4th Technical Meeting on Divertor Concepts

Radiative divertor compatible with RMP-driven, ELM-crash-suppression in fusion DEMO-type devices

Yongkyoon In[1], H.H. Lee[2], and S.J. Kwon[2]

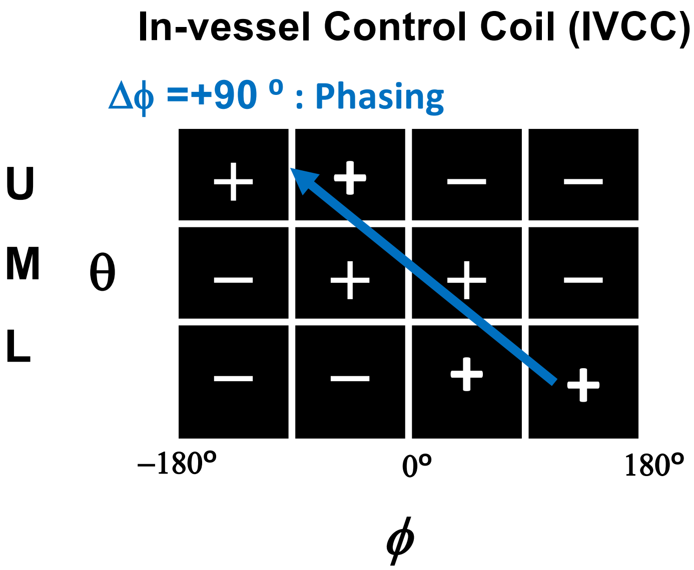
in acknowledgement of the dedicated efforts of the KSTAR team

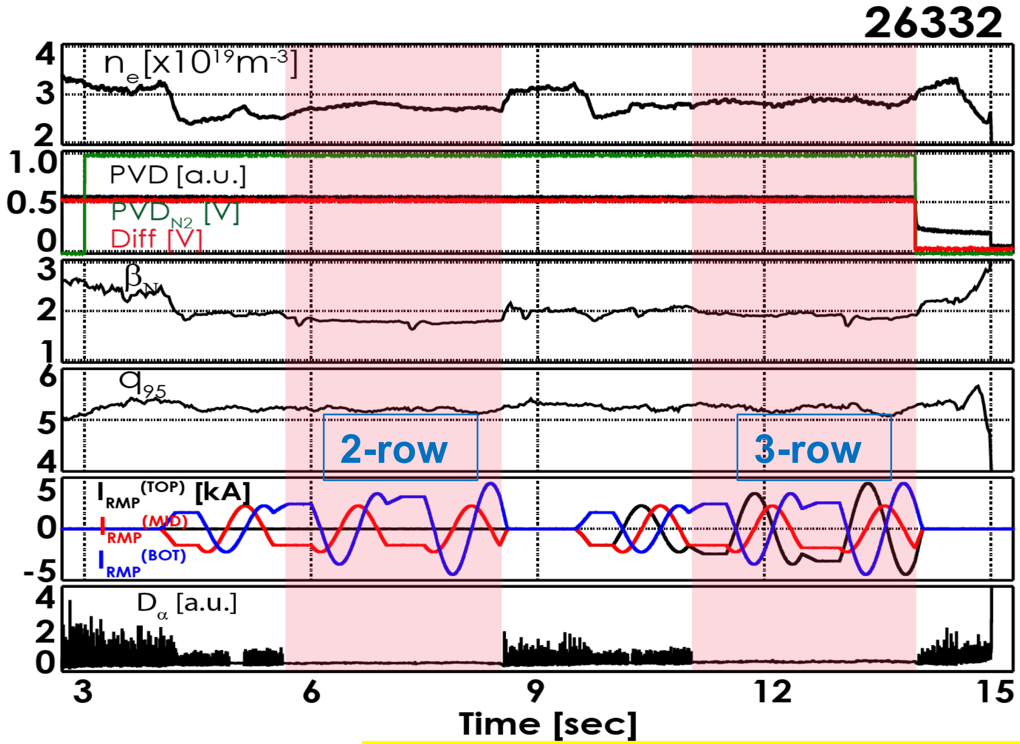
[1] Ulsan National Institute of Science and Technology (UNIST), Korea
[2] Korea Institute of Fusion Energy (KFE), Korea

November 11, 2022

Recently established radiative divertor under RMP-driven, ELM-crash-suppression in KSTAR suggests a promising venue for detached plasmas in fusion DEMO reactor

ITER-like 3-row Resonant Magnetic Perturbation (RMP)-driven ELM-crash-suppression

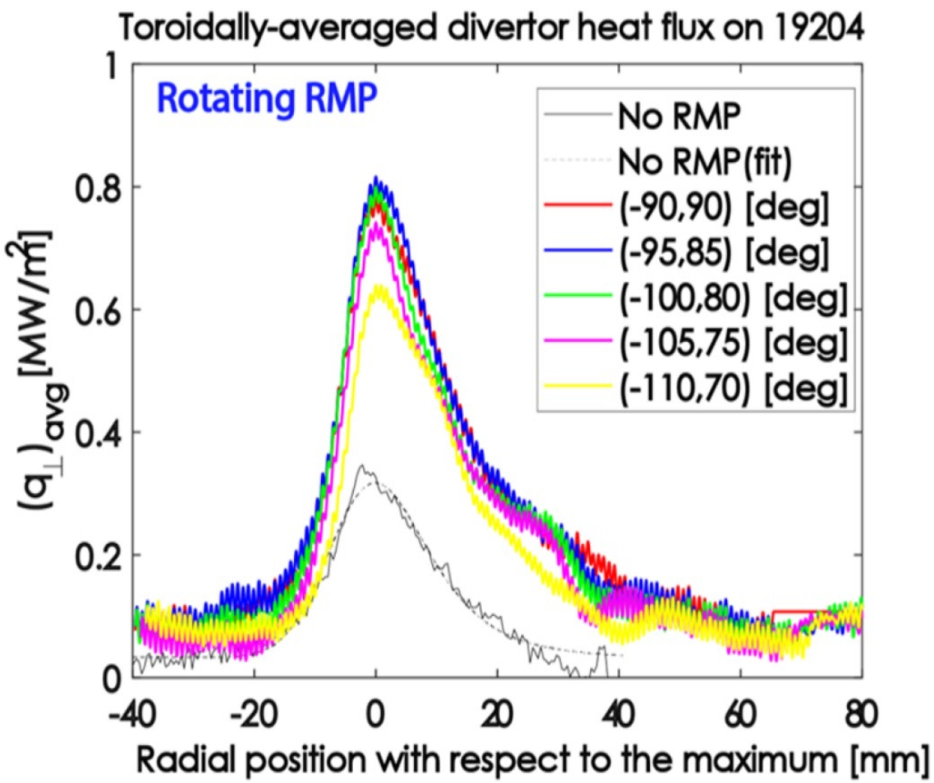




Y. In *et al*, Plenary talk at AAPPS-DPP (2021)

Demonstrated the co-existence of RMP-driven ELM-crash-suppression and radiative divertor

When RMP-driven ELM control becomes successful, the accompanying divertor thermal loading should be sufficiently low in reactor



Y. In *et al*, NF 59 (2019) 059009

- During RMP-driven ELM-crash-suppression, the divertor heat flux peaks are observed to be **2-3 times higher than that of inter-ELMs without RMP** (based on KSTAR)
  - ➔ Broadening or Lowering the peaks
- **Essential to find a solution to lower divertor thermal loading even during RMP ELM control**

➔ high n_e, detached plasma (preferably), impurity injection

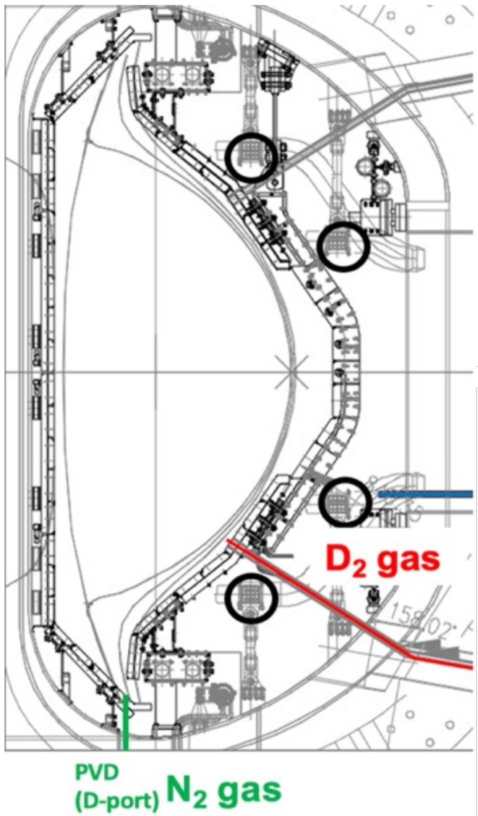
ITER Physics Basis Editors et al, NF 39 (1999) 2137

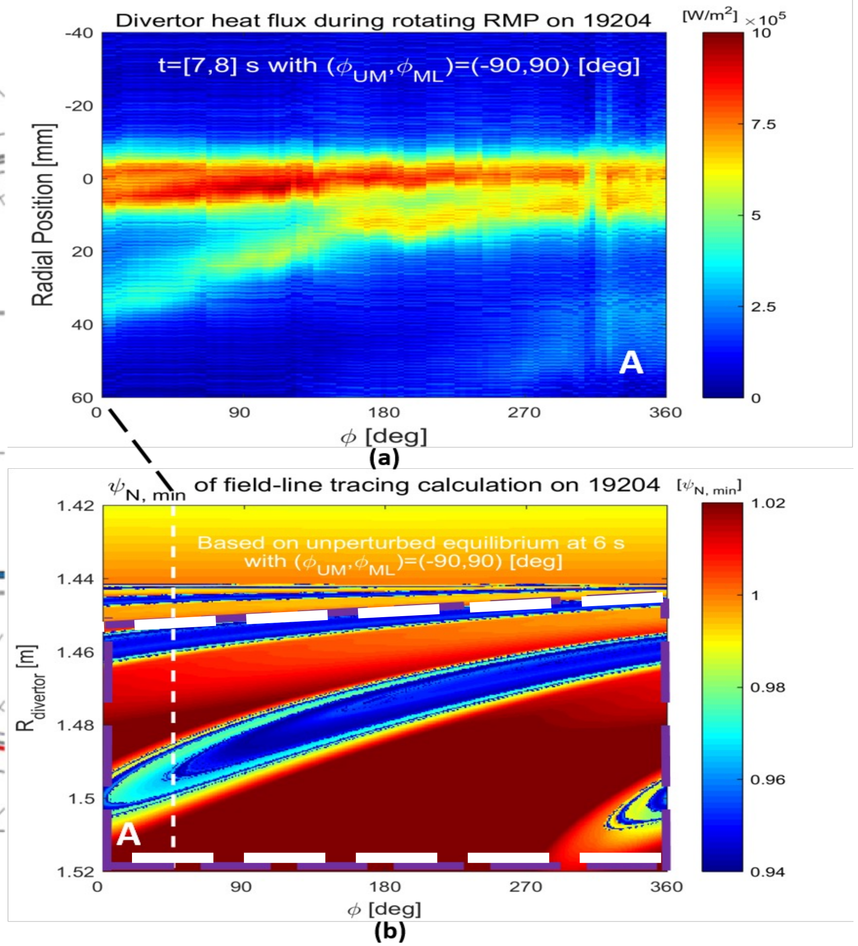
Field-line-tracing, including plasma response, has been matched quite well with diagnosed divertor heat flux striation

Divertor Gas Control

-Impurity seeding
-deuterium gas puffing

Typically, poor compatibility of detachment with RMP-driven ELM-crash-suppression had been observed for years





Y. In *et al*, NF 59 (2019) 126045

Contents

RMP-driven, ELM control

- Stochastic magnetic boundary/Decoupling core mode-locking and edge RMP
- Secured accessibility for ELM-crash-suppression with the cost of the substantial increase of divertor heat flux peaks

ITER or reactor-relevant issues

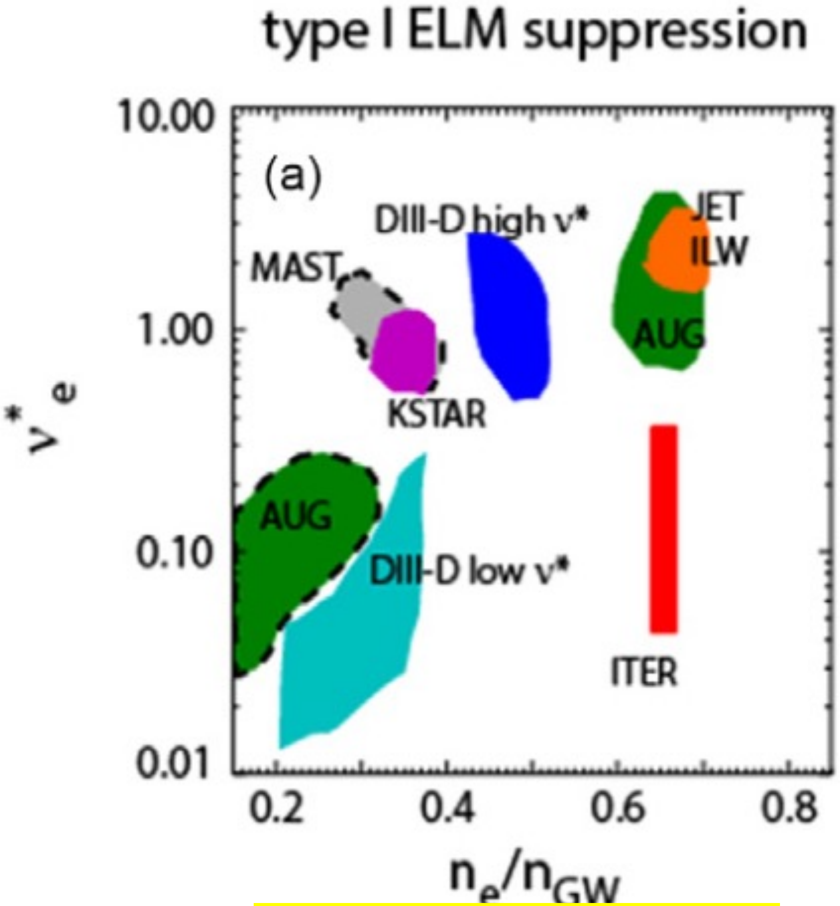
a) Divertor heat flux broadening

b) Lowering the peaks under RMP-driven, ELM-controlled periods via enhanced radiative loss at edge and SOL

c) Caveats (could be quite narrow range of operational conditions)

Reactor-oriented R&D needs

In fusion reactor, edge conditions belong to banana regime for both ions and electrons, suggesting low collisionality and high density plasmas



A. Kirk *et al*, NF (2015)

- **Collisionality**

$$\nu^* = \frac{\text{connection length}}{\text{trappped particle mean free path}}$$

$$= \frac{\text{effective collision frequency}}{\text{bounce frequency of trappped particle}}$$

$$= (\nu/\varepsilon) / \omega_b = (\nu/\varepsilon) / \varepsilon^{1/2} v_t \,(Rq)$$

$$= \nu Rq/(\varepsilon^{3/2} v_t)$$

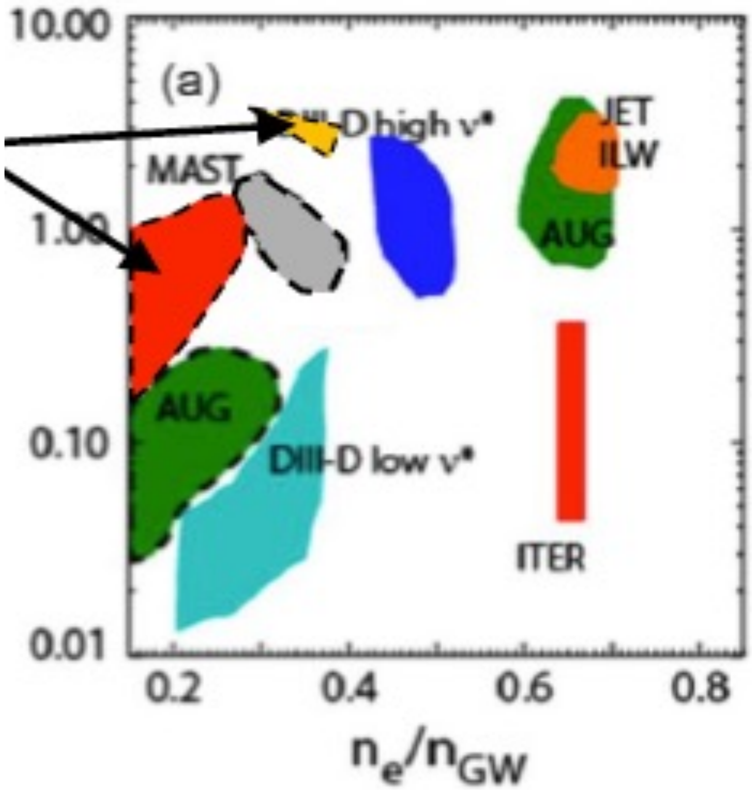
$$\propto \frac{qRn_e Z_{eff} \ln \Lambda_e}{T_e^2 \epsilon^{3/2}}$$

High edge n_e without accessing ITER-grade low ν* remains challenging (e.g. loss of ELM-crash-suppression), enhancing the radiative power loss

In fusion reactor, edge conditions belong to banana regime for both ions and electrons, suggesting low collisionality and high density plasmas

UNIST

Recent KSTAR RMP data (Revised)



M.W. Kim *et al*, AAPPS-DPP (2022)

- **Collisionality**

$$\nu^* = \frac{\text{connection length}}{\text{trappped particle mean free path}}$$

$$= \frac{\text{effective collision frequency}}{\text{bounce frequency of trappped particle}}$$

$$= (\nu/\varepsilon) / \omega_b = (\nu/\varepsilon) / \varepsilon^{1/2} v_t (Rq)$$

$$= \nu Rq/(\varepsilon^{3/2} v_t)$$

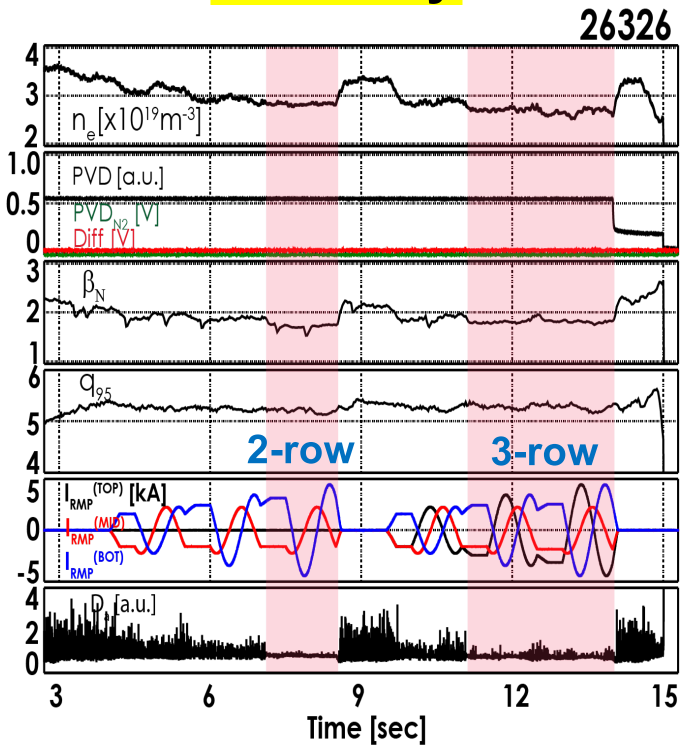
$$\propto \frac{qRn_e Z_{\text{eff}} \ln \Lambda_e}{T_e^2 \epsilon^{3/2}}$$

High edge n_e without accessing ITER-grade low ν* remains challenging (e.g. loss of ELM-crash-suppression), enhancing the radiative power loss

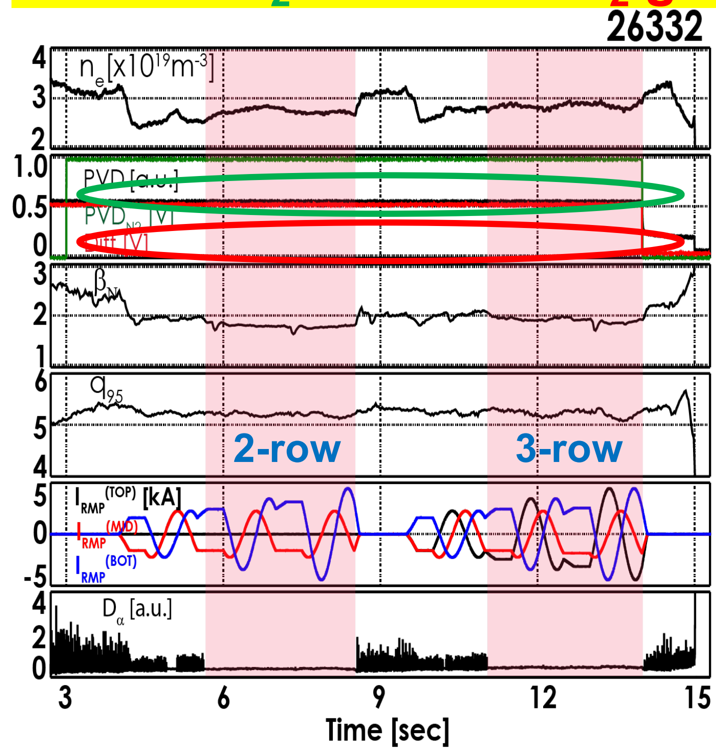
ITER-like 3-row ELM-crash-suppression, rather than 2-row RMPs would be more desirable in terms of divertor thermal loading, in particular, with impurity control

Fixed P_{NBI} = 3.1 MW, B_T=1.8 T, I_p=0.5 MA at ~3E19 m^{-2} (f_{GW} ~ 0.43)

RMP only



RMP + N_2 +diffusive D_2 gas



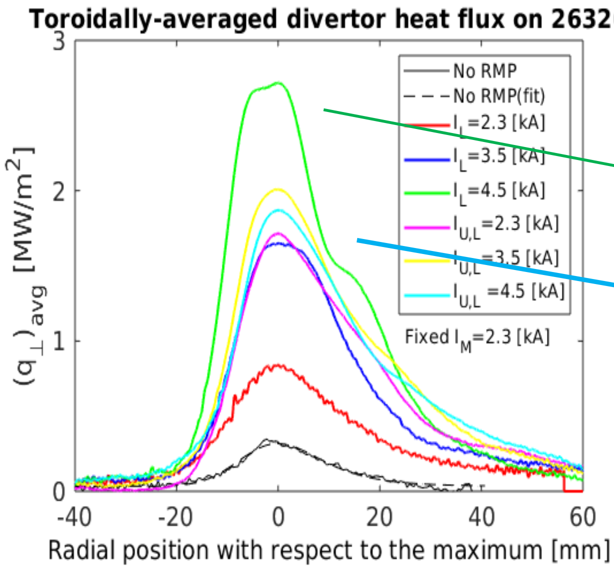
Divertor thermal loading helps us decide the most favorable RMP-driven, ELM-crash-suppression

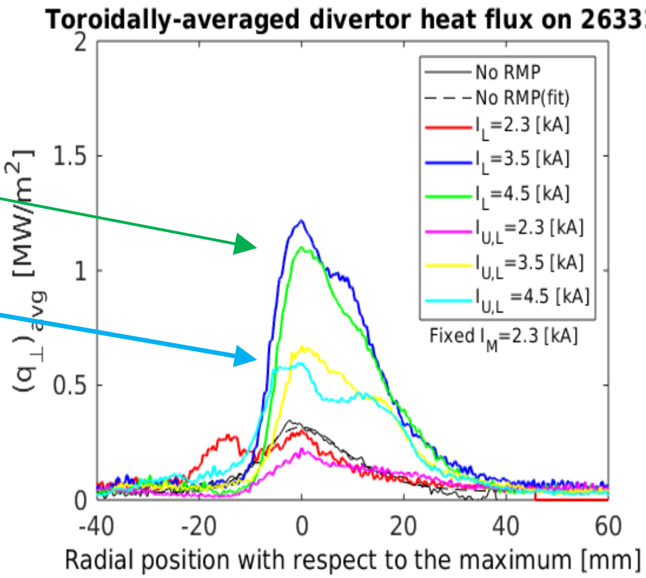
With N_2 + diffusive D_2 gas puff, the divertor thermal loading gets lowered to a manageable level (below 1MW/m^2) with 3-row RMPs

UNIST

RMP only

RMP + N_2 +diffusive D_2 gas





Y. In *et al*, Plenary talk at AAPPS-DPP (2021)

Established an exemplary case to combine RMP-driven, ELM-control and divertor thermal loading control simultaneously !

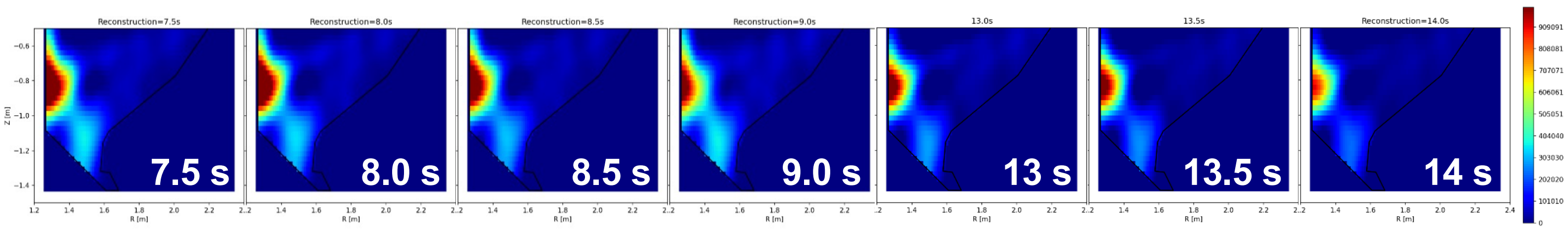
Radiatively controlled divertor is prone to re-attachment under RMP ELM-crash-suppression

RMP only

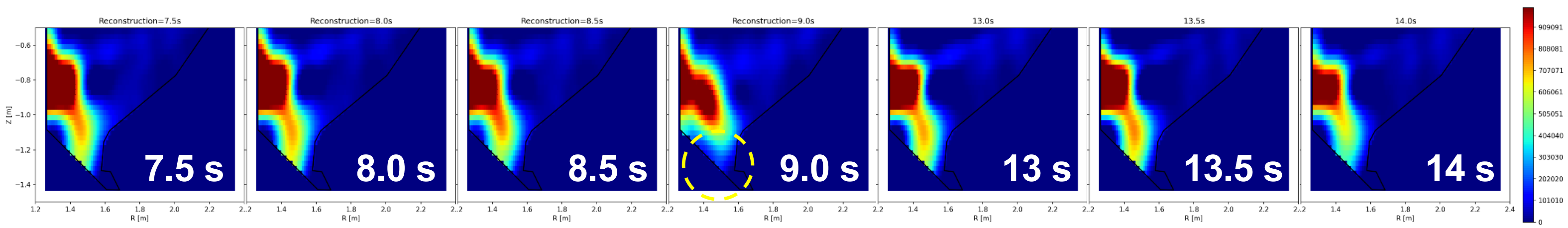
Imaging bolometer

2-row RMP ELM suppression

3-row RMP ELM suppression



RMP + N_2 +diffusive D_2 gas



Indicative of detachment
(without RMP)

In courtesy of W. Choe's group (KAIST)

Divertor thermal loading during RMP, ELM control has been favorably controlled with impurity and diffusive gas puffing

UNIST

3-row RMP ELM suppression would be more favorable in terms of peaked divertor heat flux than the counterpart of 2-row

Impurity injection and gas puff would reduce the divertor heat fluxes (lowering thermal load as low as that of no-RMP)

➔Long pulse stationary operation would be better off with 3-row RMP control with N_2 and D_2 gas puff

Higher density RMP ELM control, and detached plasmas with q_{95} ~3 would be the direction for reactor-relevant conditions with tungsten, though a low collisionality impact needs to be separately explored

R&D Needs for fusion DEMO-type devices

- Would this be valid even with partially detached plasmas in fusion reactor, including ITER?
- Seemingly conflicting needs of lower RMP current vs divertor thermal loading reduction → Optimization is essential at a certain point
- What happens to a lower q_{95} RMP experiments that would end up with higher density plasmas, prone to mode-lockings (moderate-n RMP or low-n Edge-optimized RMP (ERMP))?
- Which factors are indeed more critical ?
  - high density vs lower collisionality; both may not be simultaneously met in the existing devices, prior to the ITER-era
- Conventional MHD-simulation tools are NOT sensitive to impurity changes or gas puff, unless the relevant edge density variations are significant (probably ditto to nonlinear simulations)
- Ex-vessel low-n RMP use for ELM control, compatible with radiative divertor

BACK-UPs

K-DEMO Divertor SOL Physics Calculation using UEDGE

KFE 한국핵융합에너지연구원 KOREA INSTITUTE OF FUSION ENERGY

Key Features of UEDGE

Physics:

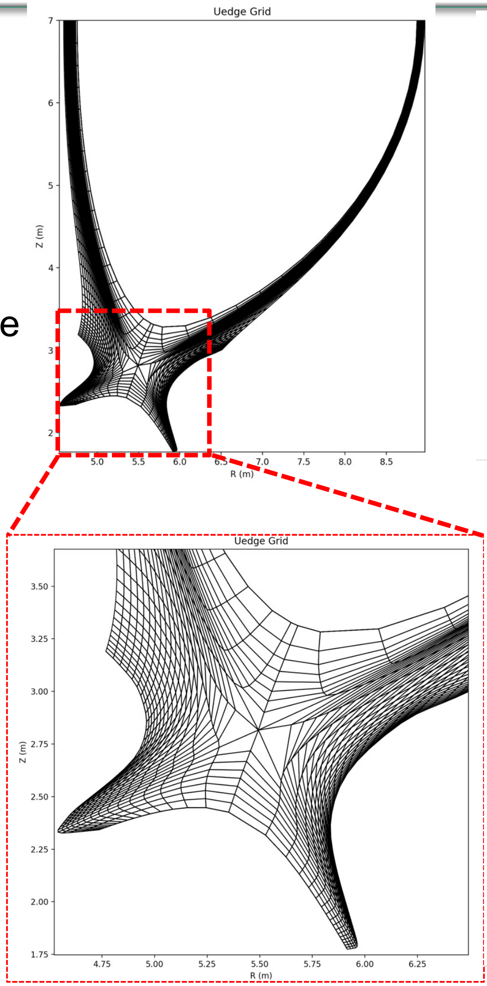
- Multispecies plasma; var. $n_{i,e}$, $u_{||i,e}$, $T_{i,e}$, φ
- Flux-limited kinetic corrections
- Fit radial plasma transport coeff.
- Reduced Navier-Stokes or Monte Carlo for wall-recycled/sputtered neutrals
- Multi-step ionization and recombination

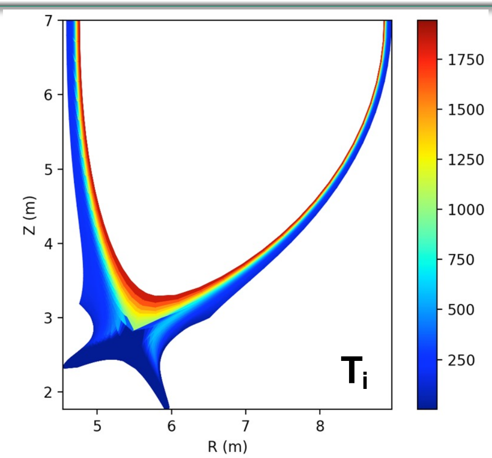
Numerics:

- Non-orthogonal mesh for fitting divertor
- Steady-state or time dependent

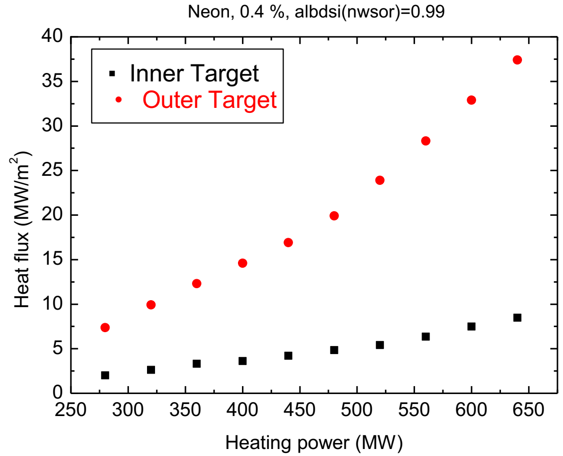
Benchmarking:

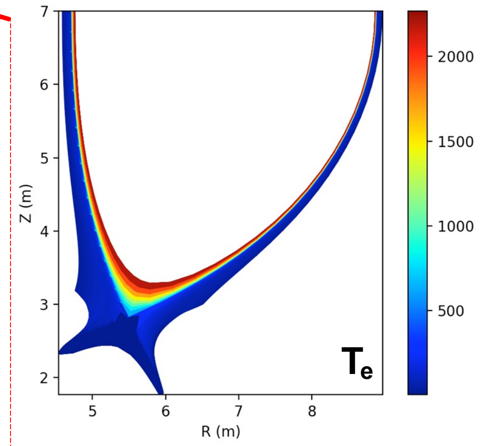
- Comparison ITER simulations give similar results as reference ITER SOLPS/EIRENE detached cases.



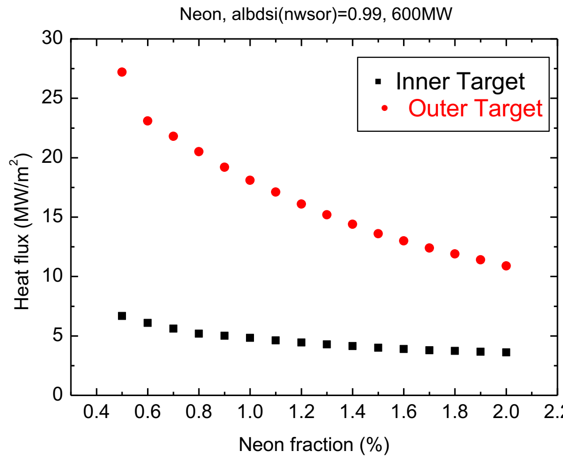


Ion Temperature





Electron Temperature



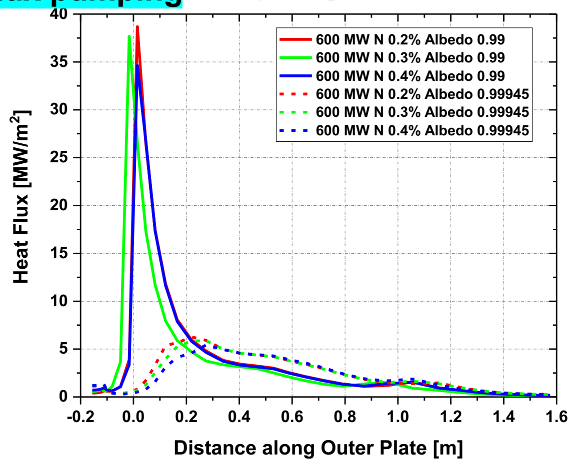
Ref.) T.D. Rognlien and M.E. Rensink, Fusion Engineering and Design , 2nd IAEA DEMO Workshop, 2017

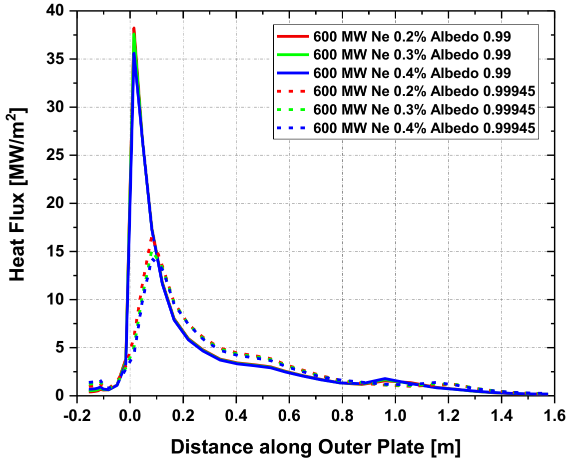
K-DEMO Case study: Heat Flux Profiles for Heating Power 600 MW

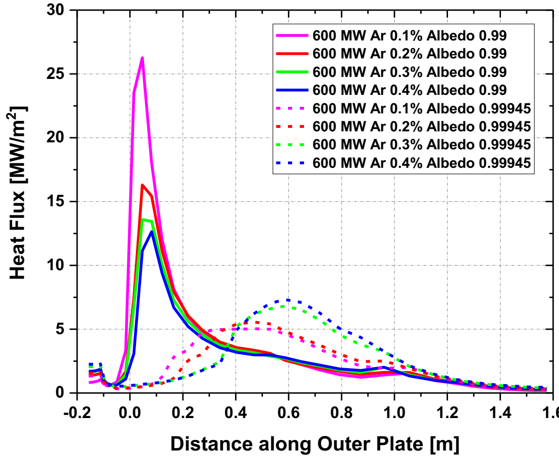
___: strong private-flux pumping
- - -: weak private-flux pumping

Impurity: N | **Impurity: Ne** | **Impurity: Ar**

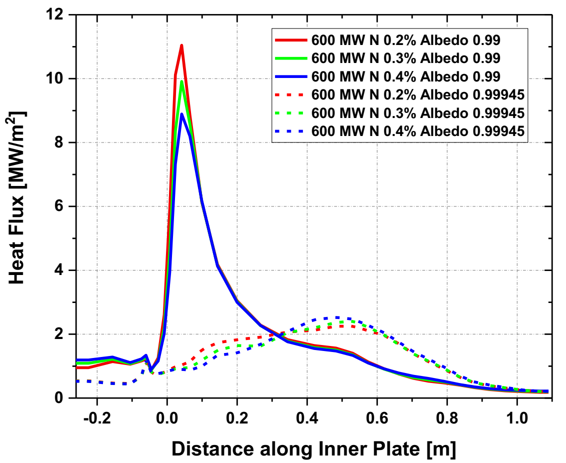
Outer Target

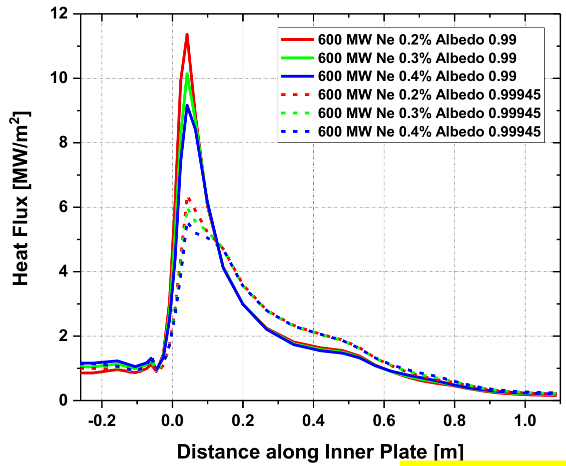


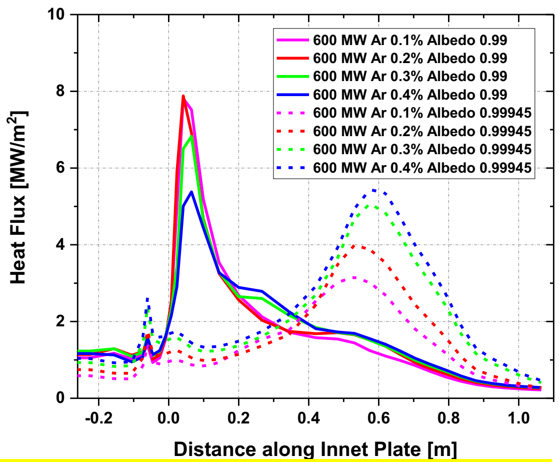




Inner Target







S.J.Kwon et al, presented at PSI-24 (2021)