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Solutions for the transients and heat load variations of the CFETR operation scenarios

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Content

- **Introduction**
- **Solutions with special emphasis on:**
  - Identification of a grassy ELM pedestal regime compatible with core and divertor
  - Long-leg radiative (detached or semi-detached) divertor
  - Vertical displacement events (VDEs) control and disruption mitigation
- **Conclusion & discussion**

Introduction

Mission of scenario development for China Fusion Engineering Test Reactor (CFETR)

CFETR is aimed to bridge the gap between ITER and DEMO/PFPP.

Missions

- **P_{fusion} = 200 ~ 1500 MW**
- **High duty time ~ 50%**
- **Tritium self-breeding**
  Tritium breeding ratio (TBR) $\gtrsim$ 1 over at least a closed cycle for tritium fueling with high fusion power
- **Exploration for self-sustained burning**
- **R&D for materials**

Scenario design

Developing long-pulse hybrid & steady-state operating scenarios with high tritium burnup fraction

Introduction

High Level Targets of Physics Design

I. **High performance -** Simultaneous achievement of Q=10 and P_{fusion}=1000 MW

II. **Stable, robust operation -** with low disruptivity and tolerance to steady-state and transient heat load

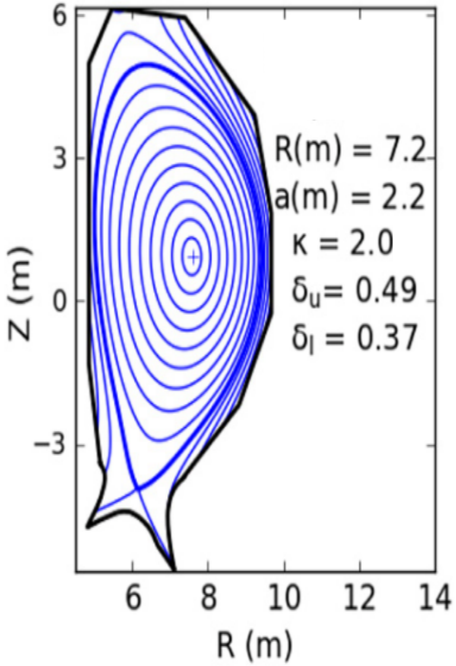
III. **Optimized for tritium self-sufficiency**

IV. **Avoidance of significant alpha particle transport loss**

Introduction

Requirements/constraints in engineering/ physics

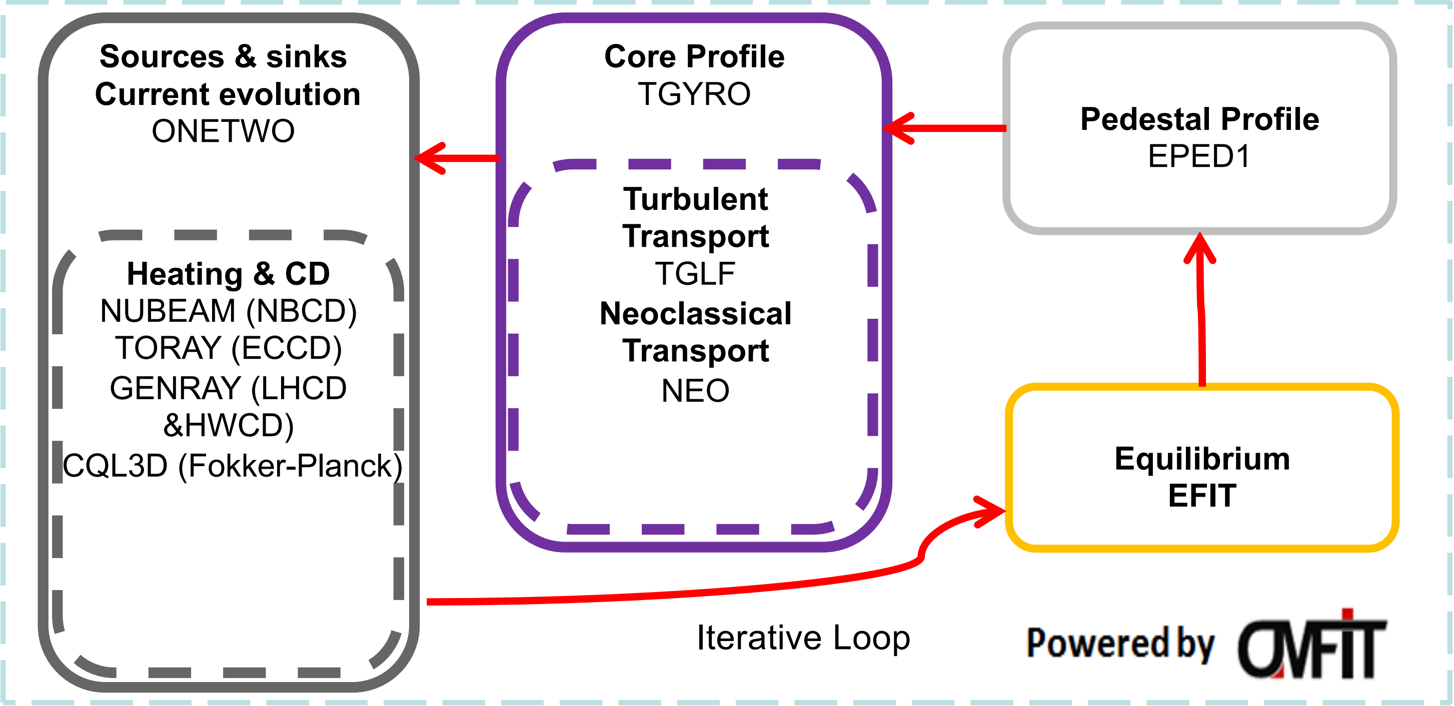
- **Shape**
  - Single null in the bottom with δ ~ 0.42
- **Ohmic Flux**
  - ~290 Volt-sec in total
  - Ramp-up consuming ~250 Volt-sec
    ~ 40-50 VS for flat-top
- **H&CD**
  - Total power ≤ 80 MW (saving space for tritium blanket)
  - Takes up only 3 ports at mid-plane LFS
  - Priority: (EC, NB), with LH and other RFs as backup
  - NBI
    - Suggested beam flux: 20MW/1MeV NNBI
    - 2 beams + 1 beam (backup)
- **Pulse Duration**
  - ≳ 4 hours (a full cycle for tritium fueling)



Introduction

Coupled core-pedestal modeling with physics-based models are applied for target plasma at flattop phase with self-consistent H&CD

Workflow for the modeling of plasma profiles beyond the preliminary 0-D design



Sources & sinks
Current evolution
ONETWO

Heating & CD
NUBEAM (NBCD)
TORAY (ECCD)
GENRAY (LHCD &HWCD)
CQL3D (Fokker-Planck)

Core Profile
TGYRO

Turbulent Transport
TGLF
Neoclassical Transport
NEO

Pedestal Profile
EPED1

Equilibrium
EFIT

Iterative Loop

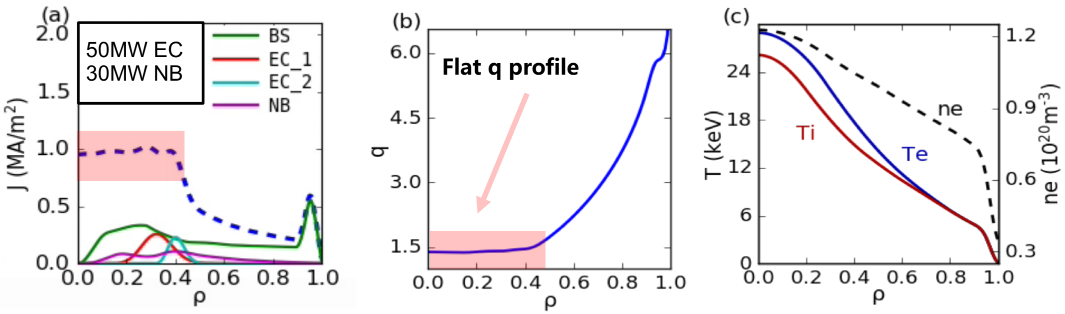
Powered by OMFIT

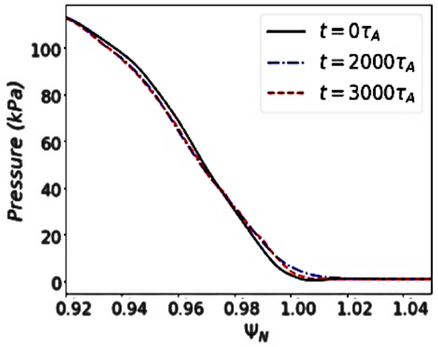
*Based on the similar workflow reported in Meneghini, O., Physics of Plasmas 2016

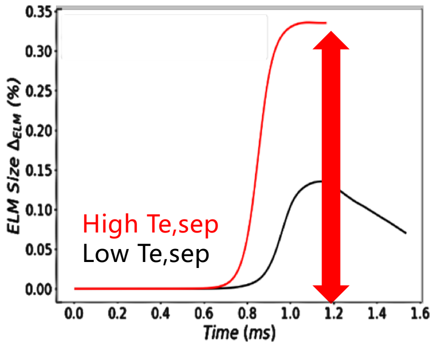
Introduction

Baseline case for hybrid scenario

- **Neutral beams and EC waves (optimized)**
  - 250 GHz EC wave
  - 1 MeV beams
- **Enhanced confinement in core plasma**
  - Flat q profile in core
  - Including EM stabilization effect
- **Grassy ELMy pedestal**
  - Nonlinear BOUT++ simulations# :
    ELM induced power loss < 0.4% pedestal energy







- ***4li* (**β_N** limit) = 3.8**
- **Assumptions: Flat profile of **Z_{eff}** and Helium fraction ~ 5%**

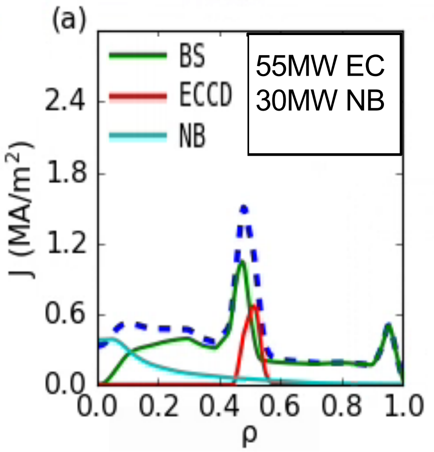
Chen, J., Nuclear Fusion 2021; Li, Z. Y. Plasma Physics and Controlled Fusion 2021

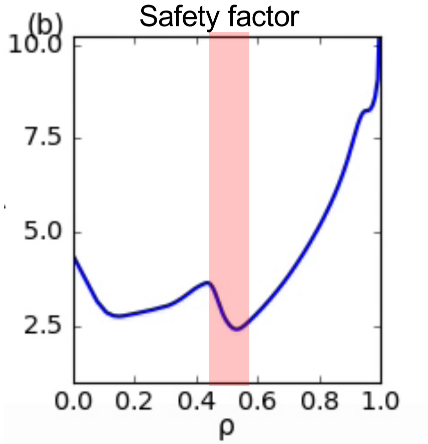
Target plasmas for steady-state scenario

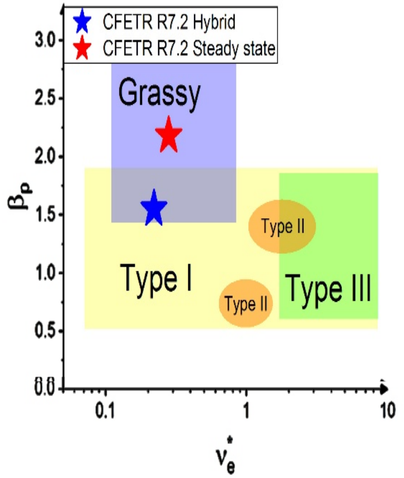
- **Neutral beams and EC waves**
  - Similar to the baseline case for hybrid scenario
- **Local reversed shear controlled by ECCD**
  - Enhanced confinement ITB*

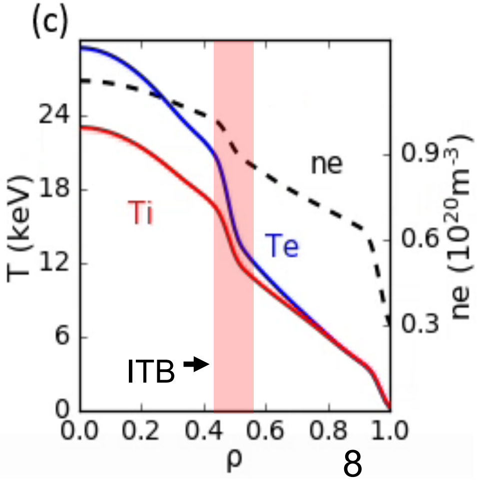
P_{fus}(GW)	H_{98y2}	β_N/β_P	f_{bs}/l_i	I_p (MA)
1.0	1.33	3.0/2.5	0.78/0.8	10.5

- **Operating point at the center of grassy ELMy regime**
- **n=1,2 modes are stable even without wall**
- **Beta limit problem (next)**









*NOTE: The turbulent transport is simulated with electrostatic TGLF for this case.

Ideal MHD instability for SS scenario

- **1.5-D simulations are guided by a rough scaling law to avoid global ideal MHD instabilities.**

$$\beta_N < \beta_{N,max} = 4li$$

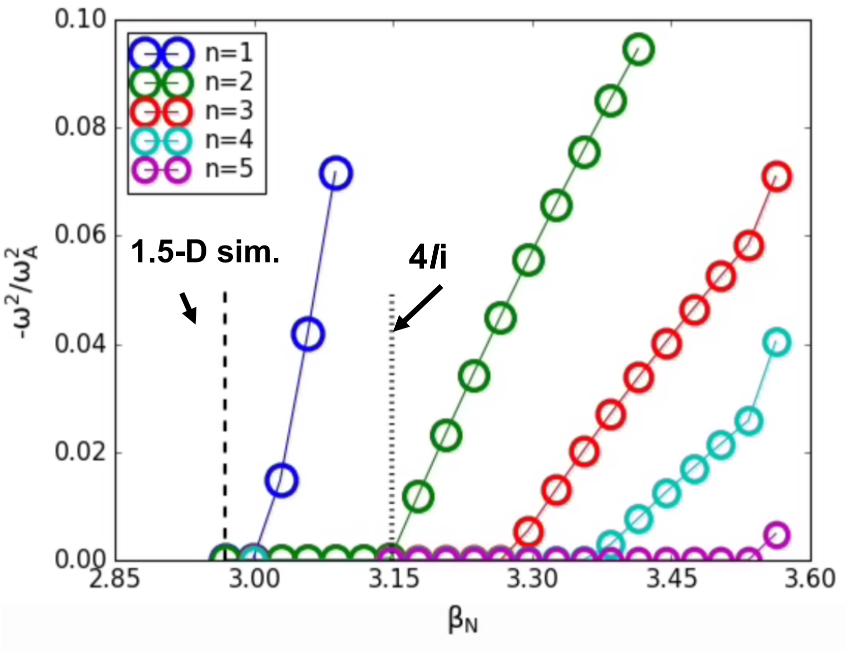
(Lin-Liu, et al. 1999 Physics of Plasmas 3934)

- **The present 1.5-D case has a small margin:**

$$\beta_{N,max} - \beta_N \approx 0.18$$

- **Ideal MHD code confirms that β_N is slightly lower than the computed ideal no-wall limit.**

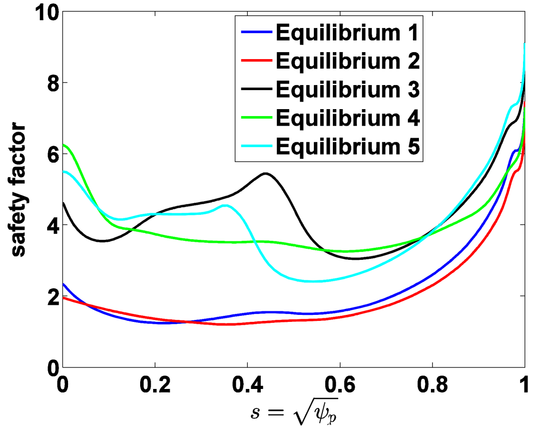
Ideal no-wall MHD instability growth rate by GATO

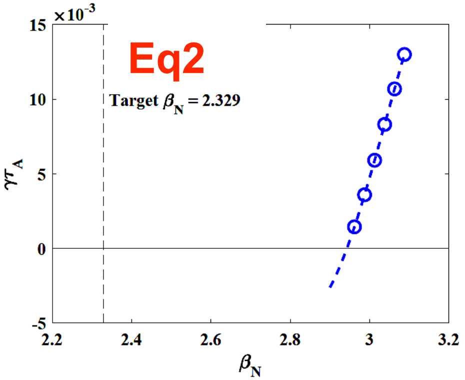


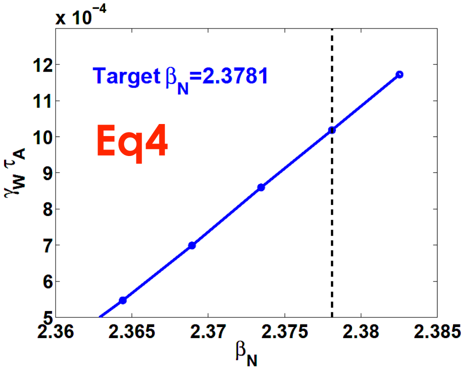
Introduction

Ideal MHD Robustly Stable – over a range of current profile

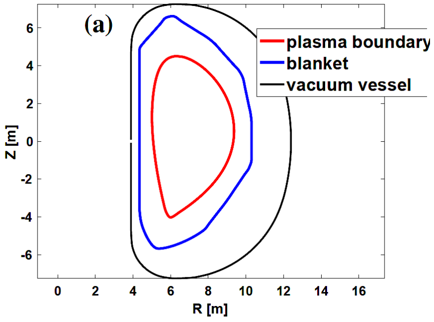
- The ideal MHD stabilities are investigated by both the MARS-F and the AEGIS codes

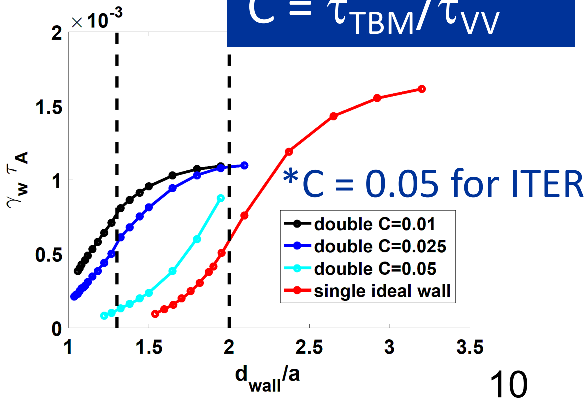






The ideal MHD mode for the CFETR scenarios is nearly marginal stable with synergistic effect of TBM and VV if material of TBM is the same to ITER.





$C = \tau_{TBM}/\tau_{VV}$

*C = 0.05 for ITER

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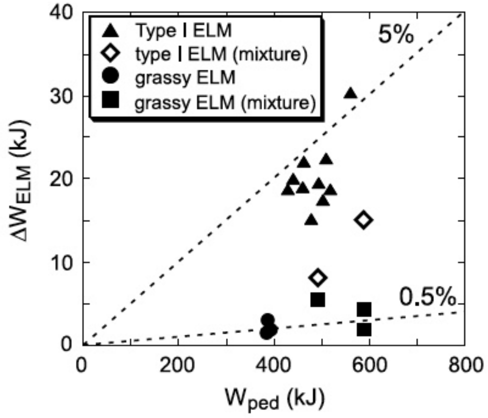
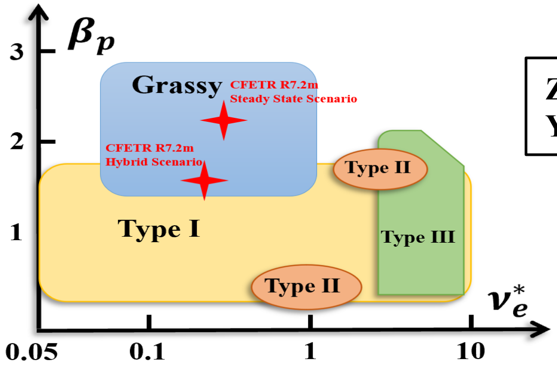
Grassy ELM Regime

Mitigation of Transient Heat Load on PFC - Grassy ELM Operation has Many Advantages

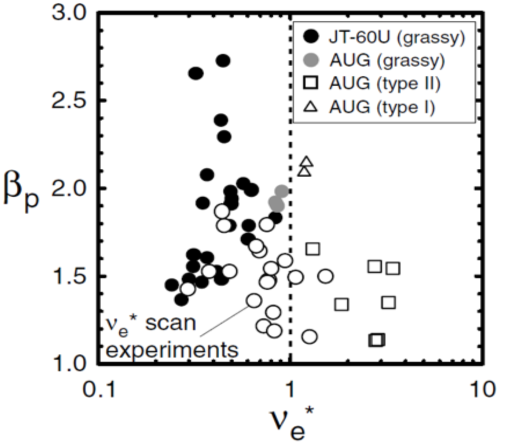
- Lower transient heat flux to the first wall (requires ΔW/Wped << 1%)
- Beneficial impurity cleansing effect
- High β_p and intermediate ν^* compatible with high bootstrap fraction and divertor solution
- The parameter space of CFETR is located in grassy ELM region



N. Oyama, NF 2005, 2010

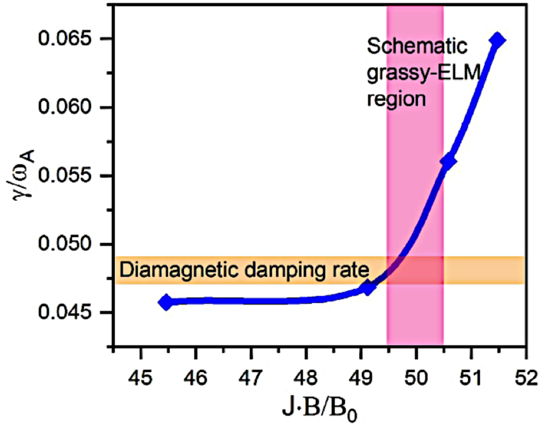


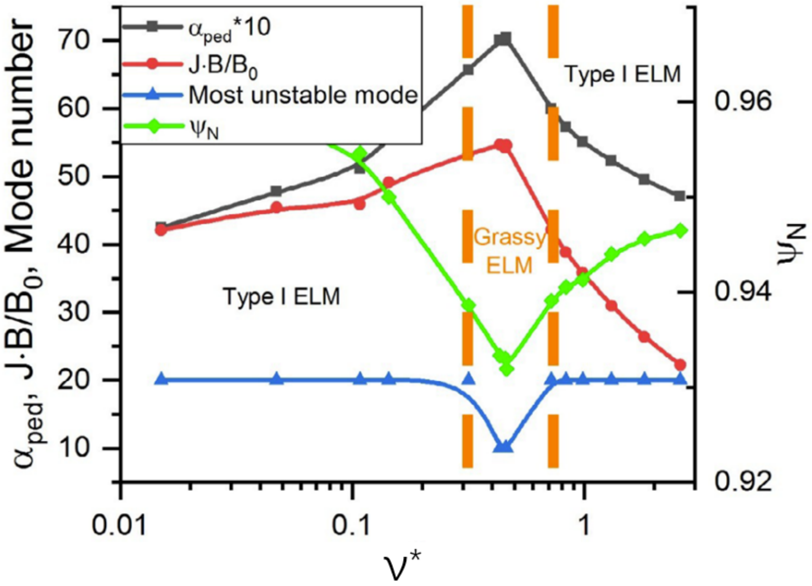
Z.Y. Li et al. PPCF 2021
Y.R. Zhu et al. NF 2020

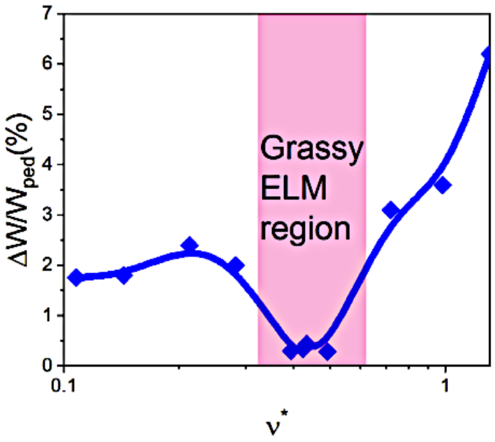


Grassy ELM Regime

Grassy regime exists at high β_p within a pedestal top electron collisionality (v^*) window – observed on DIII-D





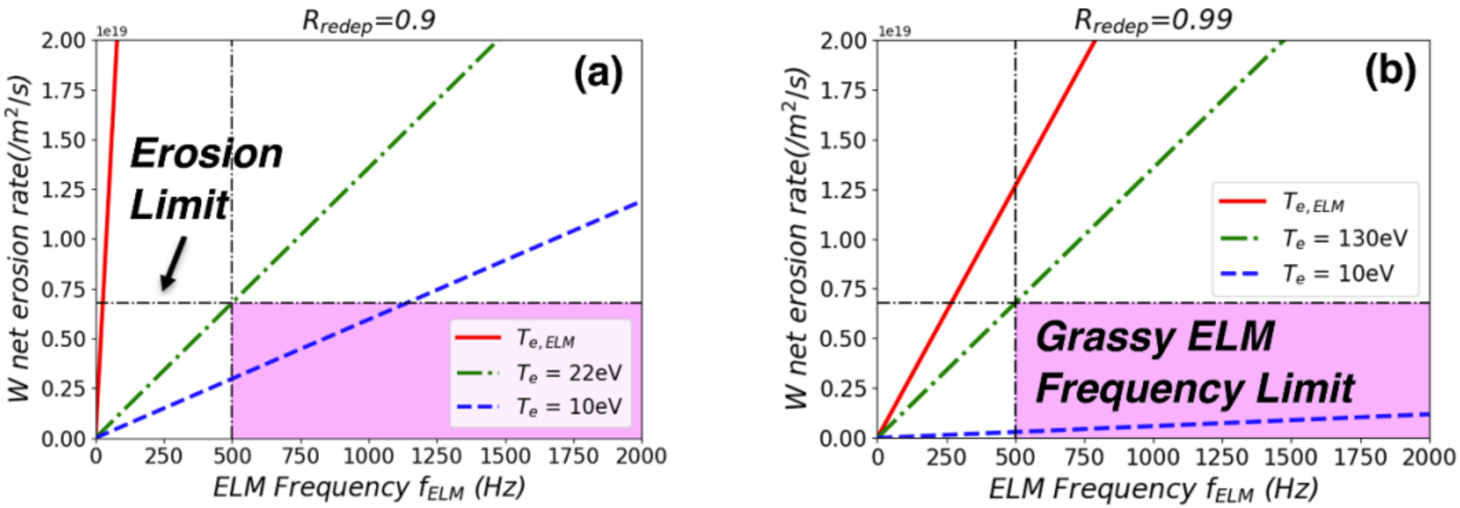


Equilibria are self-consistently generated by kinetic EFIT(OMFIT) with the consideration of core-pedestal coupling effect, analysis of pedestal stability is done with EPED and BOUT++.

Y.R. Zhu et al. NF, 2020

Grassy ELM Regime

Energy fluence caused by a single ELM pulse is below the tungsten melting limit, while tungsten erosion would exceed the material requirements



External mitigation methods, such as divertor detachment and advanced divertor geometry are likely needed for long-pulse safety operation of CFETR.

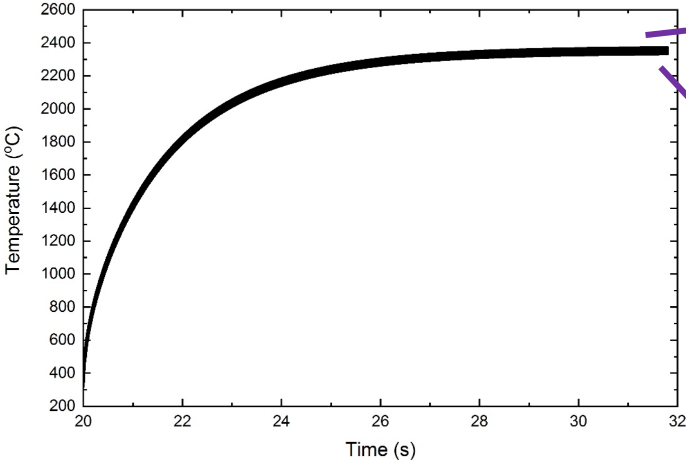
Z.Y. Li et al. PPCF 2021

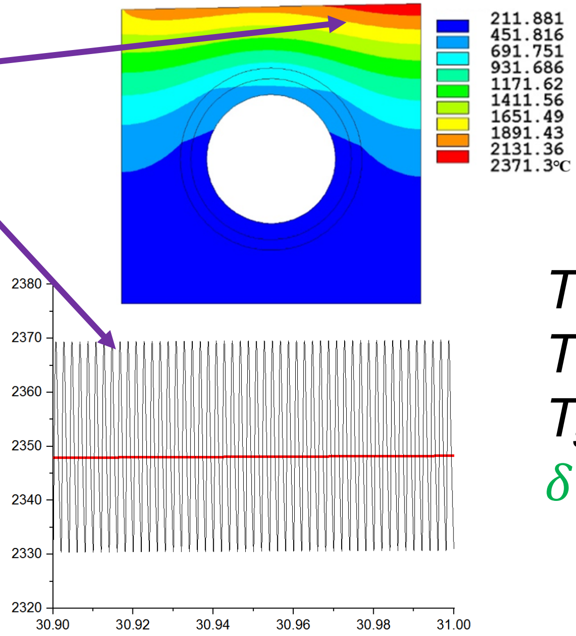
Grassy ELM Regime

ELM Effect on Material Lifetime has been Evaluated

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

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





T_{W_melt} = 3400 °C
T_{peak} = 2371 °C
T_{ss} = 2348 °C
$\delta T \approx 20$ °C

ANSYS Simulation

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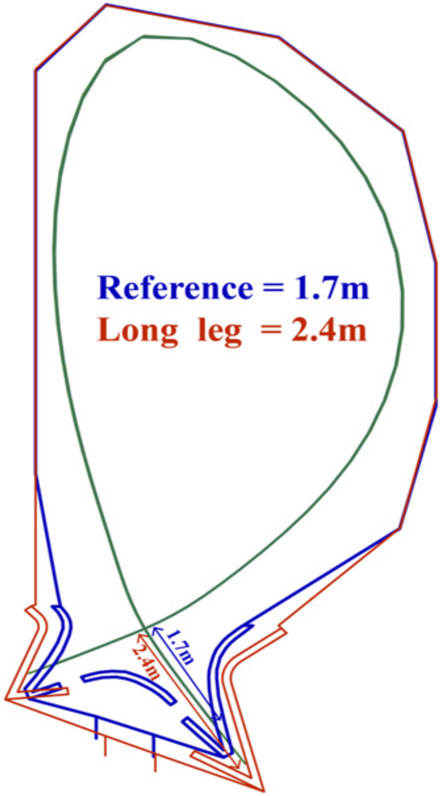
Long-leg radiative divertor

Long-leg Conventional Divertor Design

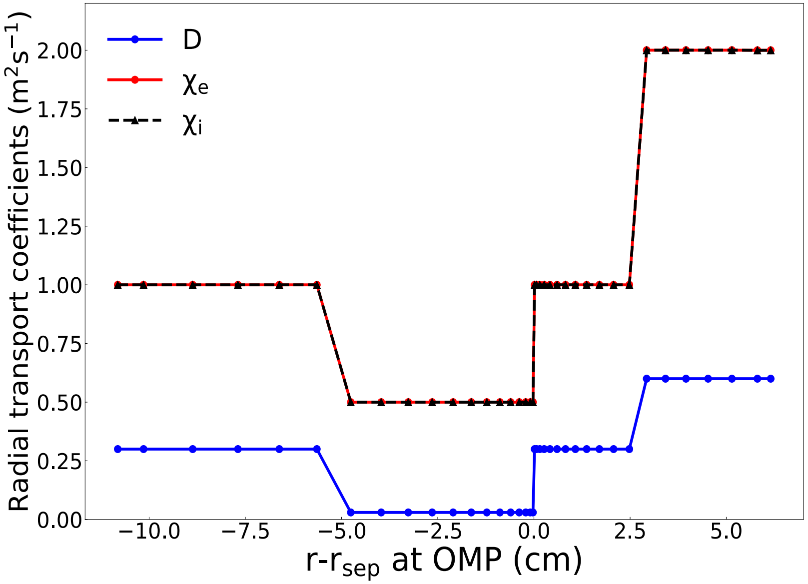
- **W-based materials for PFCs**
- **Vertical targets for both divertor**
  - Easier detachment near strike point
- **A V-shape corner**
  - Higher neutrals compression
- **Long divertor leg length**
  - Higher power radiation losses
- **Two pumping slots on the Dome**



Liu X.J. Phys. Plasmas 2020

SOLPS Modeling of Edge Plasma for CFETR

- **SOLPS-ITER (Full drifts)**
- **Simulation setup**
  - P_{CEI}=200MW (Pe=Pi=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
  - D2 puffing from upstream $\Gamma_{D}^{fuel} = (4-10) \cdot 10^{22}$ at/s
  - W divertor but no sputtering from FW
  - Anomalous transport coefficients: H mode

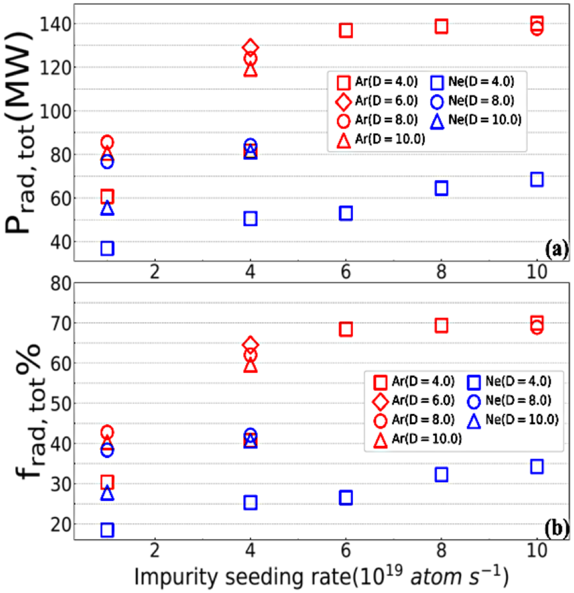


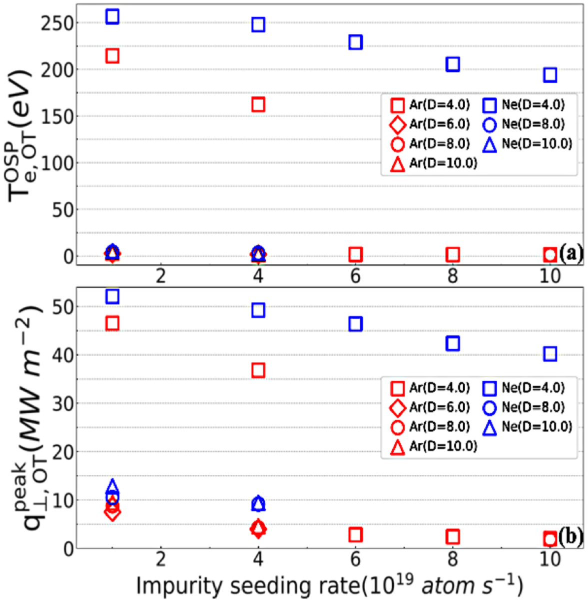
λ_q ~ 4.0mm

Liu X.J. et al Phys. Plasmas 2020

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
  - Lower heat flux and T_e at the target

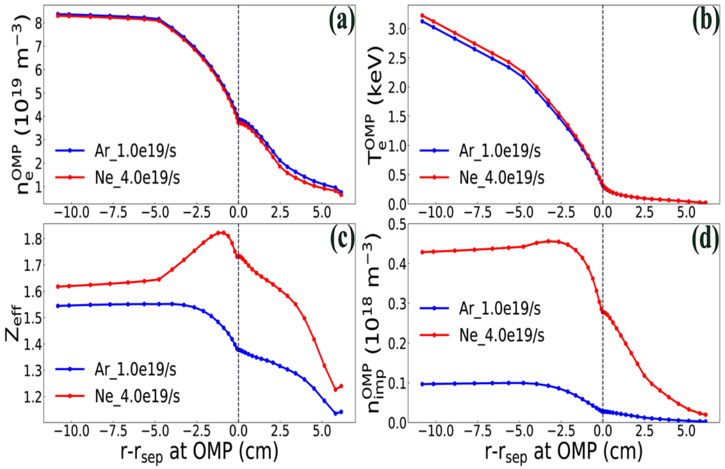


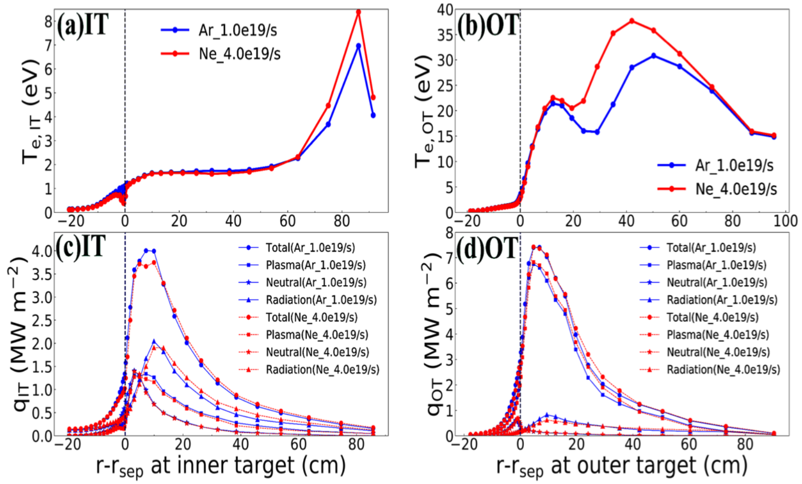


Long-leg radiative divertor

More efficient power dissipation achieved by Ar seeding than Ne

- **Much more Ne is required to have similar radiation power with Ar**
  - Higher impurity contamination for Ne
- **Compatible with core plasma $Z_{eff\text{-}ped} < 2$**
- **Partial detachment for both targets**

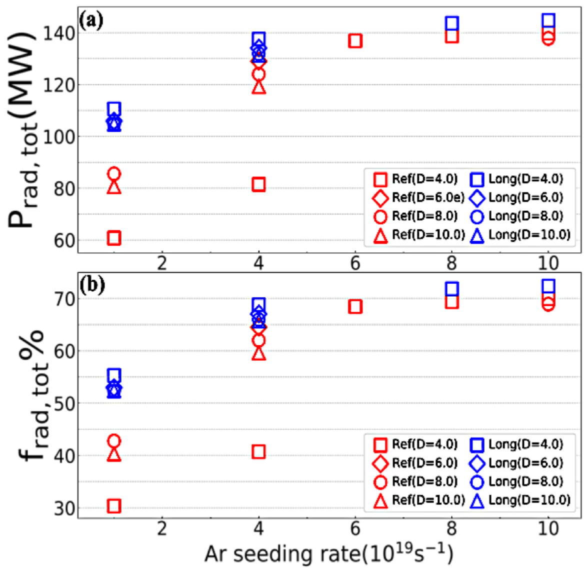


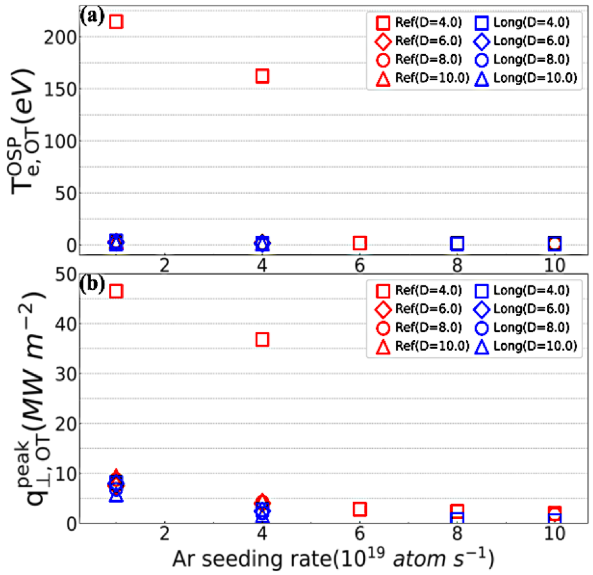


D_2 puffing rate 1×10^{23} s^{-1}

Longer Divertor Leg Length can Meet the Physics Requirements More Easily

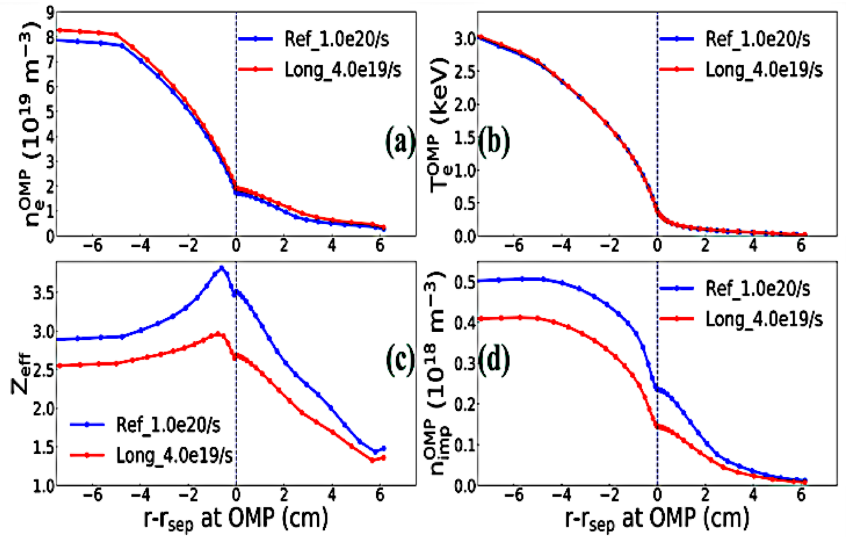
- **Radiation increased significantly for longer leg length**
  - Lower heat flux and T_e at the target
  - P_{peak} < 10 MW/m^2 for all cases



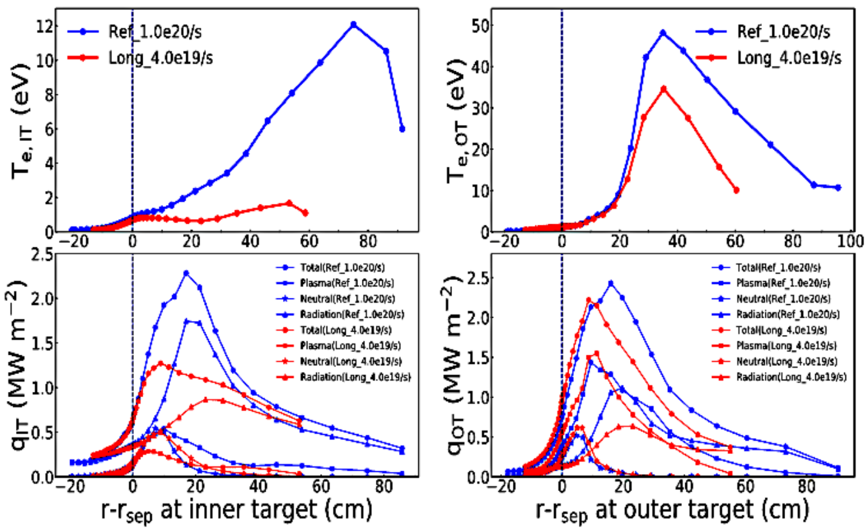


Longer Divertor Leg Length can Meet the Physics Requirements More Easily

- **Less Ar is required for long-leg divertor to have similar radiation power**
- **Partial detachment for both targets**



Ar seeding



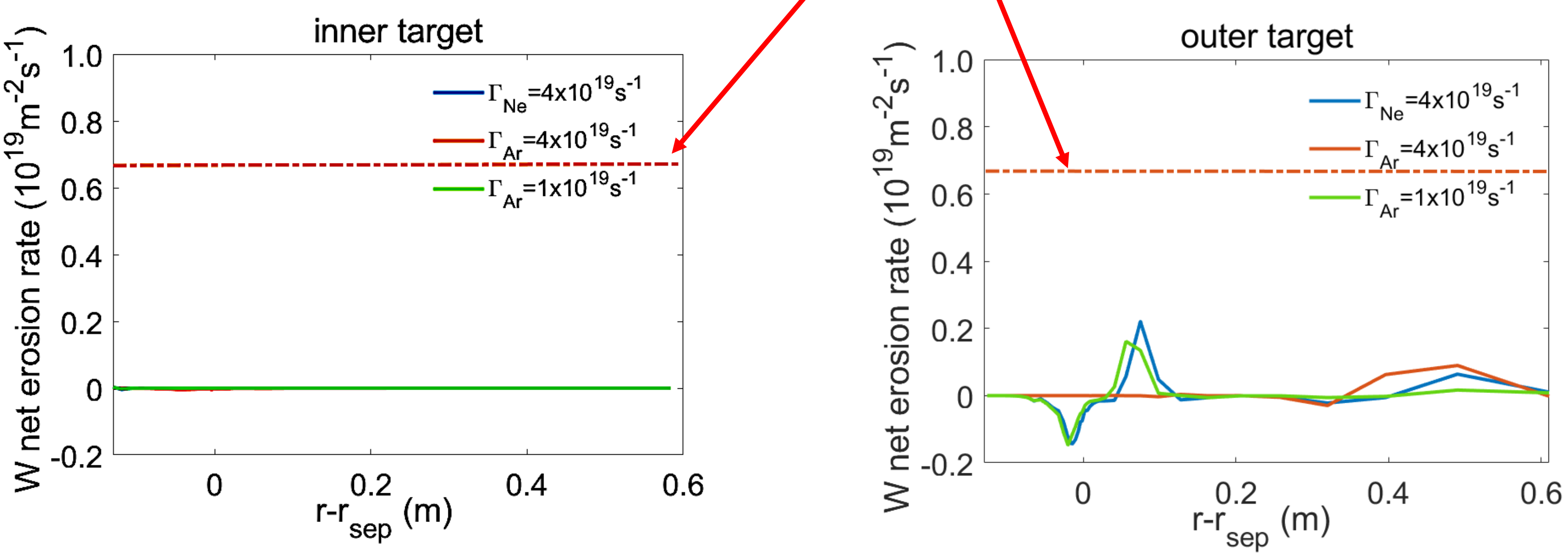
D_2 puffing rate 8×10^{22} s^{-1}

W net erosion rates at both divertor targets can 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



D_2 puffing rate 1x10^{23} s^{-1}

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Computational Model

PF coils model :
- 15 super-conductive coils

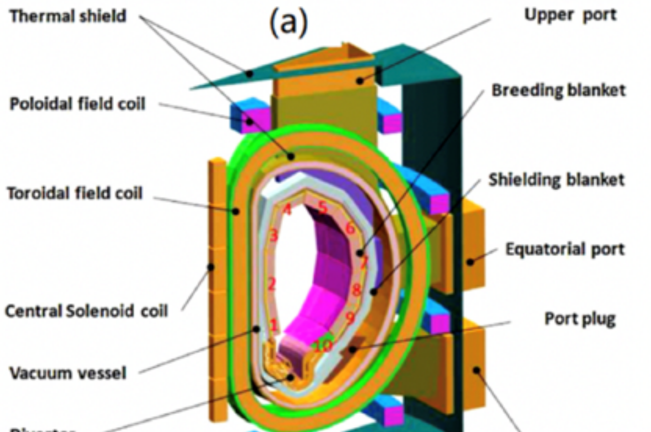
Vacuum vessel model :
- material: 316LN stainless steel
- thickness: 50mm (double shells)
- resistivity: 7.97 $\times 10^{-7}$ Ωm

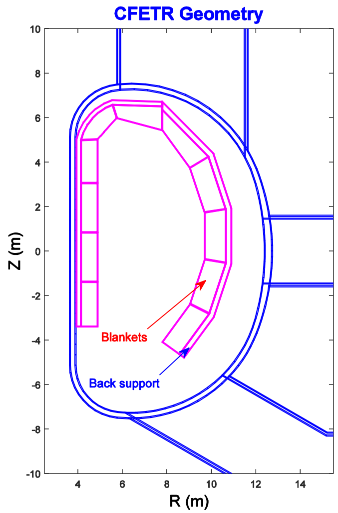
Divertor / limiter model :
- insulated in toroidal

Blanket model

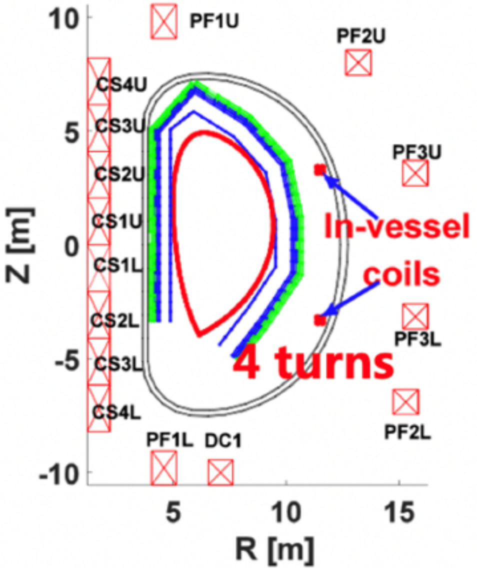
Electrical properties of Reduced Activation Ferritic/Martensitic (RAFM) steel:

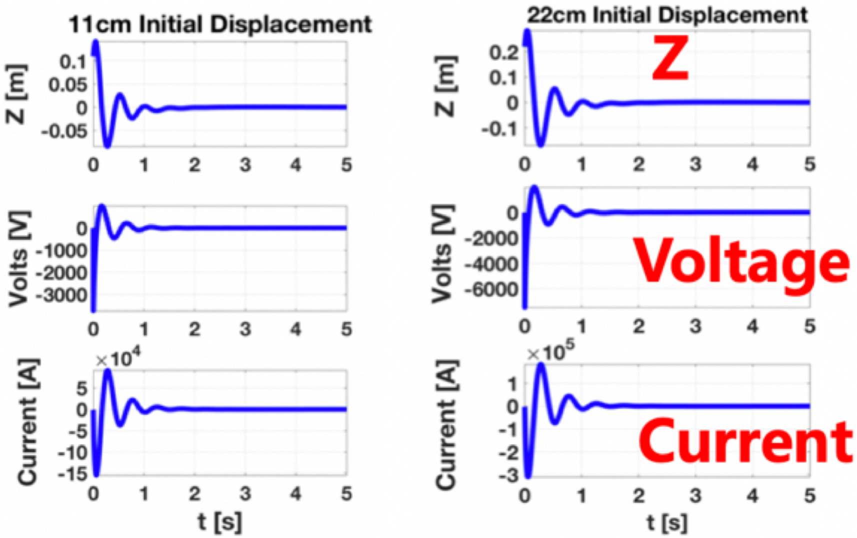
Temperature [°C]	Resistivity [Ω·m]	Conductivity [S/m]
300	**7.62×10^{-7}**	1.31×10^{6}





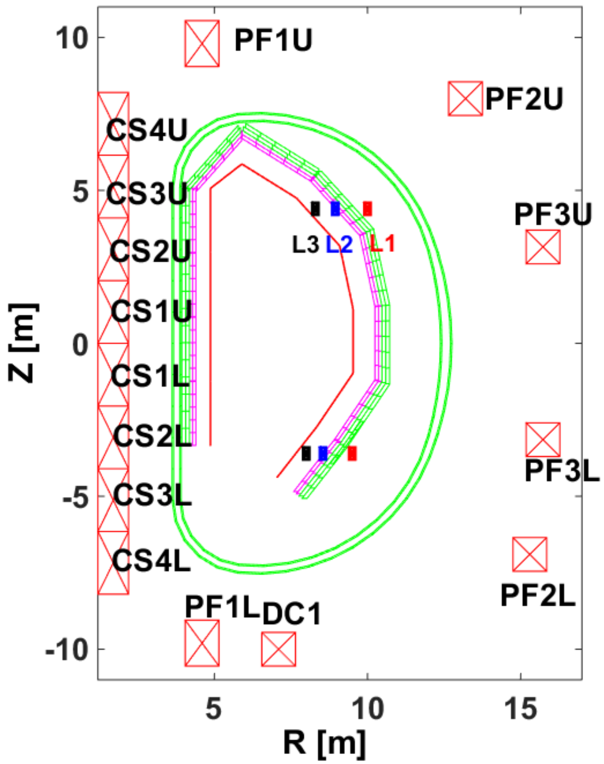
Power Supply Requirement of In-vessel Coils





	ΔZ (cm)	Max Voltage (kV)	Max Current (kA-turn)
Safe control (ΔZmax/a=5%)	11	3.73	619.48
Robust control (ΔZmax/a=10%)	22	7.46	1238.96

IC Location Optimization for Robust Control



IC: 6 turns, current/voltage on 6 turns

IC location	Resistivity factor	Voltage(kV)	Current (kA-turn)	VDE growth rates
Location 1	1	7.41	1120.9	1.91
	5	5.32	674.8	8.15
	10	4.28	597.7	15.06
Location 2	1	6.35	1049.4	1.33
	5	4.25	453.24	4.65
	10	4.26	365.16	7.78
Location 3	1	6.35	559.7	0.88
	5	4.24	316.8	2.36
	10	4.24	272.9	3.43

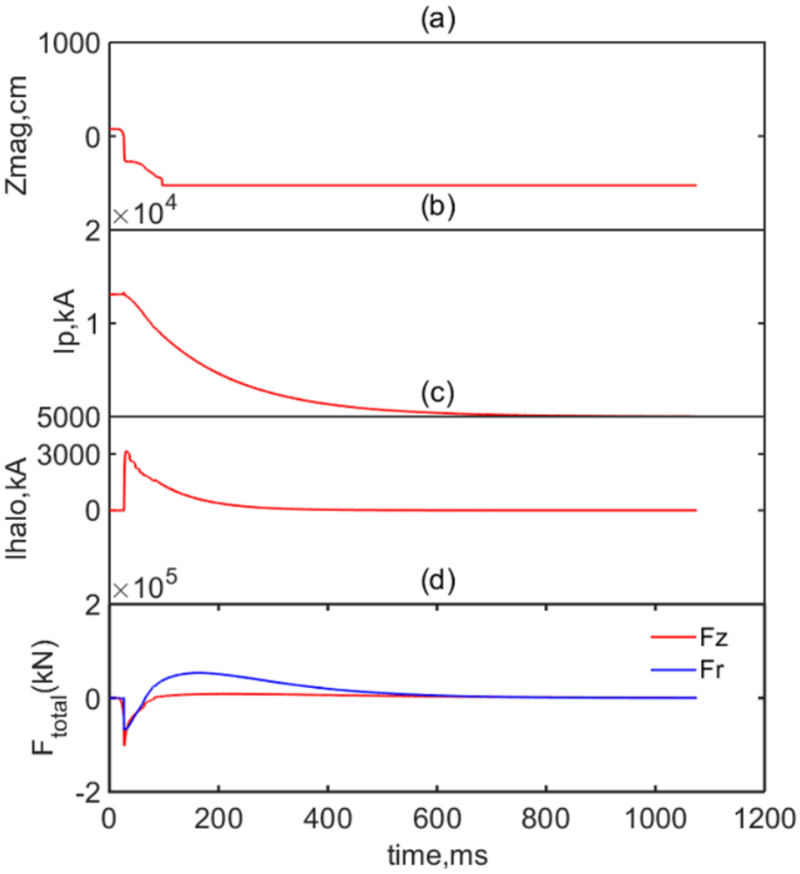
The capability requirements of IC power supply can be reduced significantly if the windows limitation and neutron irradiation issue can be solved.

VDEs & Disruption Control

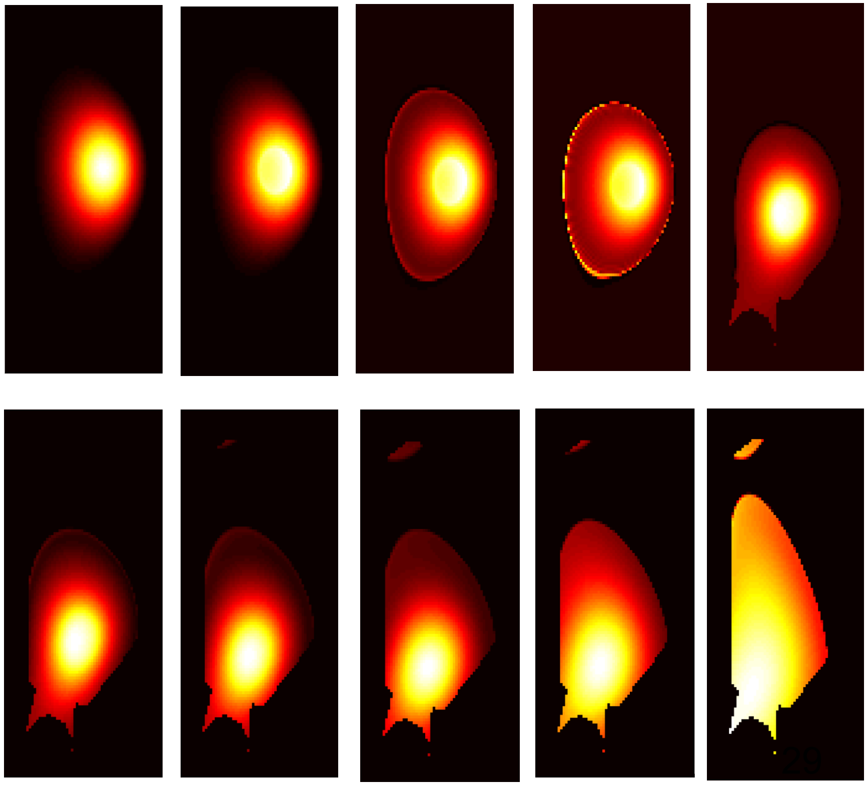
Hot VDE at <Te> = 10keV

DINA simulation

Unified blanket reference resistivity: 7.62×10^{-6} Ω·m



- ➢ Peak halo current 3.16MA (24.3% Ip)
- ➢ Maximum vertical EM force 10220 tons
- ➢ Maximum horizontal EM force 6914 tons



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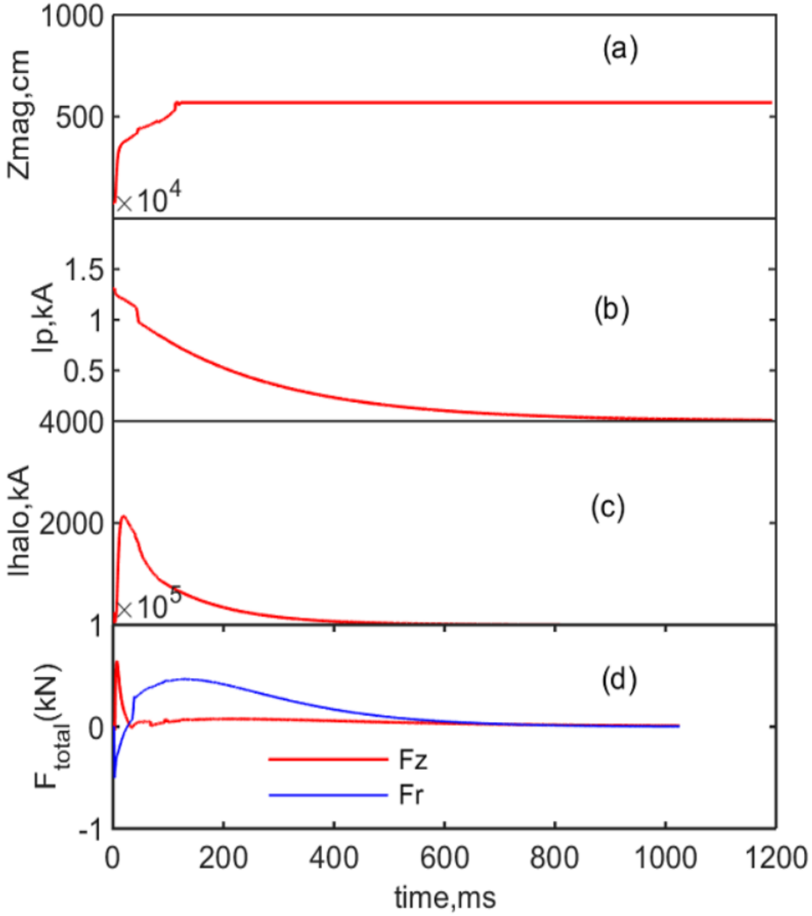
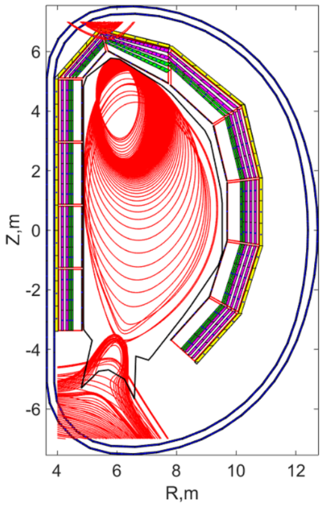
VDEs & Disruption Control

Cold VDE at <Te> = 10 keV

DINA simulation





- Peak halo current 2.13MA, 16.4%Ip;
- Maximum vertical EM force 6464 tons (<Hot VDE:11820 tons), Maximum horizontal EM force 5042 tons (<Hot VDE: 7980 tons)

Comparison of disruption consequences for ITER and CFETR

Thermal quench and divertor energy loading attributes

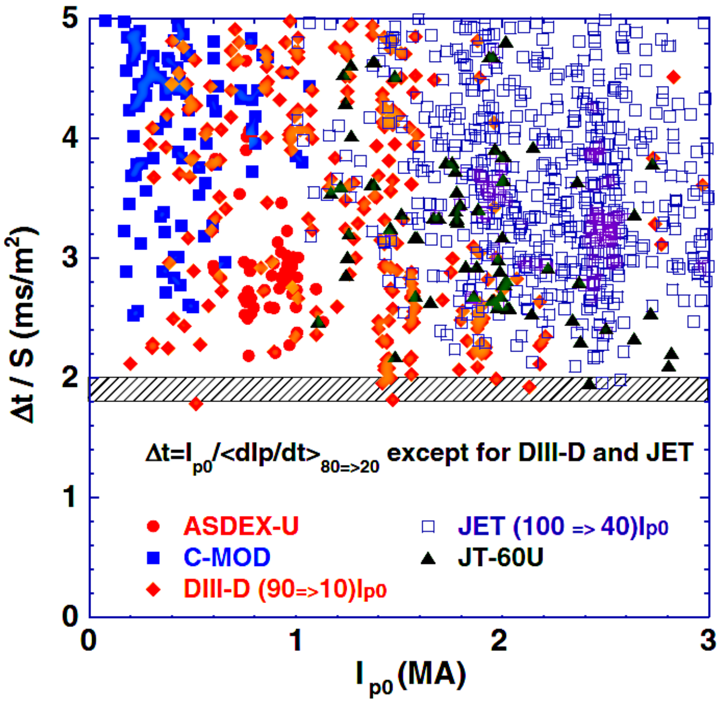
Parameters	ITER (S.2)	CFETR (A.3)	Basis or comment
A_{div}(m^2)	~3.5	~4.1	Effective divertor target area
$U_{TQ} = W_{th}/7A_{div}$ (MJ m^{-2})	14.1	24.4	For 7-x SOL expansion during-disruption TQ
t_{TQ} (ms)	0.7	0.8	IPB scaling (~a^1)
$U_{TQ}/t_{tQ}^{0.5}$(MJ m^{-2} s$^{-0.5}$)	530	860	C or W vapour / melt onset at 40-60 MJ m^{-2} s$^{-0.5}$
Runaway electron conversion and mitigation attributes			
E_{int} (V m^{-1})	38	27	In-plasma E-field
$n_{e,RB}$ (m^{-3})	4.2×10^{22}	3.0×10^{22}	n_e to suppress avalanche growth
$G_{avalanche}$	1.9×10^{16}	9.2×10^{14}	Coulomb avalanche gain = exp[2.5 × I_p (MA)]
$I_{RA,seed}$ (A)	4.0×10^{-10}	7.5×10^{-9}	Seed current for I_{RA} = 0.5 I_p

Disruption Mitigation System is necessary for CFETR!

L. Zeng

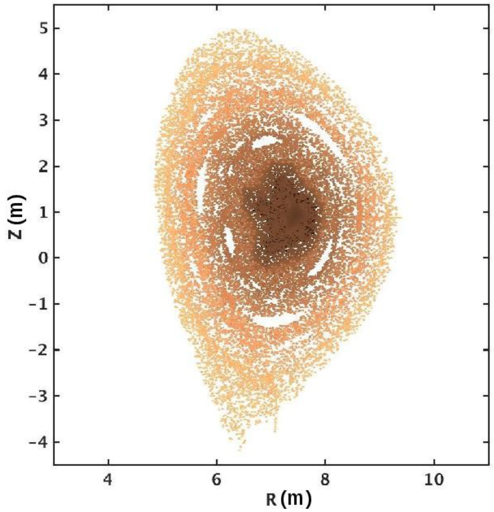
Minimum current quench duration and halo current asymmetries

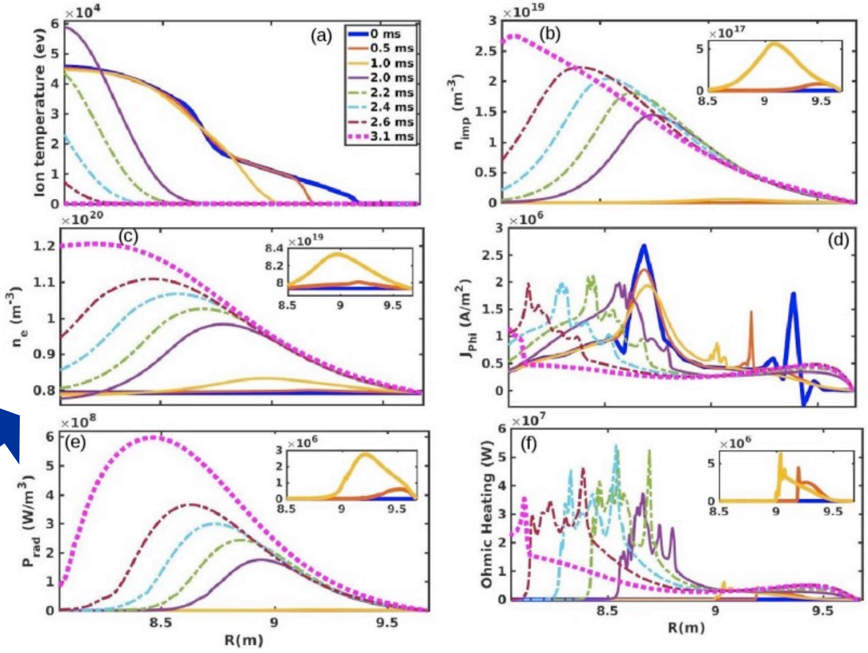
- **For ITER(S.2), $\tau_{CQ}/S \geq 1.67$ ms/m^2**
  - $\tau_{CQ} \geq 35$ms
- **For CFETR(A.3), $\tau_{CQ}/S \geq 1.67$ ms/m^2**
  - $\tau_{CQ} \geq 46.5$**ms**
- **For CFETR(A.3), $I_p = 13.78$MA *$TPF*I_{halo}(max)$* $\leq$ 10MA with TPF ≤ 2**
  - Empirically data bounded by $TPF*I_{halo}(max)/I_p \leq 0.75$



Disruption mitigation by impurity injection

- **Disruption mitigation simulation with massive neon injection on CFETR using 3D nonlinear MHD code NIMROD.**
  - The n = 1 mode dominates before and during the thermal quench.





Plasma parameter evolution during the current quench.

Content

- Introduction
- Solutions with special emphasis on:
  - Identification of a grassy ELM pedestal regime compatible with core and divertor
  - Long-leg radiative (detachment or semi-detachment) divertor
  - Vertical displacement events (VDEs) control and disruption mitigation
- Conclusion & discussion

Conclusion & Discussion

- Target plasma at flattop phase for CFETR scenarios modeled and optimized by 1.5-D simulations.
  - For hybrid scenario, *q* profile in the deep core region flatten by the combination of NBCD and ECCD.
  - For steady-state scenario, Local reversed shear is controlled by localized ECCD to maintain an ITB at mid-radius; optimizing the position of the local reversed shear stabilizes all the destructive low-n modes.
  - Ideal MHD robustly stable
- Some critical issues are identified for the CFETR operation scenarios, corresponding solutions are addressed and explored.

Critical Issue	Key ideas & solutions
Disruption control	**VDE feedback control; β_N below no wall limit**
Transient heat load on PFC	**Grassy ELM pedestal**
Steady-state heat exhaust	**Long-leg radiative divertor**

Thank you for your attention!