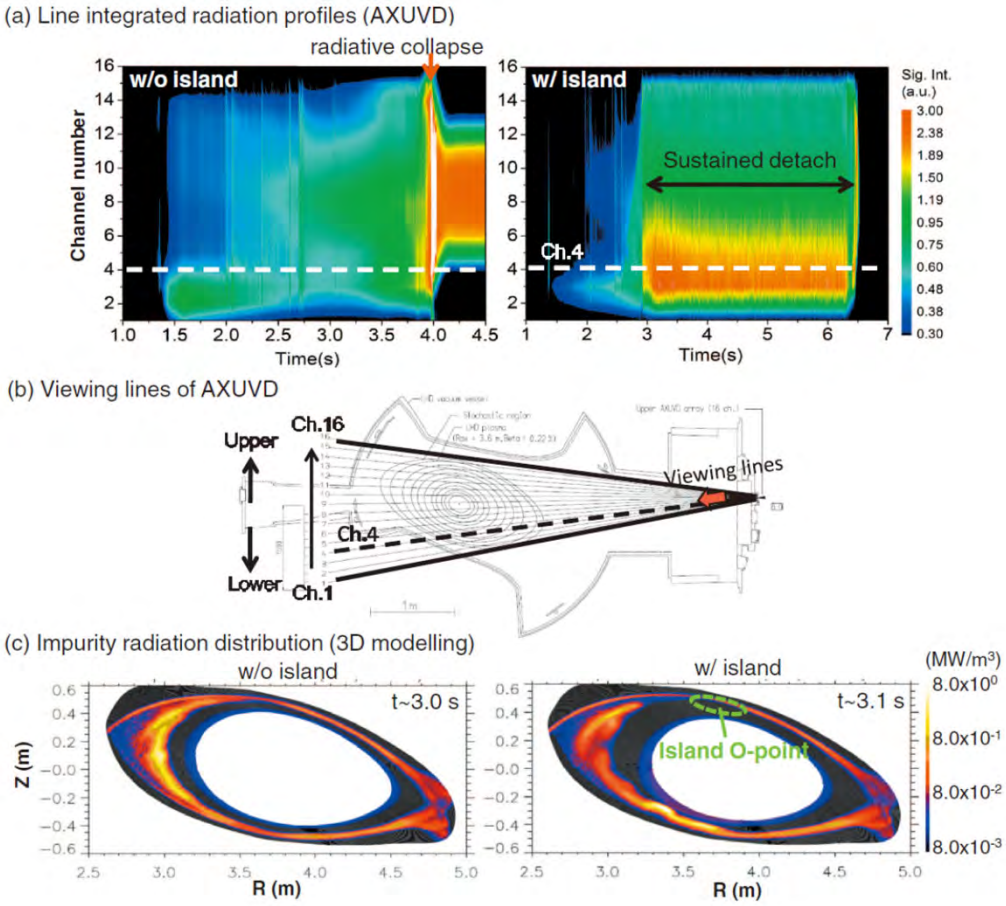
Active control to sustain long duration discharge

Long sustainment of detached plasma with ***edge modification***

M. Kobayashi, Phys. Plasmas **17**, 056111 (2010)

Selective cooling around X-point of the island stabilized outside of the last closed flux surface throughout the detachment phase.





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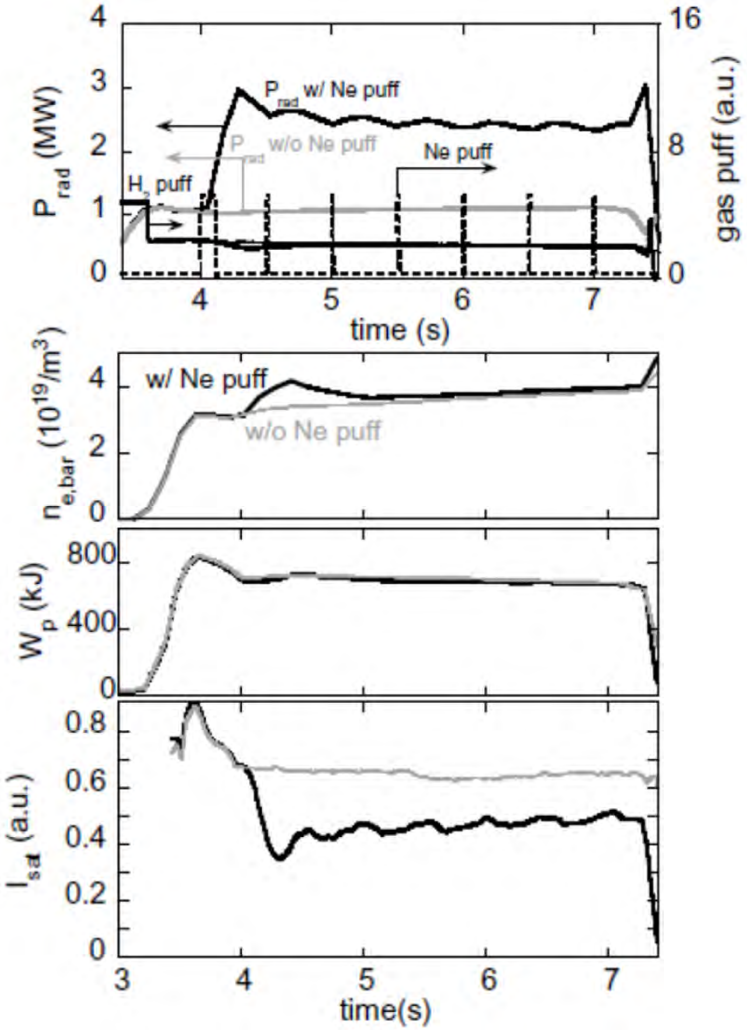
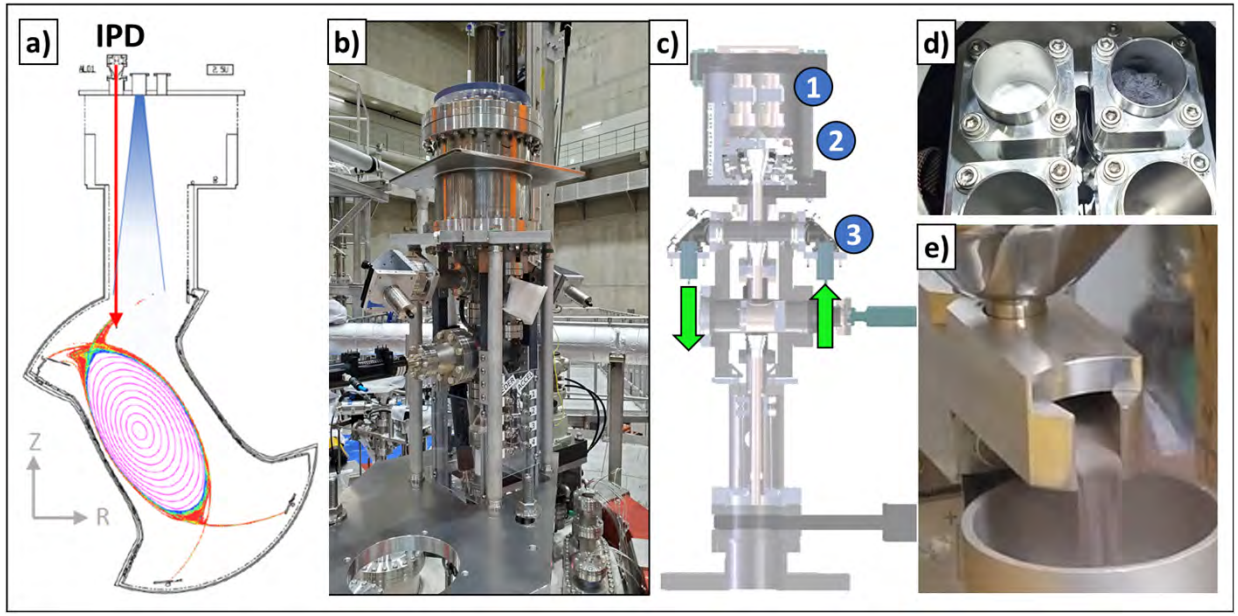
Long sustainment of detached plasma with repetitive ***Ne seeding***

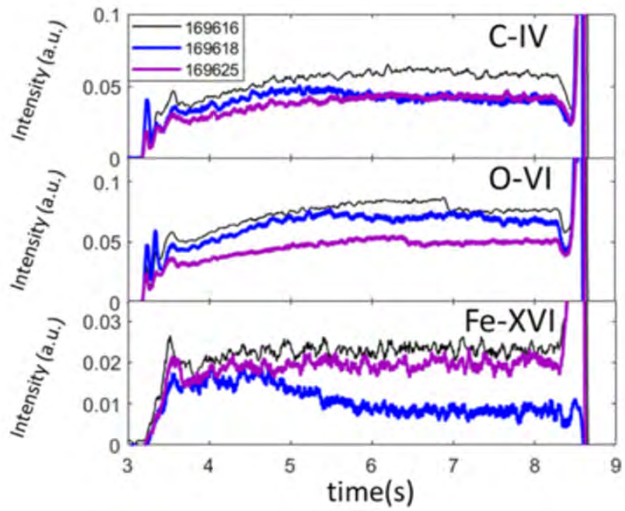


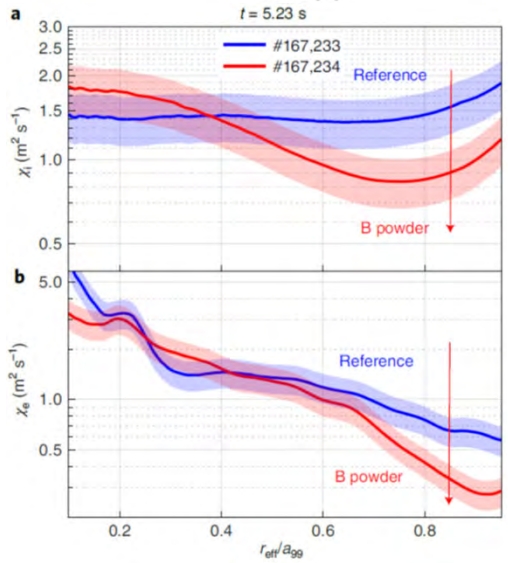
Divertor heat load control is mandatory for steady state operation.

- Ne was seeded with repetitive puff with ~ 0.5 sec interval.
- Radiated power increases more than twice → decrease in divertor flux
  (P_{rad}/P_{NBI} ~ 0.3 is achieved until the end of discharge)
- Almost no impact on core confinement (Wp)
- Smaller seeded amount of Ne (< half of the first puff) is enough for later phase to sustain the radiated power
  → Indicate recycling nature of Ne

Real-time wall conditioning utilizing boron and boron nitride powder injections







Boron powder injection is effective not only for wall conditioning but also for improving core plasma performace

F. Nespoli (PPPL) et al., Nature Physics (Jan. 2022)

R. Lunsford et al 2022 Nucl. Fusion **62** 086021

Data-driven approach to avoid radiative collapse

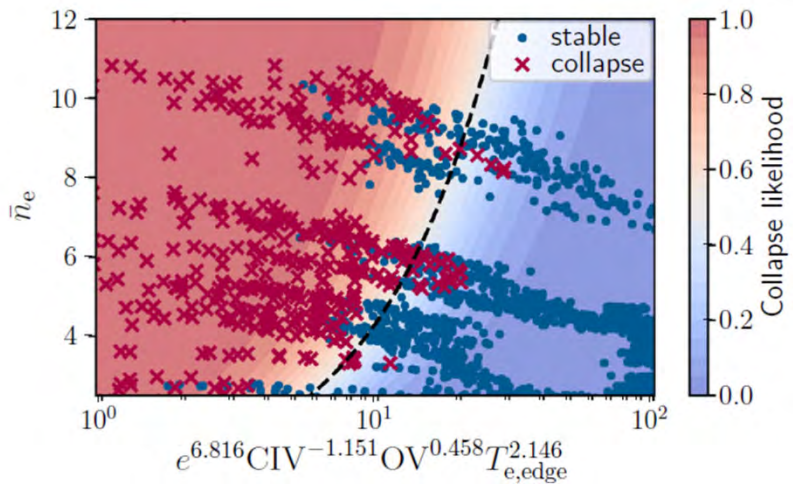
T. Yokoyama, JoFE, 2021

Radiative collapse predictor has been developed with machine learning model

- Key parameters were extracted by using sparse modeling technique: $\bar{n}_e$, CIV, OV, $T_{e,edge}$.

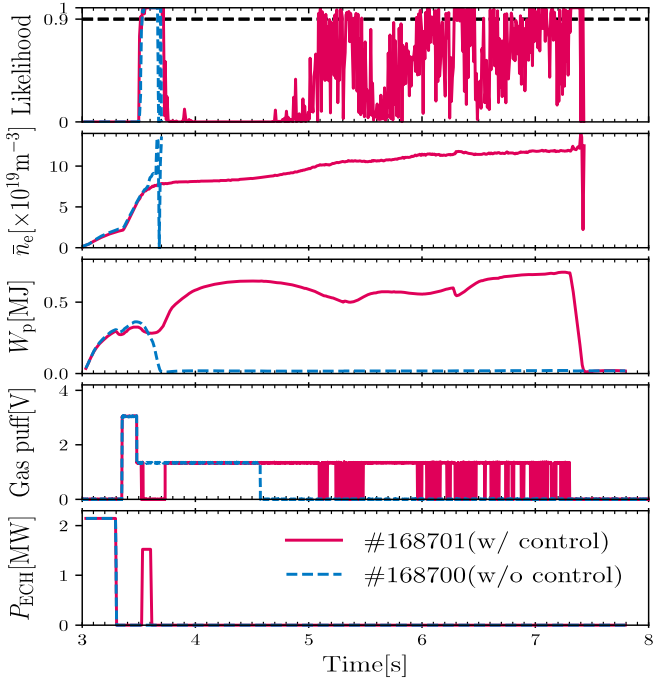
Collapse likelihood has been quantified based on the key parameters

- Safe operational regime is described by likelihood
- Predictions with a probability of > 85% succeeded more than 30 ms before the collapse.



Real-time feedback control

- Input: $n_e L$ (FIR), T_e (ECE), CIV, OV (VUV)
- Actuators: Boosting ECH, regulating gas puff
- Collapse likelihood is calculated in real time by a single-board computer (Raspberry Pi)



$\bar{n}_e \sim 1.3 \times 10^{20}[\mathrm{m}^{-3}]$ achieved, avoiding radiative collapse

Yokoyama, Tue. afternoon

Higher density and longer operation can be secured with this system

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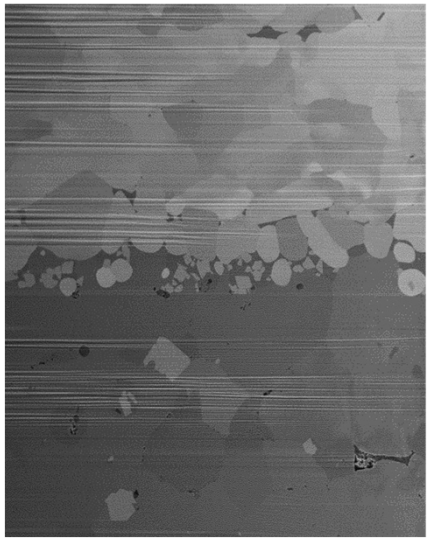
Development of high heat flux components

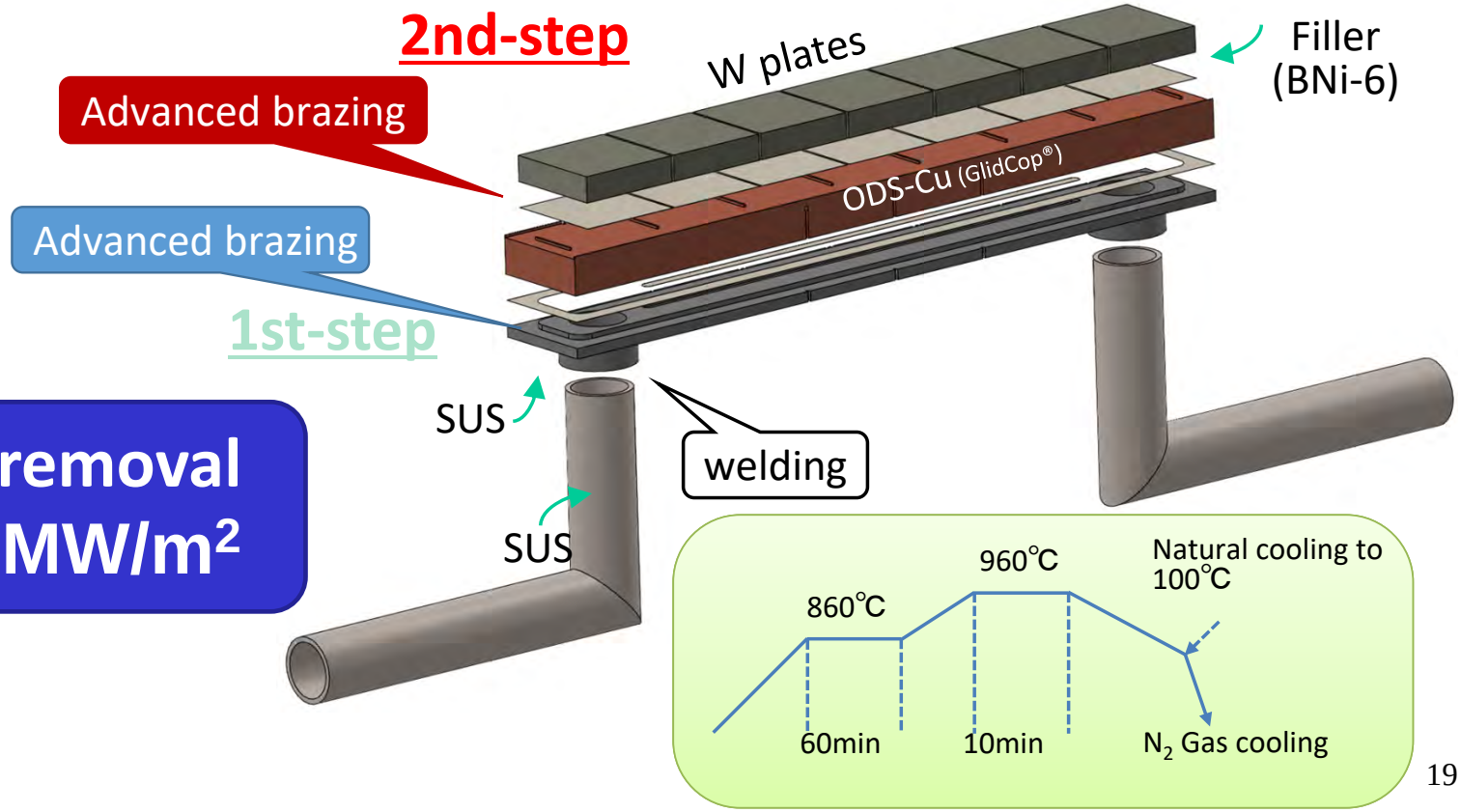
Novel fabrication method for divertor target plates

☐ Advanced Multi-Step Brazing (AMSB)

M. Tokitani *et al* 2021 *Nucl. Fusion* **61** 046016



① SUS/ODS-Cu ➡ Machining ➡ ② W/ODS-Cu ➡ SUS pipe welding



Extremely high heat removal capability: over ~30 MW/m²

Towards steady-state high-performance regime

- LHD has pioneered challenging operational regime where we should pass through for realizing the future fusion reactor.
- LHD has made steady progress, overcoming many challenges and obtaining new physics knowledge that is not available in pulsed operation.
- Steady-state operation is difficult even for superconducting stellarators/heliotrons which are inherently good at steady-state operation.
- Innovative ideas to overcome physics and engineering issue must be tried in the future devices.
- Accelerating development of research, international collaboration should be important and powerful.