Physics Basis and Design of Tungsten Divertor for CFETR

by

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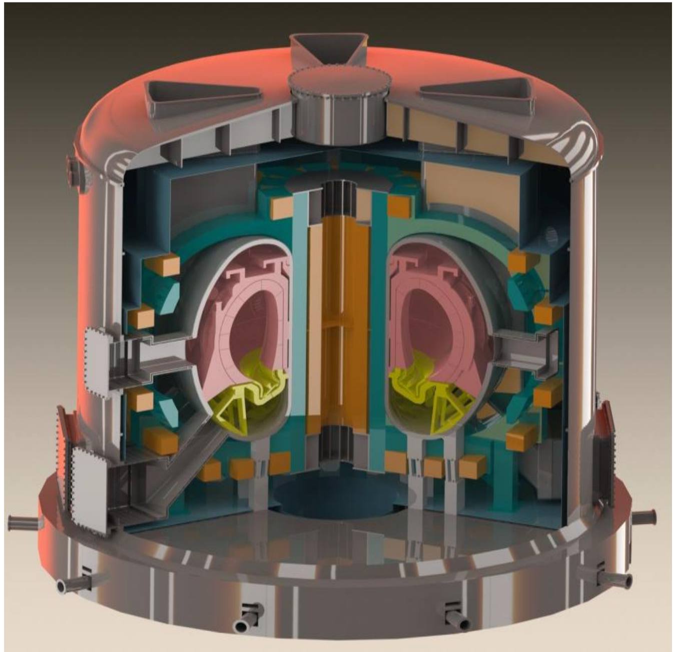

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Vienna, Austria, Nov. 7-10, 2022

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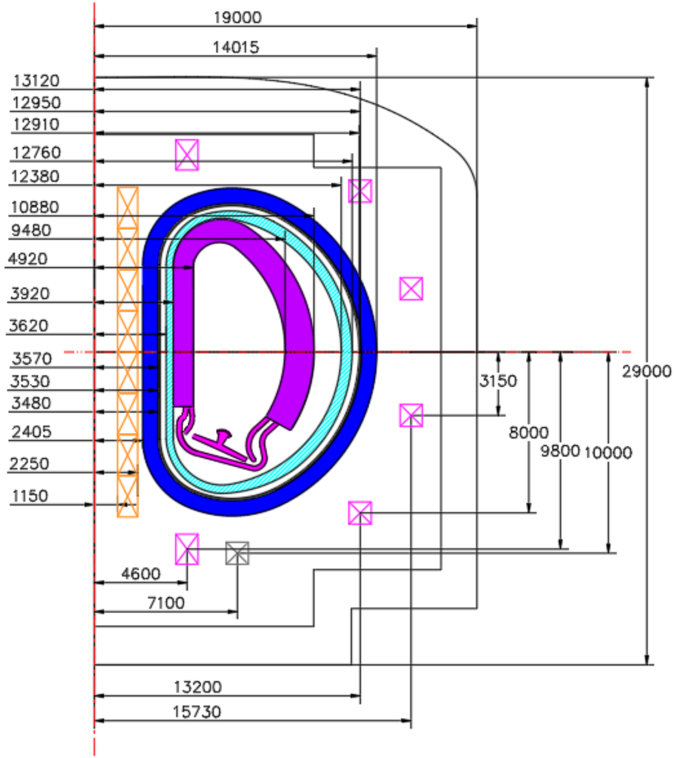
Outline

- Challenges and Requirements
- Considerations on CFETR Divertor Design
- Edge Modeling Results
- Effects of PFC Shaping and ELM
- Summary and Future Plans

CFETR aims to bridge the gaps between the fusion experimental reactor ITER and the demonstration reactor DEMO

- **Chinese Fusion Engineering Testing Reactor (CFETR) Missions**
  - Obtained burning Plasma for fusion power
  - Steady-state operation for fusion energy
  - Breeding tritium for T self-sustained

Major Radius R_0	**7.2 m**
Minor Radius a	**2.2 m**
Elongation	**2**
Toroidal B Field B_T	**6.5 T**
Plasma Current I_p	**14 MA**
Duty Cycle	**0.3-0.5**



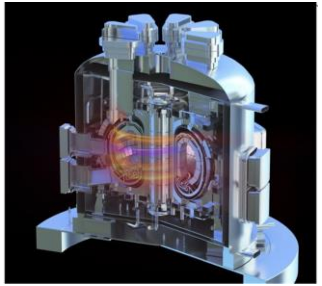
G. Zhuang et al., Nucl. Fusion 59 (2019) 112010

Plasma Exhaust Solution for CFETR Must Meet Requirements Beyond that of ITER

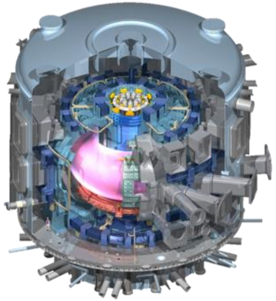
- **Material limits**
  - Divertor target heat load ≤ 10 MW/m²
  - Negligible divertor target erosion rate
- **Plasma limits**
  - Low impurity contamination
  - Efficient He exhaust
- **Engineering limits**
  - Compatible with the first-wall and blanket

Parameters	Steady-State (SS)	Hybrid	ITER (Q=10)
P_{fus} (GW)	1.0	0.92	0.5
$P_{heat}=P_{\alpha}+P_{aux}$ (MW)	305	251	173
P_{rad}^{core} (MW)	86	74	70
P_{sep} (MW)	219	177	103
P_{sep}/R (MW/m)	30	25	17

CFETR



ITER



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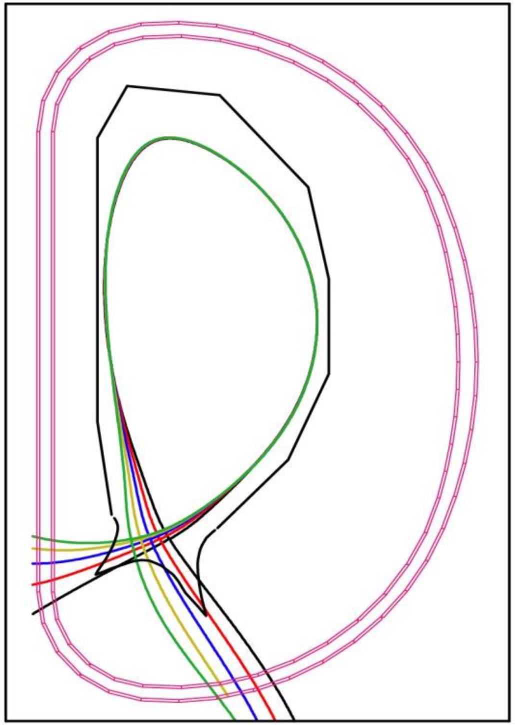
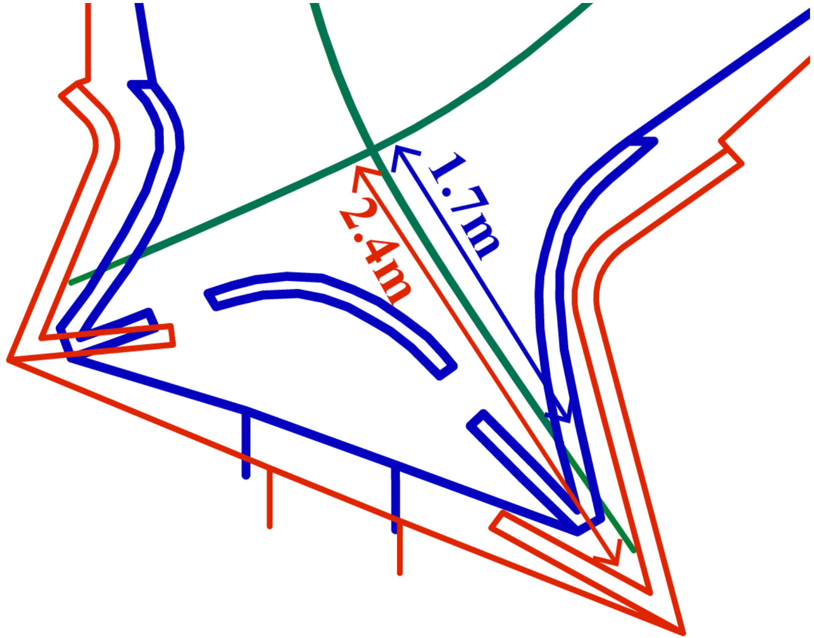
Considerations on CFETR Divertor Design

- **W-based materials for PFCs**
- **Magnetic configuration and the first wall geometry**
  - High δ limited by the design of first wall and divertor (optimal δ ~0.42)
  - Optimal X-point for enough space of divertor and blanket
  - dRsep ~ 6 cm is selected to avoid the secondary separatrix touches the first wall



Considerations on CFETR Divertor Design

- **W-based materials for PFCs**
- **Magnetic configuration and the first wall geometry**
- **Physics requirements**
  - $P_{peak} \leq 10\ MW/m^2$
  - $T_e \leq 5\text{-}10\ eV$
  - $n_{e\text{-}sep} \leq 3\times10^{19}\ m^{-3}$
  - $Z_{eff\text{-}ped} \leq 3$
- **Divertor configurations**
  - Conventional (Different leg length)



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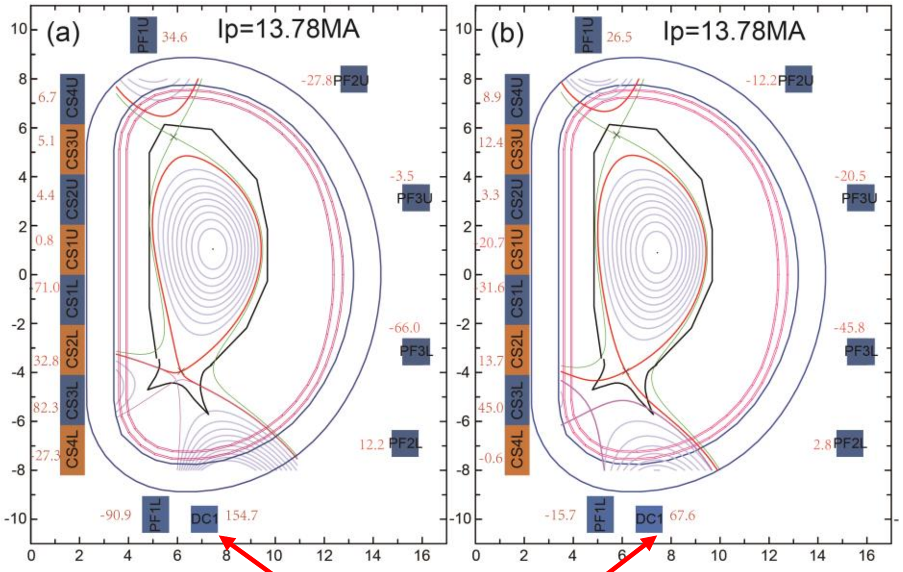
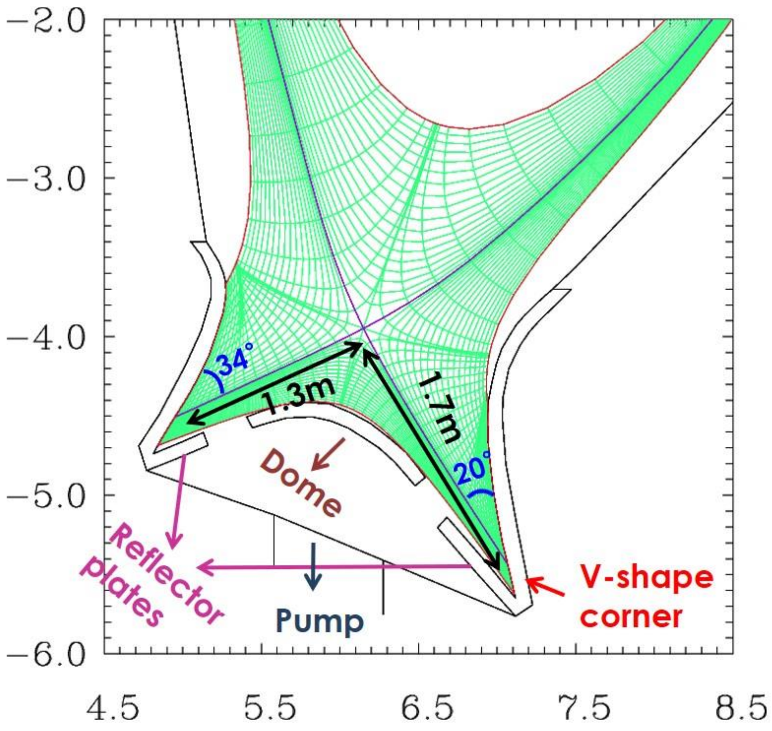
- **Divertor configurations**
  - Conventional (Different leg length)
  - Snowflake or XD not allowed



DC1 current exceeds the limit

The Baseline Conventional Divertor Design

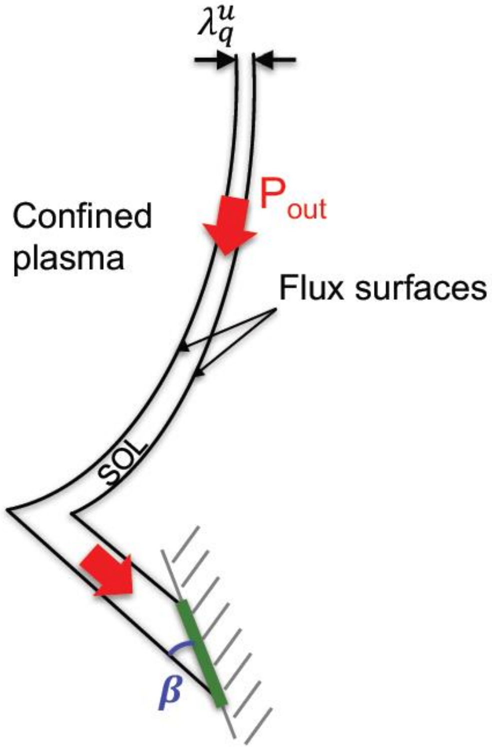
- **Vertical targets for both divertor**
  - Easier detachment near strike point
- **A V-shape corner**
  - Higher neutrals compression
- **Long divertor leg length**
  - Higher power radiation losses
- **Two pumping slots on the Dome**



0D Estimation of Divertor Peak Heat Flux

$$q^t_{\perp,peak} \approx \frac{P_{sep}(MW)}{A_w(m^2)} \approx \frac{P_{sep}\sin\beta}{4\pi R_t \lambda^u_q f_{\exp}} \qquad f_{\exp} = \frac{(B_p/B)_u}{(B_p/B)_t}$$

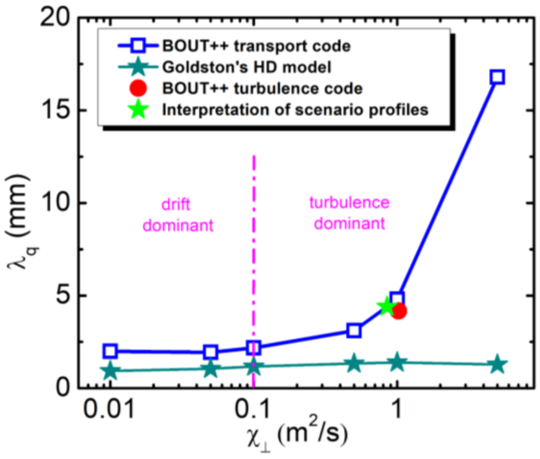
Parameters	Steady-State	Hybrid	ITER (Q=10)
P_{sep}(MW)	219	177	103
β(°)	20	20	25
R_t(m)	7.1	7.1	5.6
λ^u_q(mm)	2	2	1
f_{exp}	3.5	3.5	3.0
$q^t_{per,peak}$(MW/m2)	120	97	206

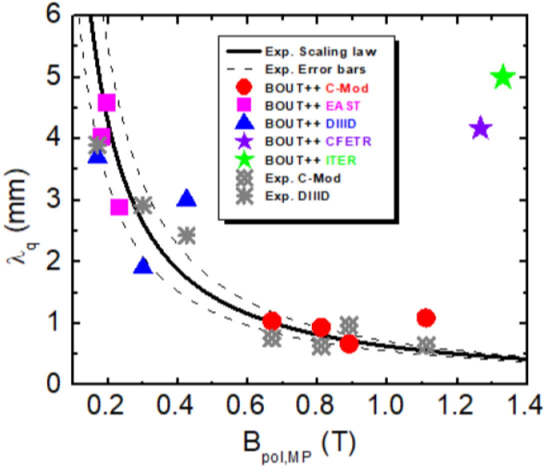


λ^u_q **Eich's scaling law** PRL 107 (2011) 215001

BOUT++ Simulation indicates that CFETR could have a Broadened Heat Flux Width

- **Two different mechanisms determine radial transport and heat flux width**
  - Drift dominant regime: follows Goldston's model and Eich's scaling
  - Turbulence dominant regime: determined by the turbulence thermal diffusivity
- **CFETR could be in a turbulence dominant regime**
  - $\chi_{\perp} > 0.1\, m^2/s$, turbulence dominant
  - $\chi_{\perp} < 0.1\, m^2/s$, Drift dominant





Z.Y. Li et al., Nucl. Fusion (2019)
X.Q. Xu et al., Nucl. Fusion (2019)

$\chi_{\perp}$~1.0m²/s , λ_q ~ 4.0mm

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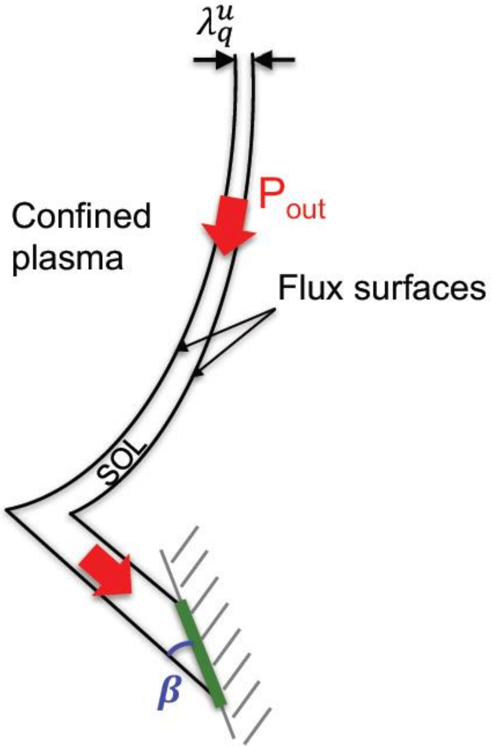
R_t(m)	7.1	7.1	5.6
λ_q^u(mm)	4	4	5
f_{exp}	3.5	3.5	3.0
$q^t_{per,peak}$(MW/m2)	60	48	41



λ_q^u BOUT++ simulation

0D Estimation of Divertor Peak Heat Flux

$$q^{t}_{\perp,peak} \approx \frac{P_{sep}(MW)(1-f^{div}_{rad})}{A_w(m^2)} \approx \frac{P_{sep}(1-f^{div}_{rad})\sin\beta}{4\pi R_t \lambda^u_q f_{\exp}}$$

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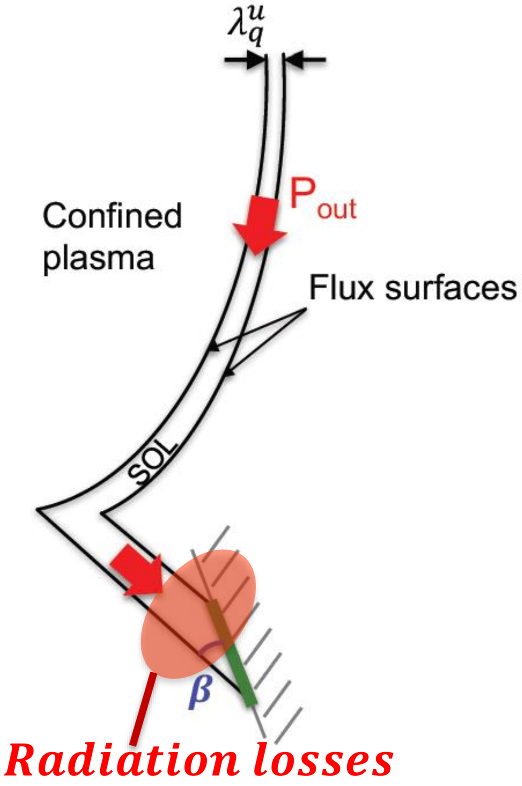
β(°)	20	20	25
R_t(m)	7.1	7.1	5.6
λ^u_q(mm)	4	4	5
f_{exp}	3.5	3.5	3.0
f^{div}_{rad}	0.84	0.8	0.76
$q^t_{per,peak}$(MW/m2)	9.6	9.6	9.8



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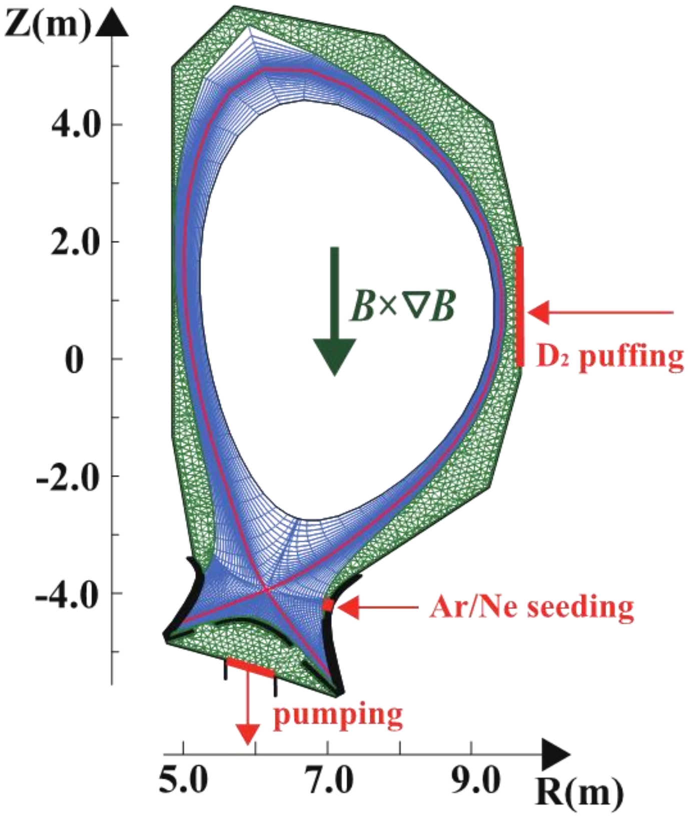
SOLPS Modeling of Edge Plasma for CFETR

- **SOLPS-ITER (Full drifts)**
- **Simulation setup**
  - P_{CEI}=200MW (P_e=P_i=100MW)
  - $\Gamma_{He}^{core} = 3.5 \cdot 10^{20}\ s^{-1}$
  - Ar/Ne puffing at outer divertor $\Gamma_{Ar/Ne}^{seed} = (1-10) \cdot 10^{19}$ at/s
  - D_2 puffing from upstream $\Gamma_{D}^{fuel} = (4-10) \cdot 10^{22}$ at/s
  - W divertor but no sputtering



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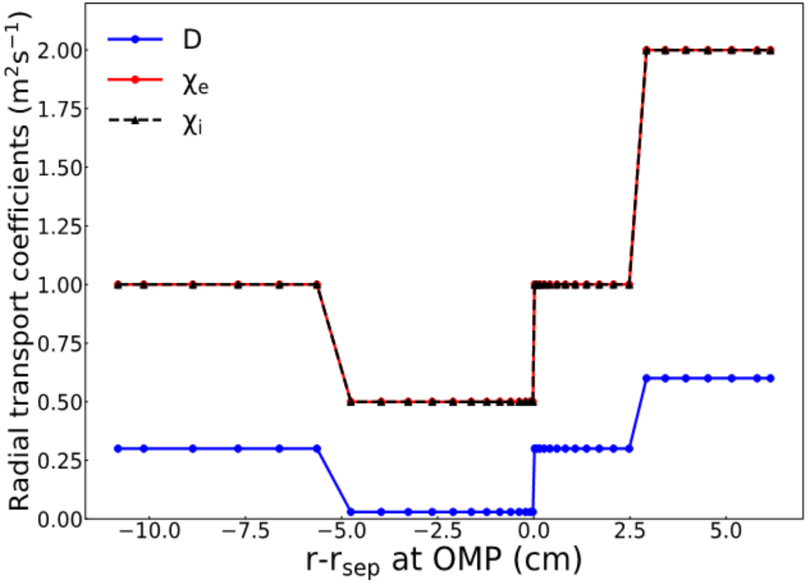
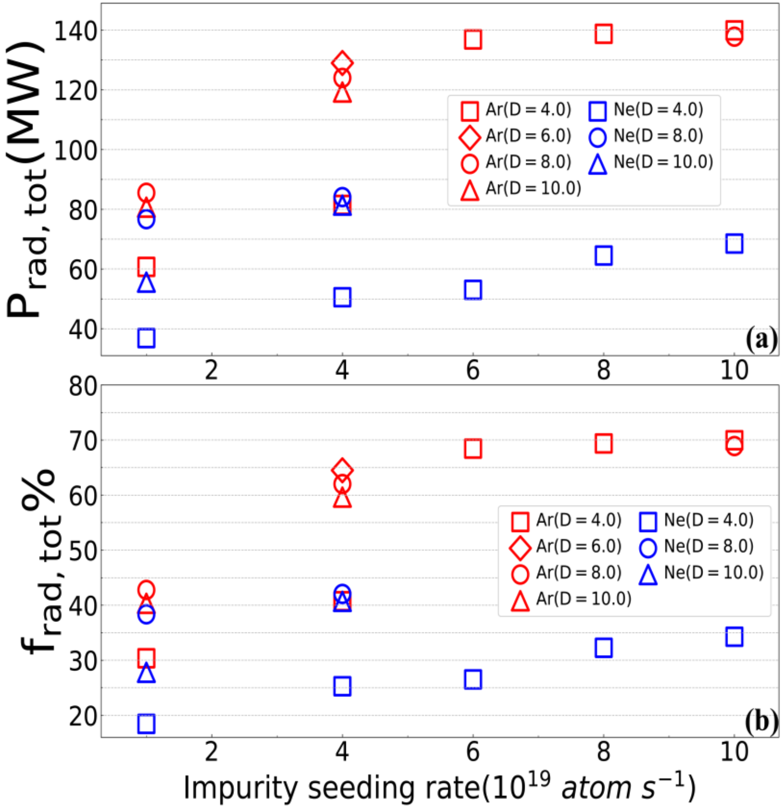
  - W divertor but no sputtering
  - Anomalous transport coefficients: H mode



λ_q ~ 4.0mm

More Efficient Power Dissipation by Ar seeding than Ne

- **Radiation can be increased by higher impurity seeding rate and fueling rate**
  - The highest radiation power ~140 MW



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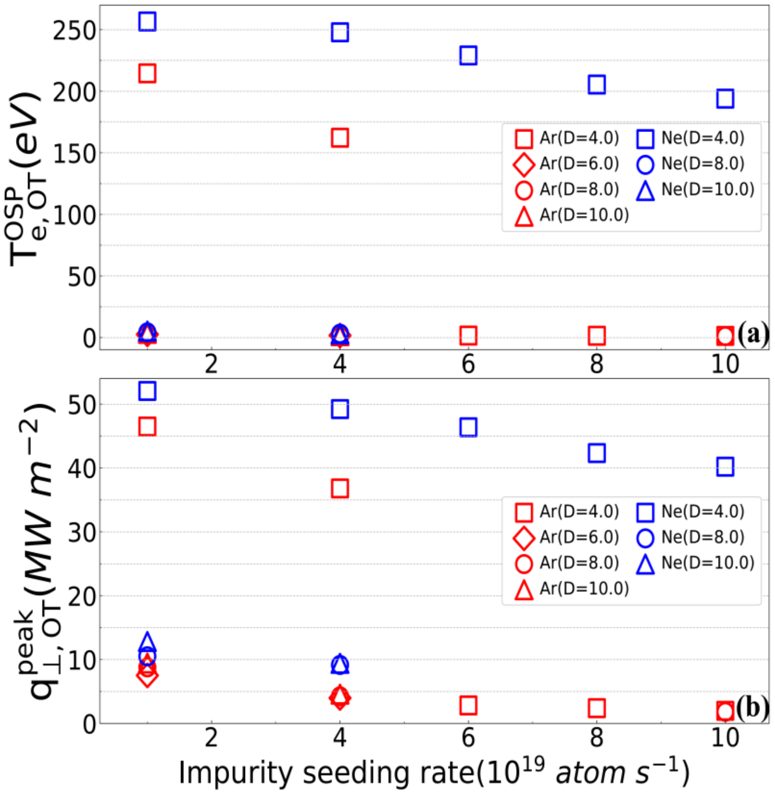

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- **Radiation can be increased by higher impurity seeding rate and fueling rate**
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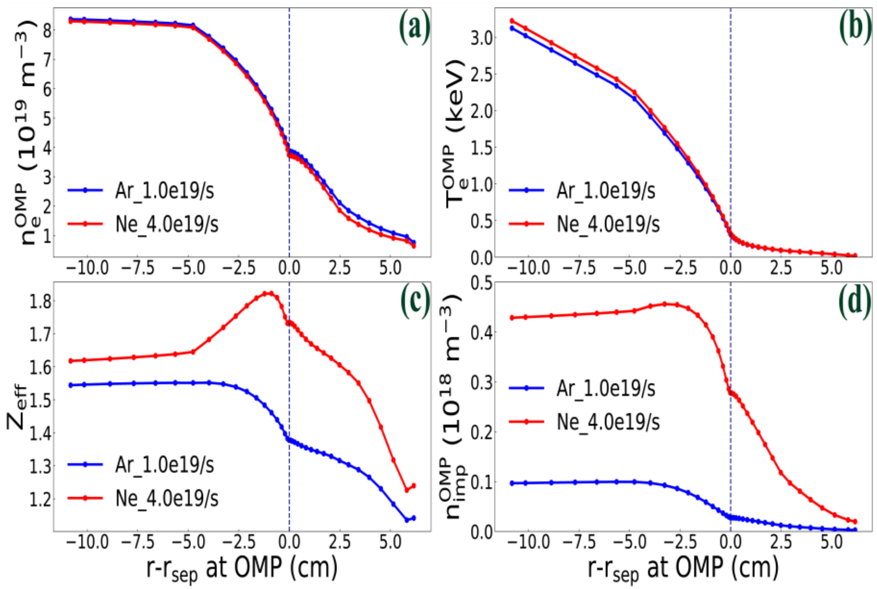
  - Lower heat flux and T_e at the target
- **Much more Ne is required to have similar radiation power with Ar**
  - Higher impurity contamination for Ne
- **Compatible with core plasma**
  - $Z_{eff\text{-}ped} < 2$



D_2 puffing rate 1×10^{23} s^{-1}

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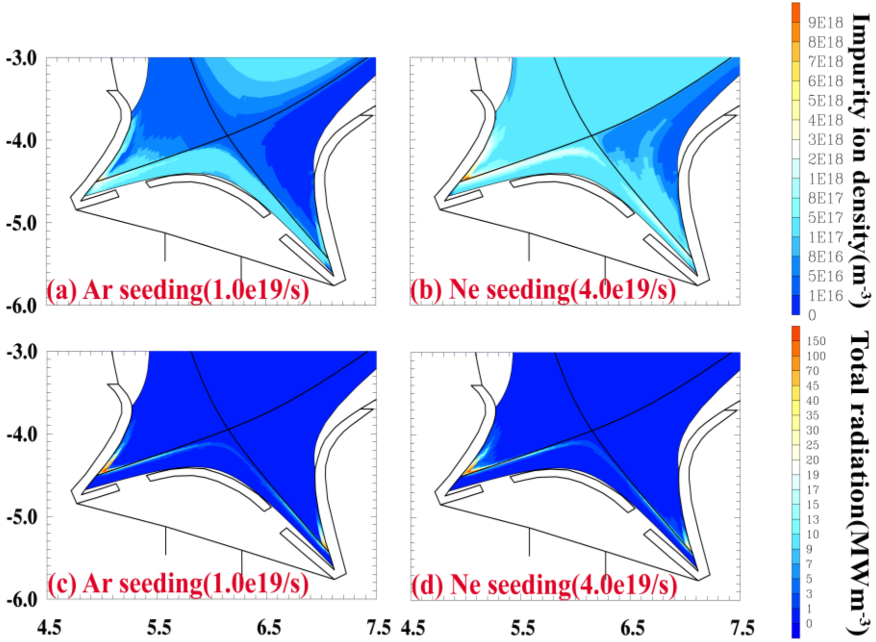

D_2 puffing rate $1\text{x}10^{23}$ s^{-1}

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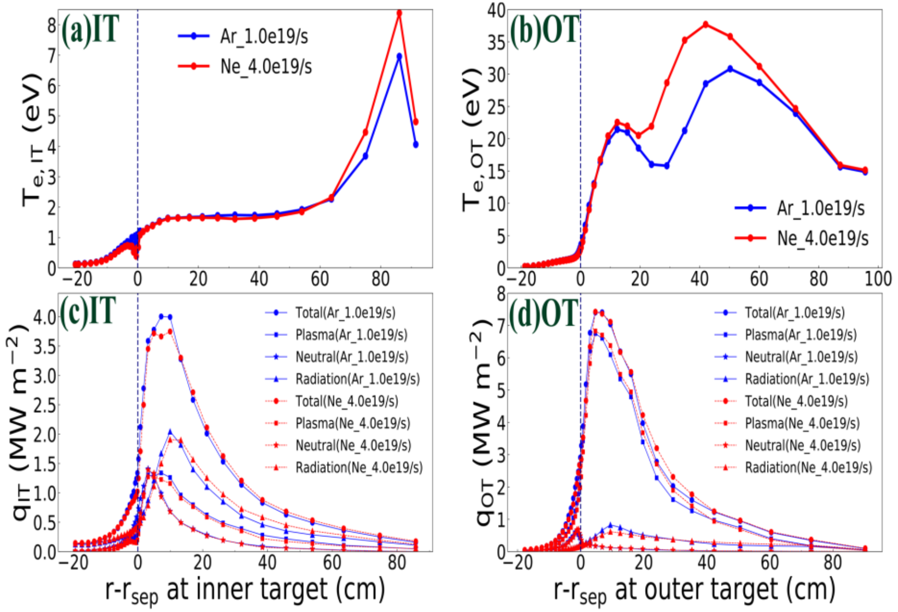
- **Compatible with core plasma**
  - $Z_{eff\text{-}ped} < 2$
  - Radiation mainly in divertor
- **Partial detachment for both targets**
  - $P_{peak} < 8$ MW/m^2
  - High T_e at the far-SOL region



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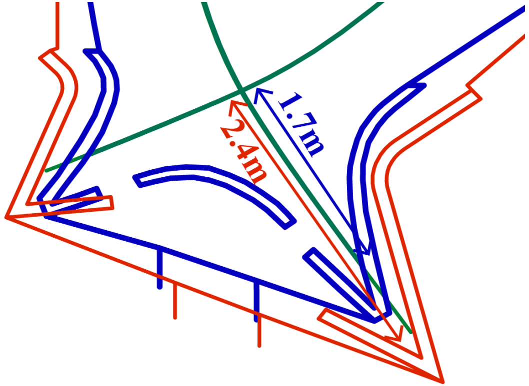
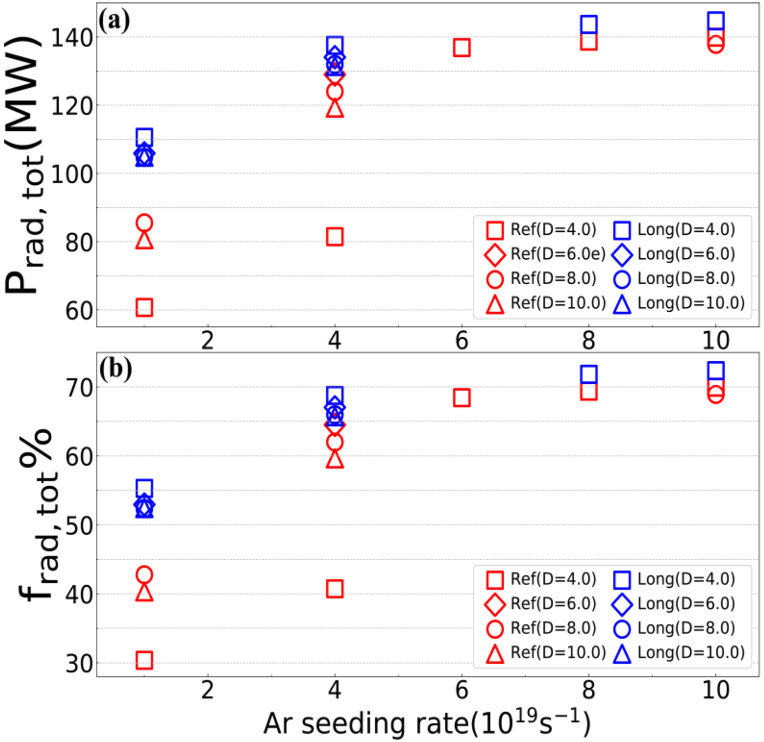
Longer Divertor Leg Length can Meet the Physics Requirements More Easily

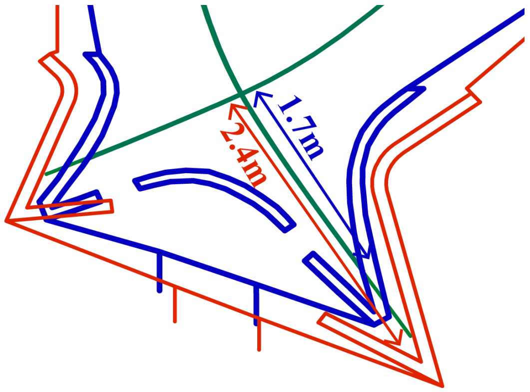
- **Radiation increased significantly for longer leg length**

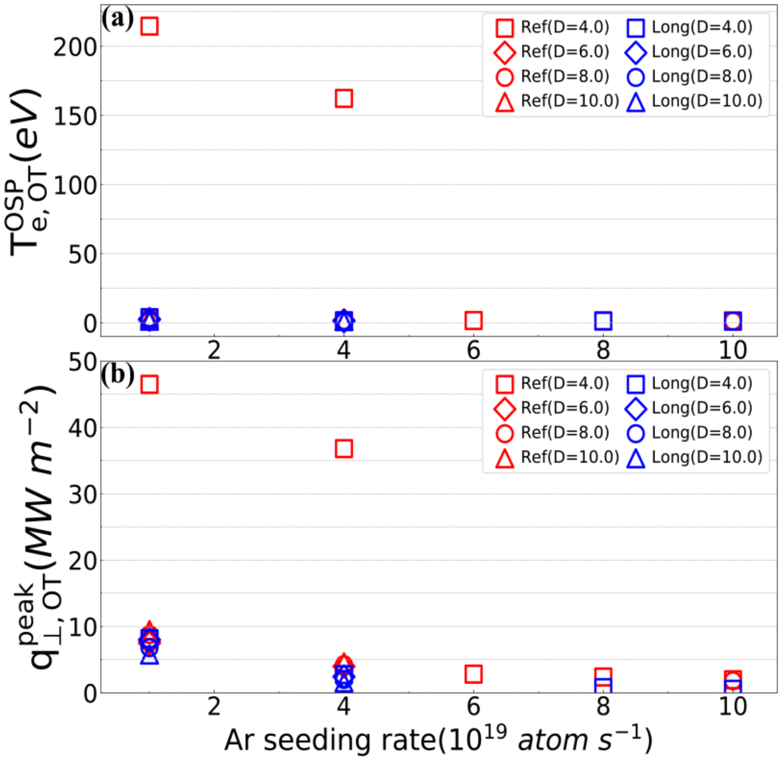




Longer Divertor Leg Length can Meet the Physics Requirements More Easily

- **Radiation increased significantly for longer leg length**
  - Lower heat flux and T_e at the target
  - $P_{peak} < 10\ MW/m^2$ for all cases





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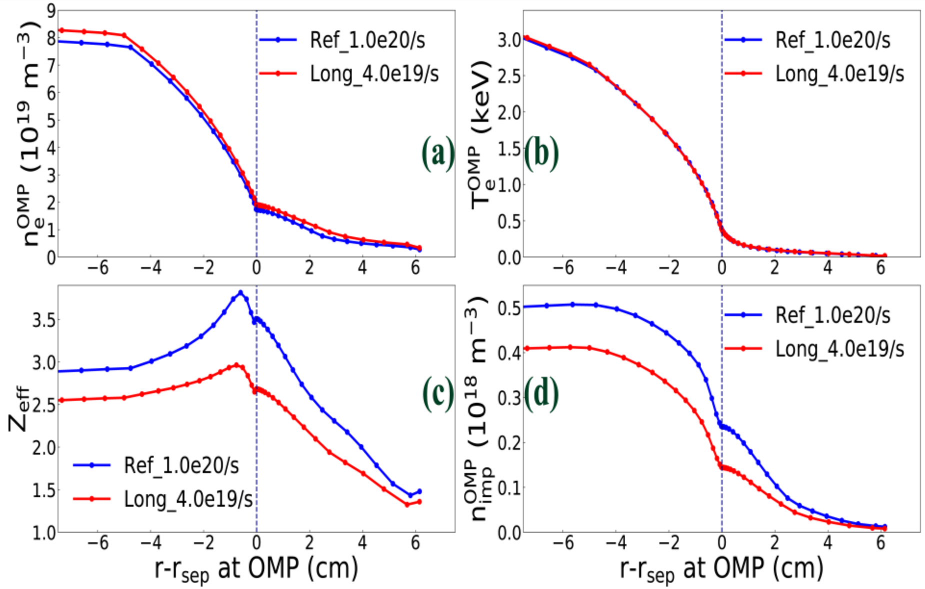
- **Less Ar is required for long-leg divertor to have similar radiation power**
  - Lower impurity contamination

Ar seeding



D_2 puffing rate $8x10^{22}\ s^{-1}$

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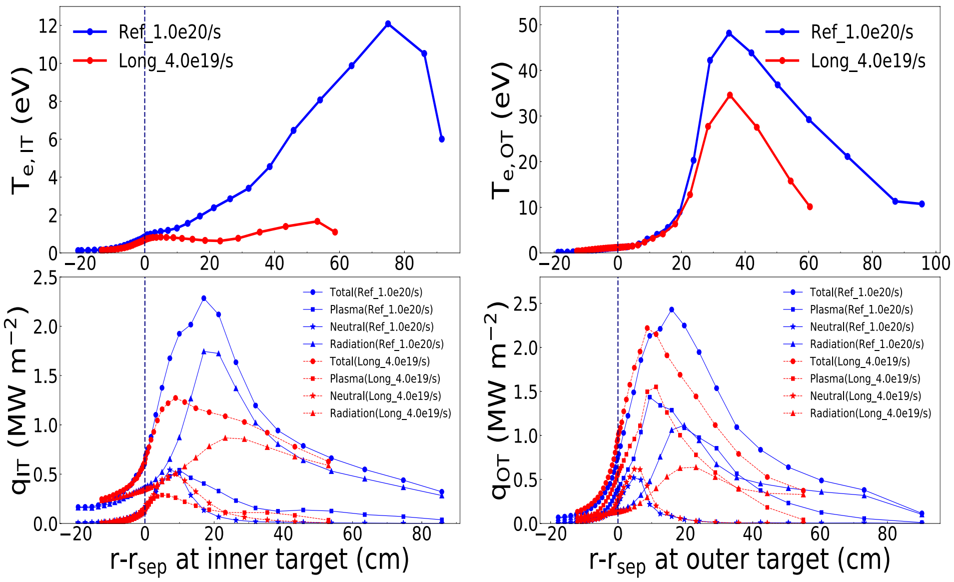


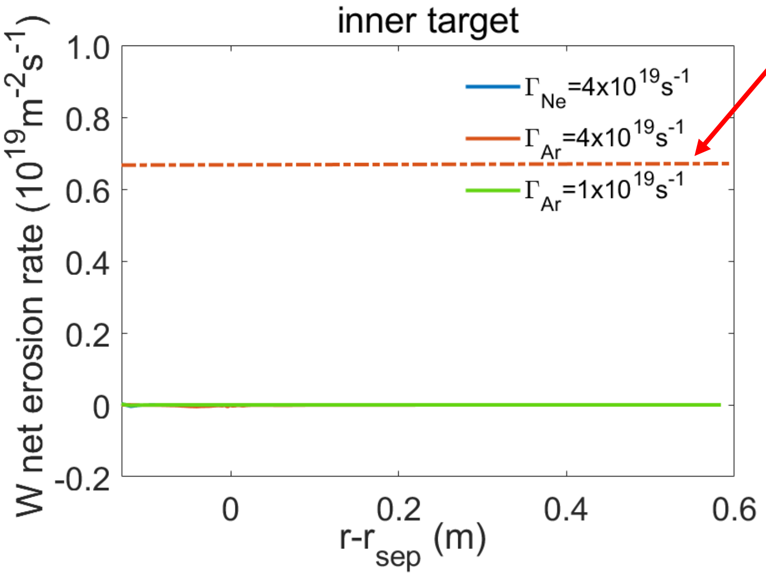
D_2 puffing rate $8x10^{22}\ s^{-1}$

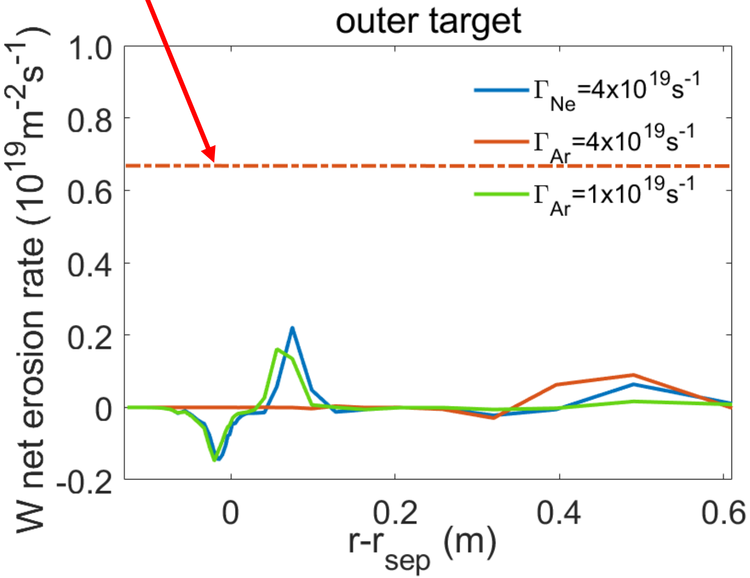
W Net erosion Rates at Both Divertor Targets Meet the Lifetime Requirements

- **Similar W erosion rate for Ne and Ar seeding**
- **Inner divertor: net deposition**

Lifetime requirements:
3 years, 0.5 duty cycle
5 years, 0.3 duty cycle

DIVIMP Simulation





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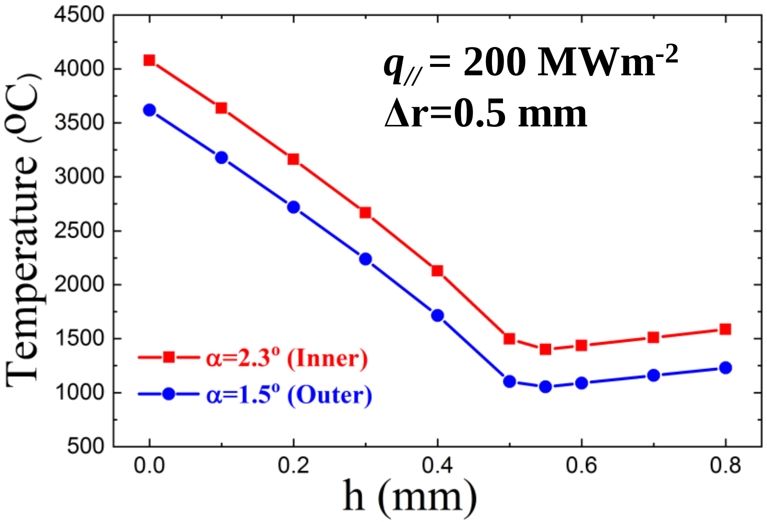
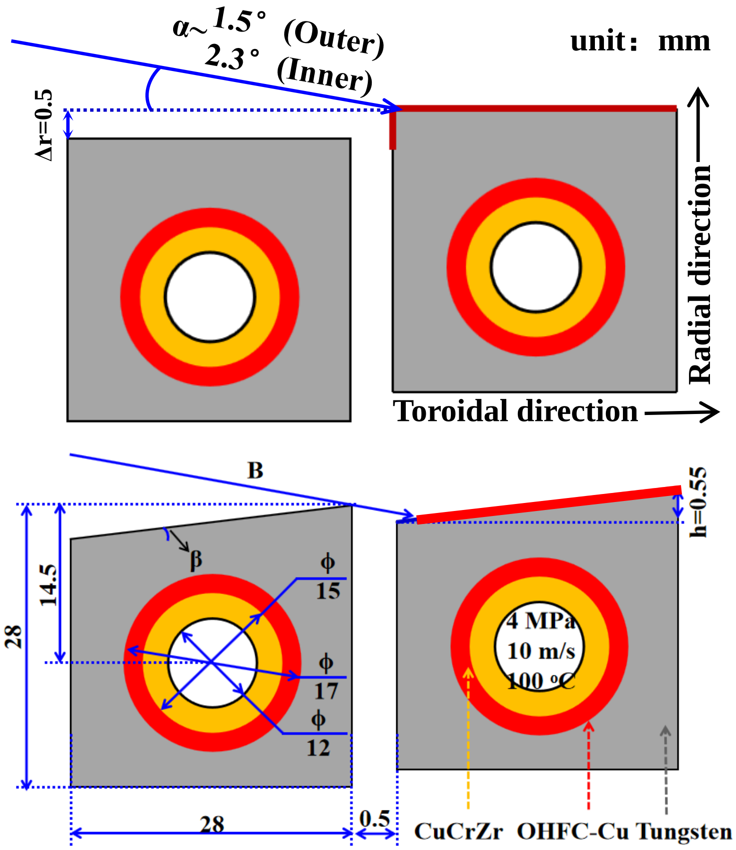
W PFCs Need to be Shaped to Avoid Leading Edges

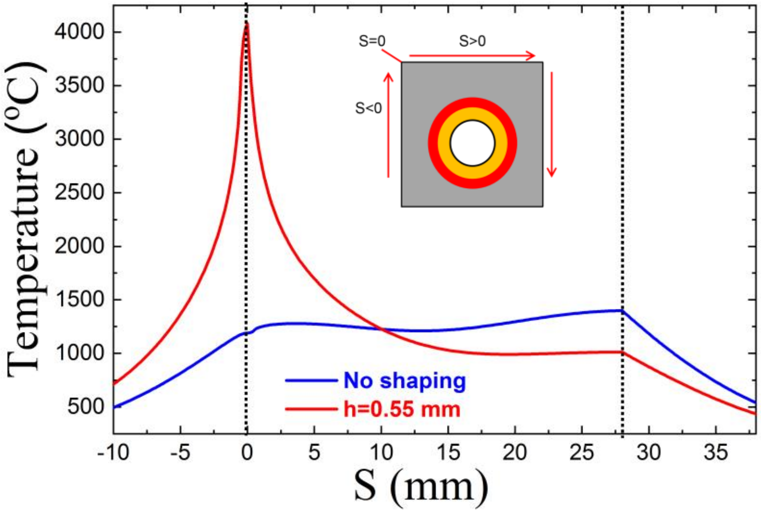
- **Misalignment between adjacent PFCs leads to extremely high local heat flux**
- **Toroidal chamfer to protect edges but minimize shadowed region**
  - ITER-like fishscale shaping, h=0.55mm

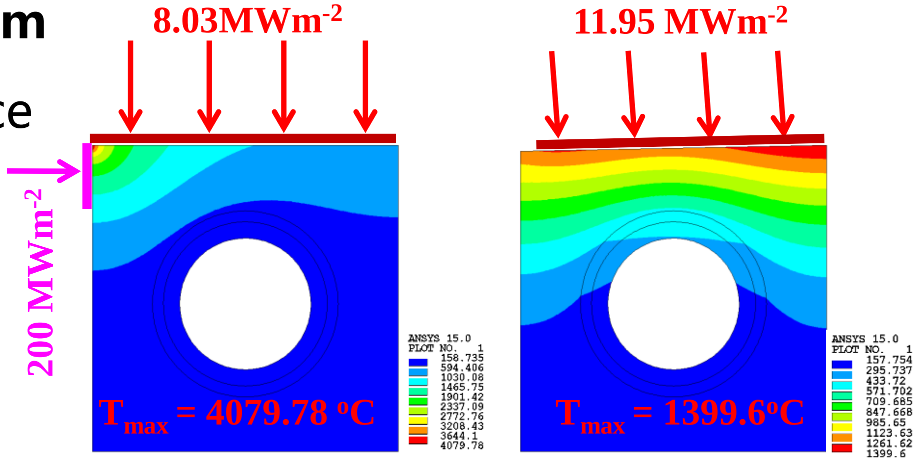




W PFCs Need to be Shaped to Avoid Leading Edges

- **ITER-like fishscale shaping, h=0.55mm**
  - Increase field line angle and surface heat loading by 49%
  - Reduce maximum surface temperature by 66%





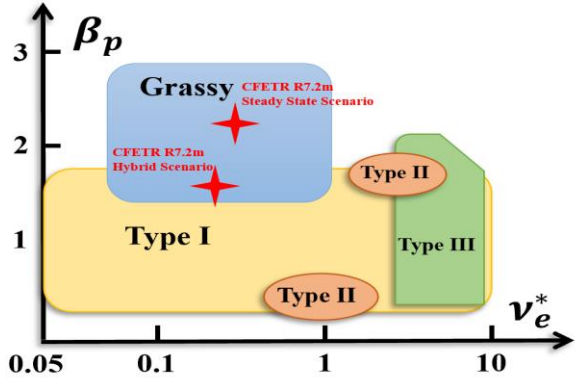
No shaping

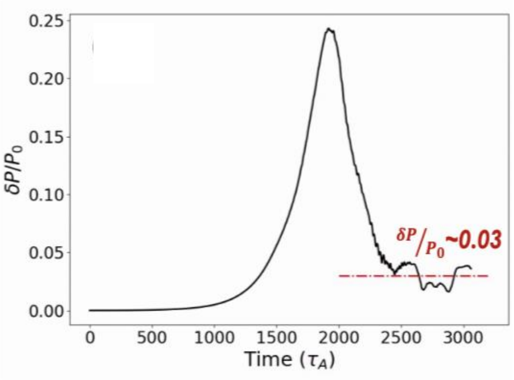
h=0.55mm

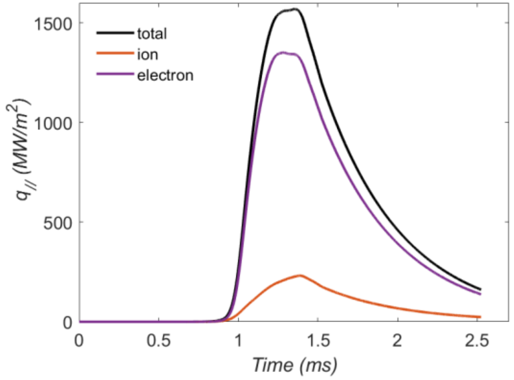
ANSYS Simulation

Transient Heat Flux has been Calculated using the BOUT++ Simulations

- **BOUT++ nonlinear simulation shows a grassy ELMy characteristic for hybrid scenario**
  - Relative low pressure perturbation level ~3%
  - ΔW/W ~ 0.13%
- **Parallel peak transient heat flux is around 1600MW/m²**
- **Needs further modeling on various pedestal parameters**





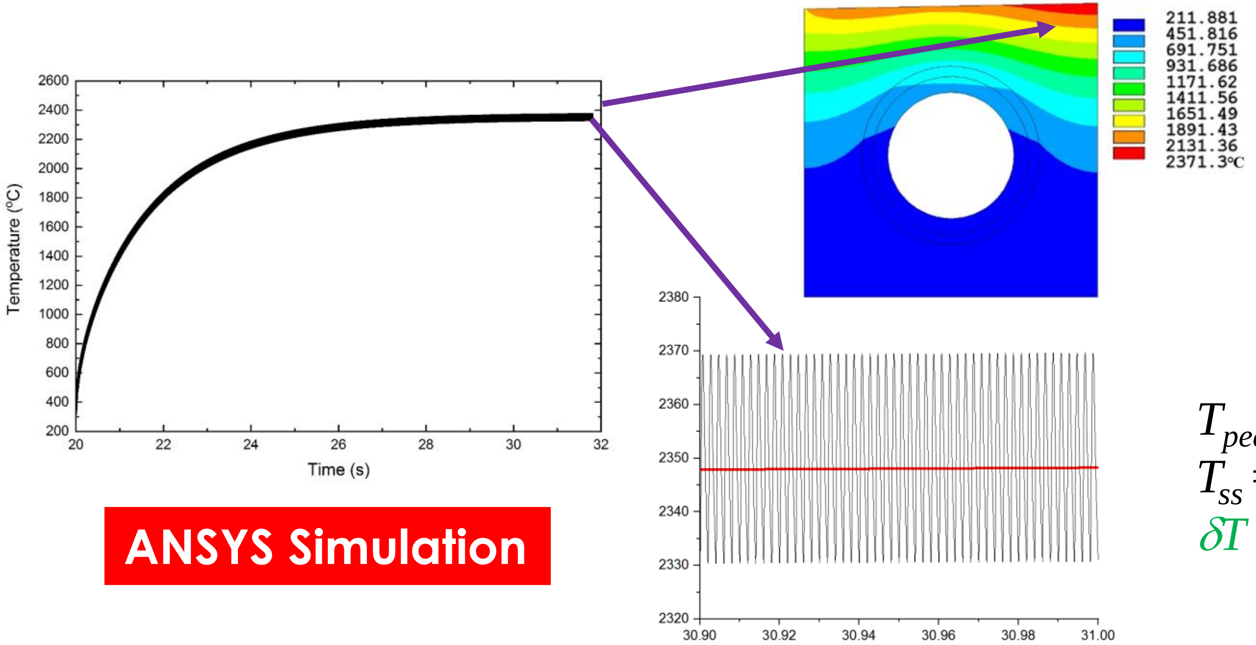


Y.R. Zhu Nucl. Fusion (2020), Z.Y. Li et al., PPCF (2021)

ELM Effects on Material Lifetime has been Evaluated

- **Total heat flux including ELM contribution can not melt W PFCs**

$Q_{ELMpeak//}$ (MW/m²)	t_{ELM} (ms)	f_{ELM} (Hz)	$Q_{inter\perp}$ (MW/m²)	$\frac{\partial W}{W}$
1600	1.0	500	2	0.13%

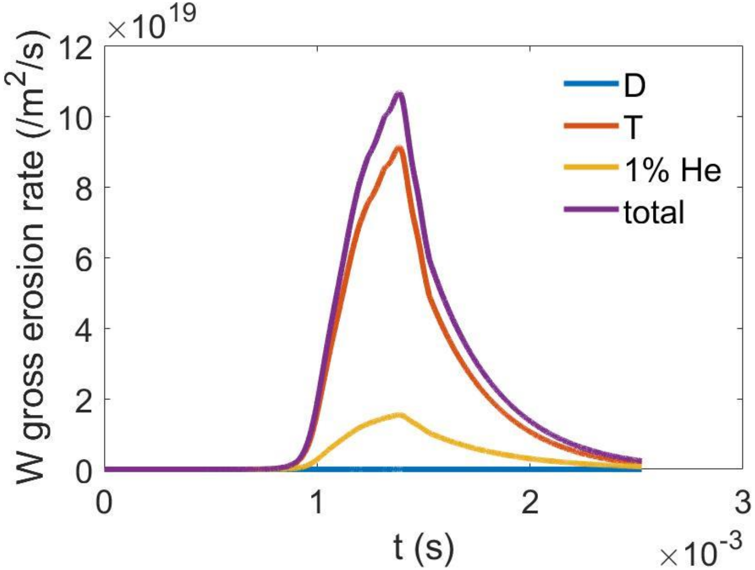


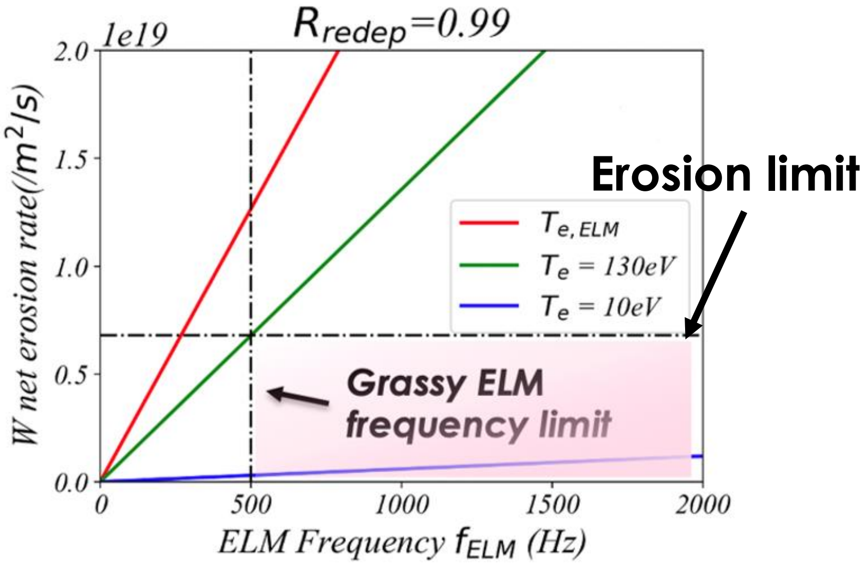
ANSYS Simulation

$T_{peak} = 2371$ °C
$T_{ss} = 2348$ °C
$\delta T \approx 20$ °C

ELM Effects on Material Lifetime has been Evaluated

- **Intra-ELM W erosion rate strongly depends on the target sheath conditions**
- **A detached divertor helps to broaden the operation regime**





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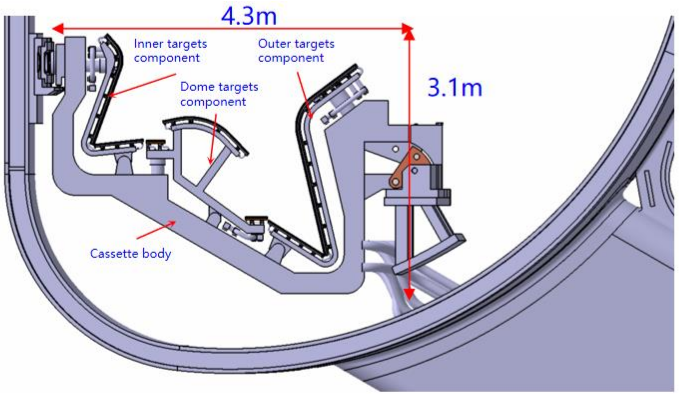
Summary and Future Plans

- **Conventional divertor configurations with different geometries have been designed and evaluated**
- **SOLPS simulations helps to obtain a possible solution for CFETR conventional divertor**
  - Target heat flux, PFCs lifetime and core compatibility meet the physics requirements
  - Longer divertor leg length has a distinct advantage on radiation losses
- **Influence of ELMs on target lifetime has been preliminarily evaluated**
- **Nest step**
  - Optimization of divertor geometry
  - Sensitivity scan of uncertain parameters



Thank you for your attention !