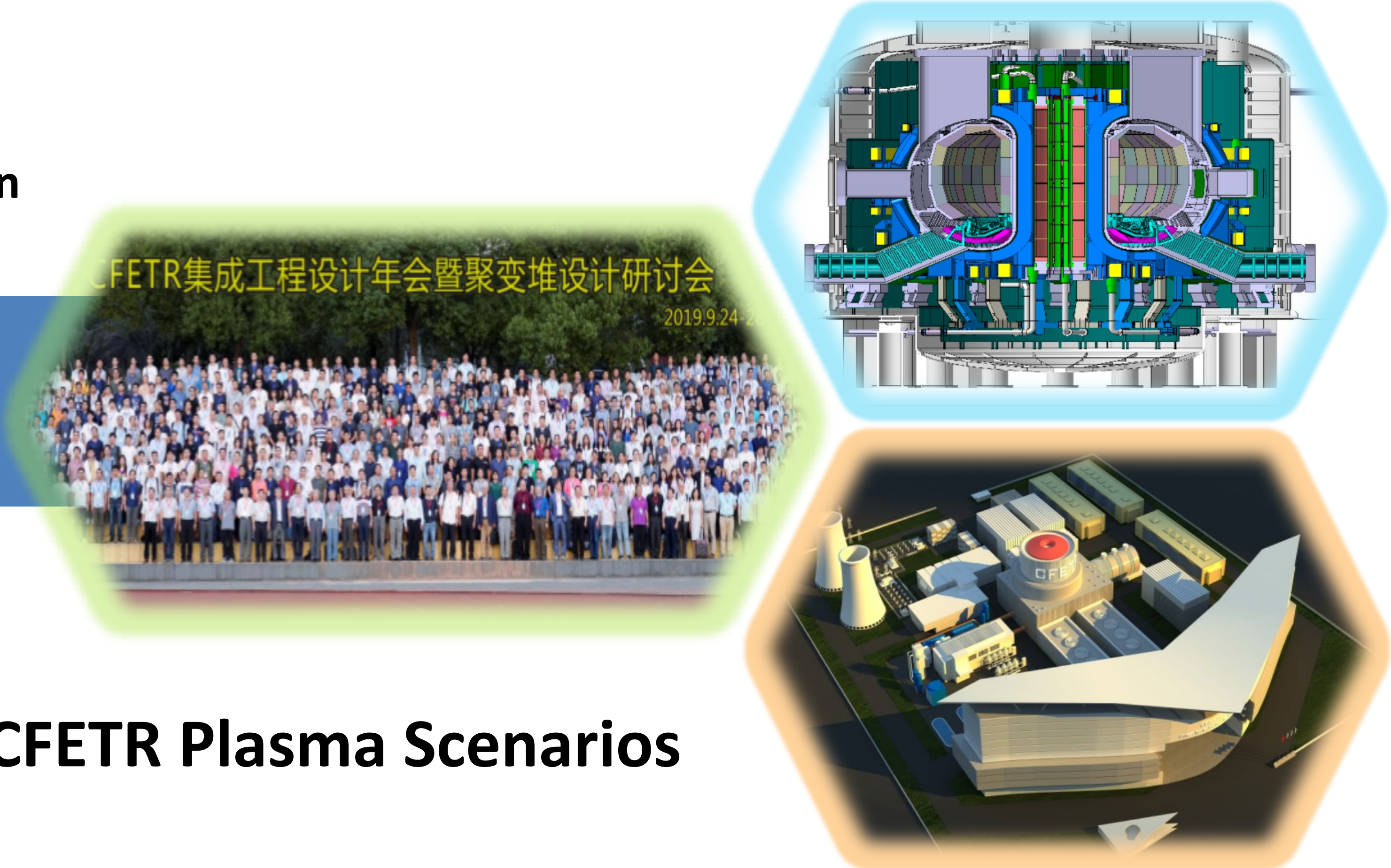
10th US-PRC Magnetic Fusion Collaboration
Virtual Workshop



Progress in Physics Design of CFETR Plasma Scenarios

Jiale Chen[1] for CFETR physics team

[1]Institute of Plasma Physics, CAS, China

2020/03/23 - 2020/03/26

China Fusion Engineering Test Reactor (CFETR)

Missions

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

$P_{\text{fusion}} = 200 \sim 1500$ MW

High duty time ~ 50%

Tritium self-breeding

Tritium breeding ratio (TBR) > ~1 over at least a closed cycle for tritium fueling with high fusion power

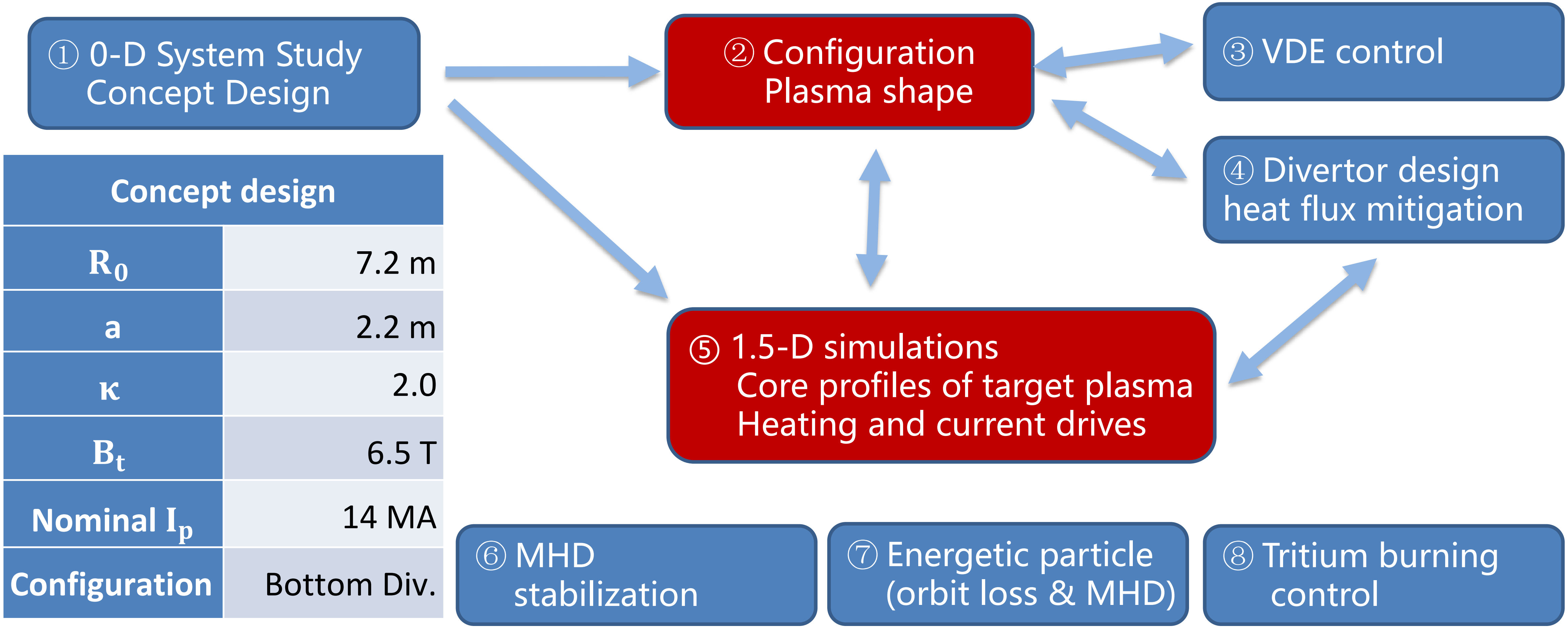
Exploration for self-sustained burning

R&D for materials

Scenario design

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

Top-down physics design with multiple task forces



① 0-D System Study
Concept Design

② Configuration
Plasma shape

③ VDE control

④ Divertor design
heat flux mitigation

⑤ 1.5-D simulations
Core profiles of target plasma
Heating and current drives

⑥ MHD
stabilization

⑦ Energetic particle
(orbit loss & MHD)

⑧ Tritium burning
control

Concept design	
R_0	7.2 m
a	2.2 m
κ	2.0
B_t	6.5 T
Nominal I_p	14 MA
Configuration	Bottom Div.

0-D studies based on experimental scaling laws identify requirements: high elongation / large power exhaust / moderate high confinement

Concept design at top level	
R_0	7.2 m
a	2.2 m
κ	2.0
B_t	6.5 T
Nominal I_p	14 MA
Configuration	Bottom Div.

Performance target	
P_{fus}	1 GW
Pulse length	> 4 hours

	Hybrid	steady-state
P_{fus}	1128	974
Qplasma	15.30	11.89
Pn/wall(MW/m^2)	1.15	0.99
β_T(thermal)	0.019	0.019
β_N(thermal)	2.00	2.0
fbs	0.50	0.50
$H_{ITER98Y2}$	1.19	1.41
Pcd	74	82
Ip	13.78	13.78
Ti(0)/Te(0)	24/24	36/36
n(0)	1.16	0.78
<n>/nGR	0.85	0.57
Zeff	2.45	2.45
P/R	19.11	15.69
q95_iter	5.54	5.54
Ohmic fraction	0.3	0

By Vincent Chan using GASC

*Zhuang, G., et al 2019 Nuclear Fusion 112010

Benchmarked with PROCESS, ZDEIM and SCoF.

Top-down physics design with multiple task forces

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Concept Design

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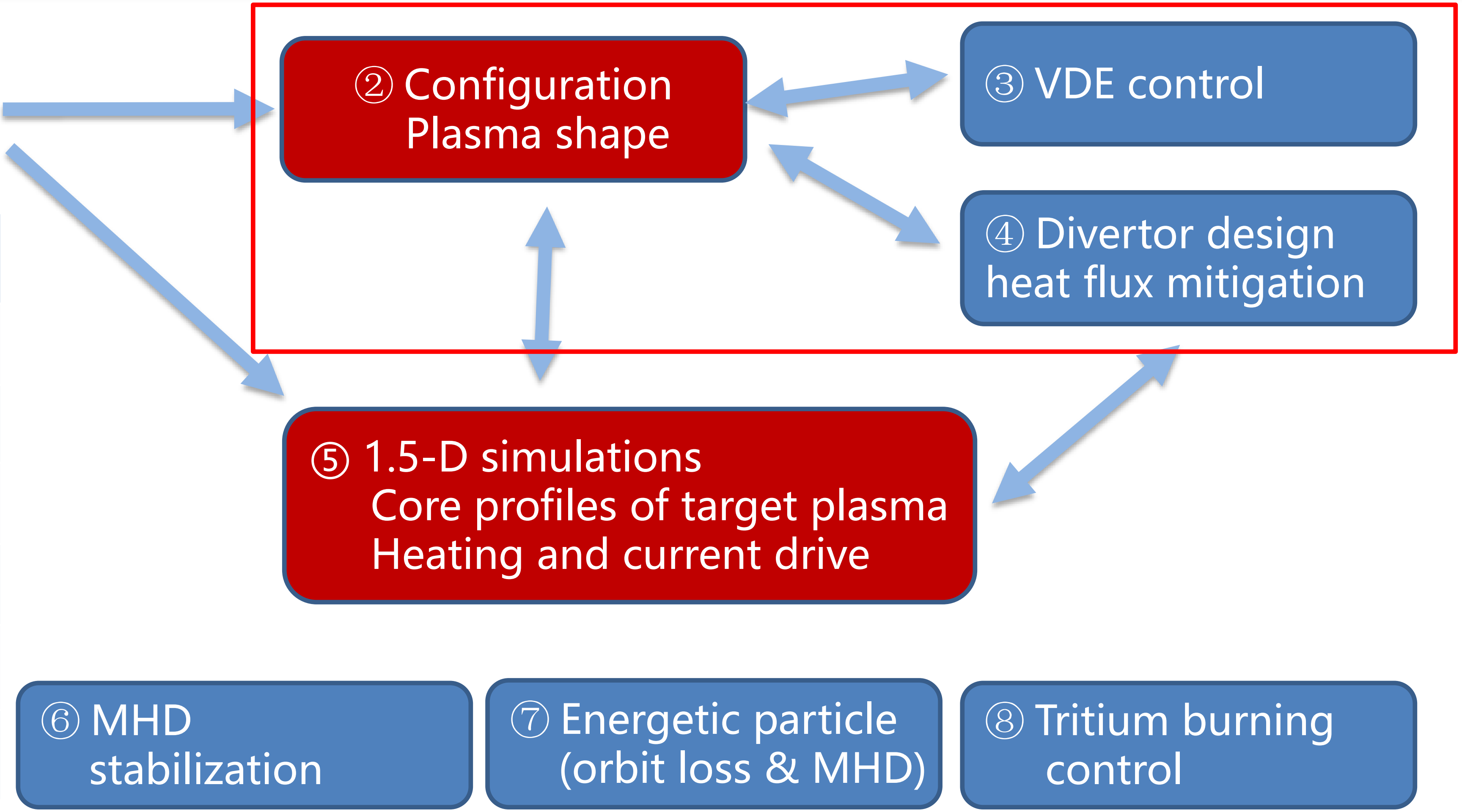

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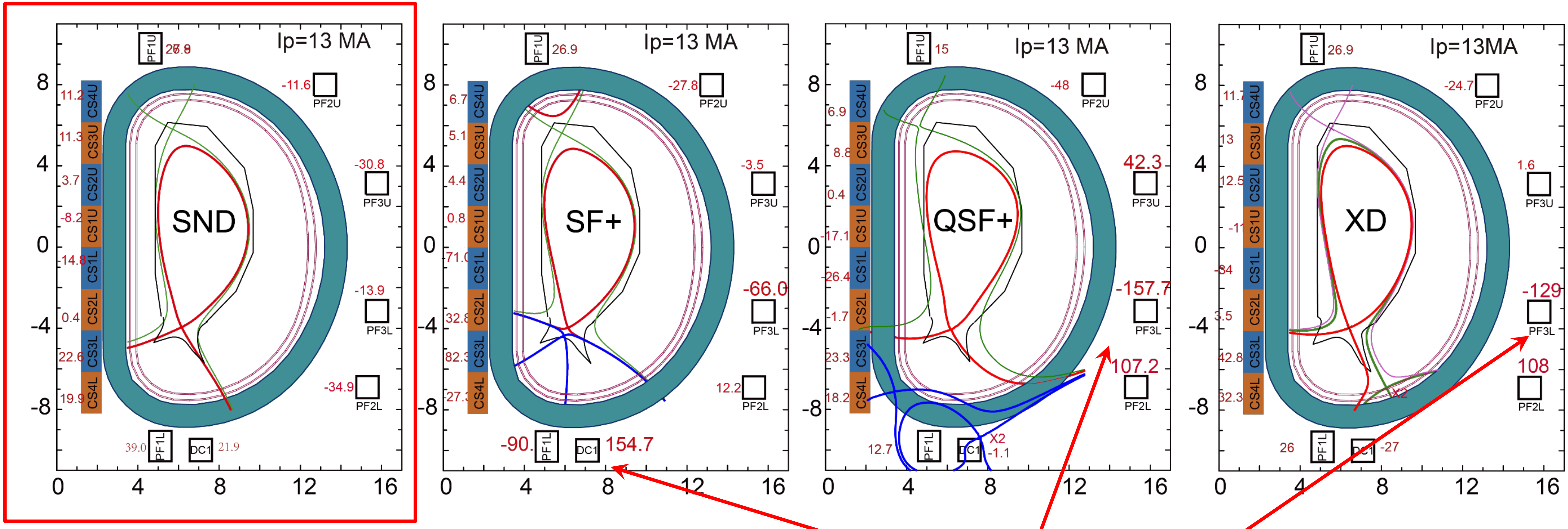
Only conventional single-null divertor (SND) is compatible with the current limitation of PF coils.

- **Advanced divertor configurations are explored with consistent PF coil currents.**



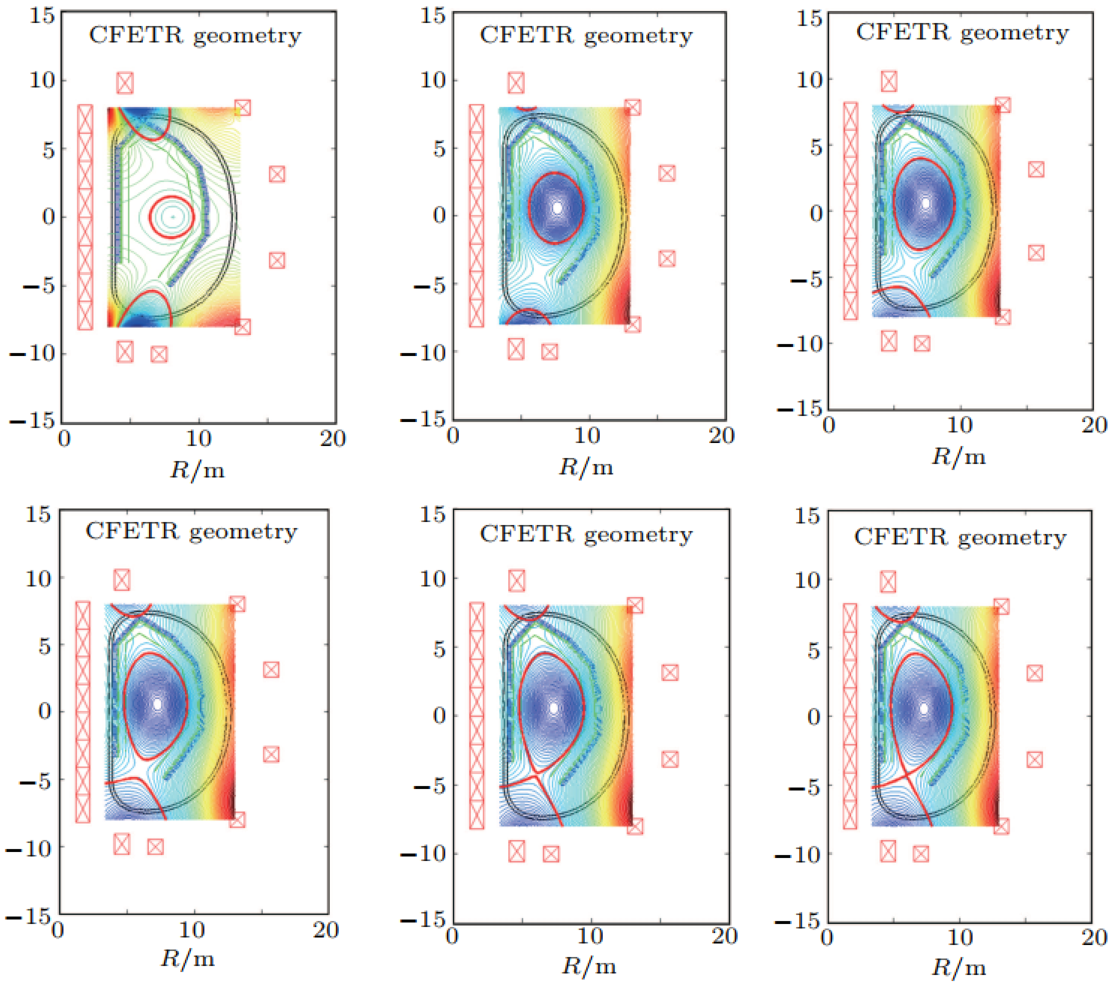
Excessive coil current

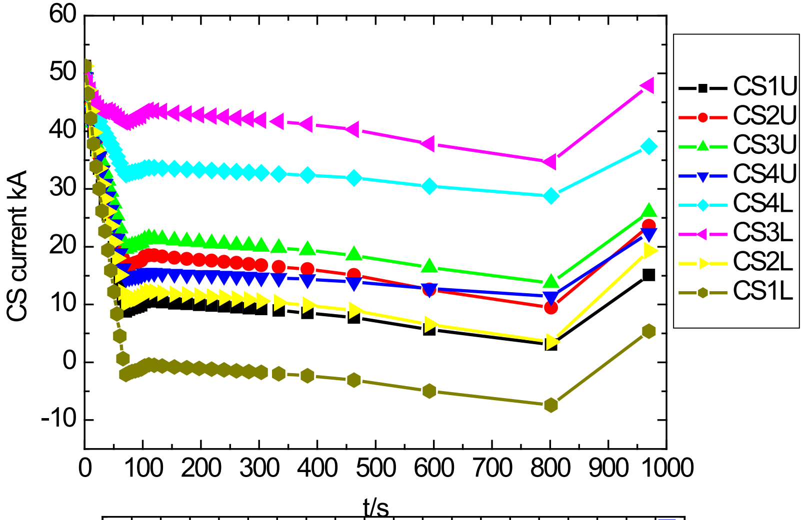
By Hang Li using TEQ code

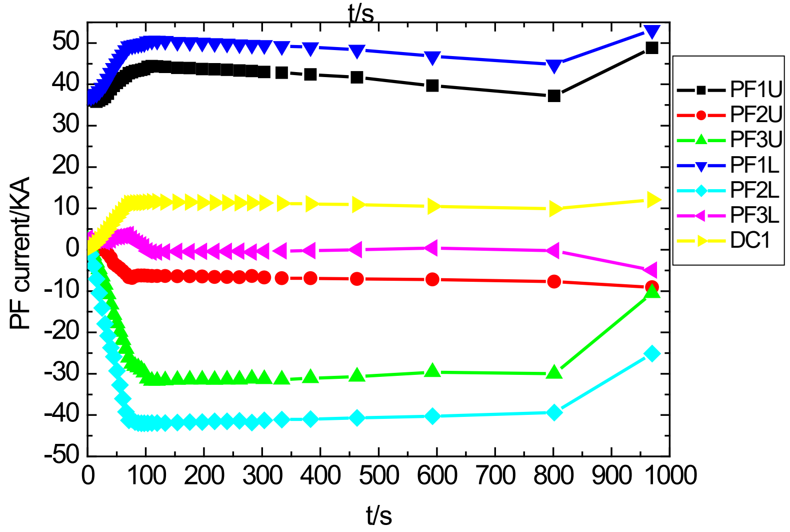
*Li, H., et al. 2020 Fusion Engineering and Design 111447

Demonstration of the SND configuration by time-dependent simulations

- **The SND configuration can be formed in the ramp-up process.**



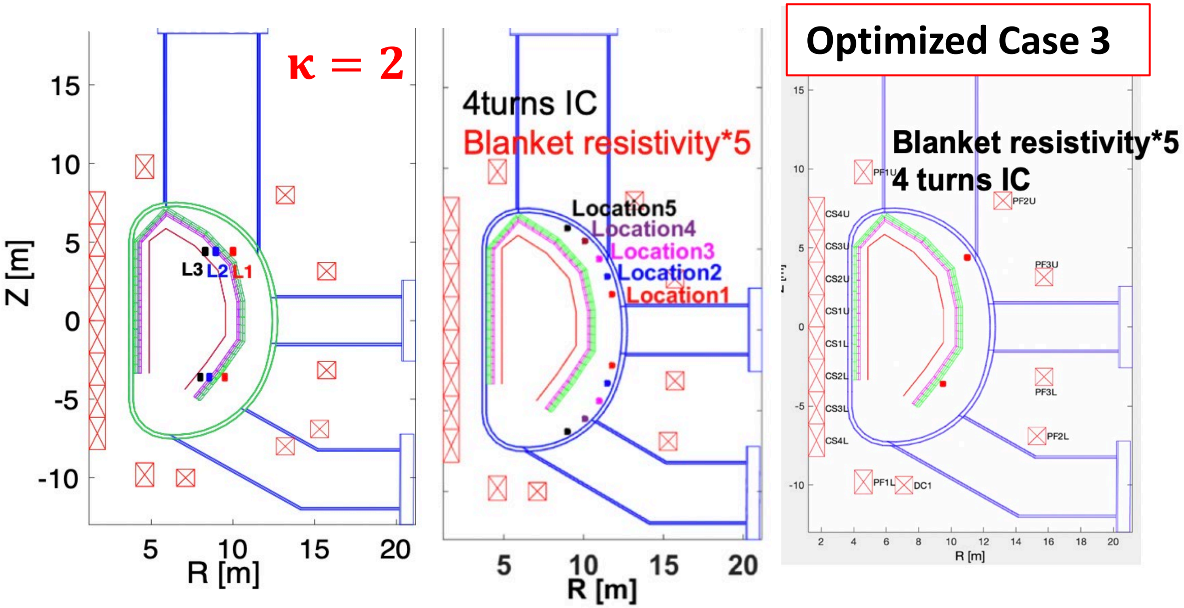




* By Cheng Yue Liu using TSC

VDE can be controlled by internal coils and passive stabilization of the blankets to enable high elongation configuration.

- **The setup of internal coils is optimized based on a trade-off between the spatial occupation and the robust control.**



- **The total IC current lower than the engineering limit (1 MA) with the optimized location (case 3)**

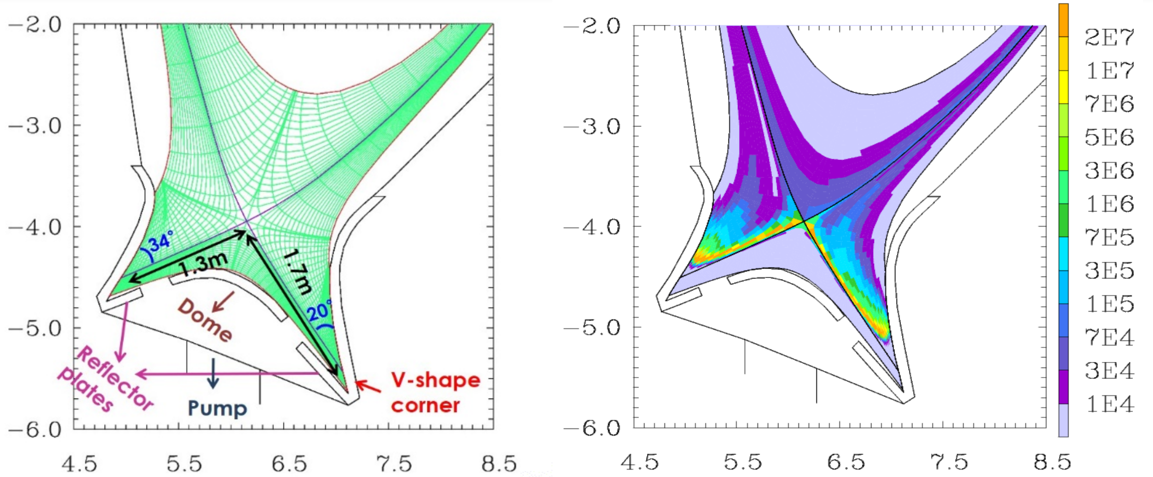
IC location	Coil Voltage (kV)	Coil Current (kA·turn)	VDE growth rate(/s)
Case1 (L1)	5.32	674.8	8.15
Case2 (Loc. 2)	7.46	1238.96	9.48
case3	6.39	940.12	9.01

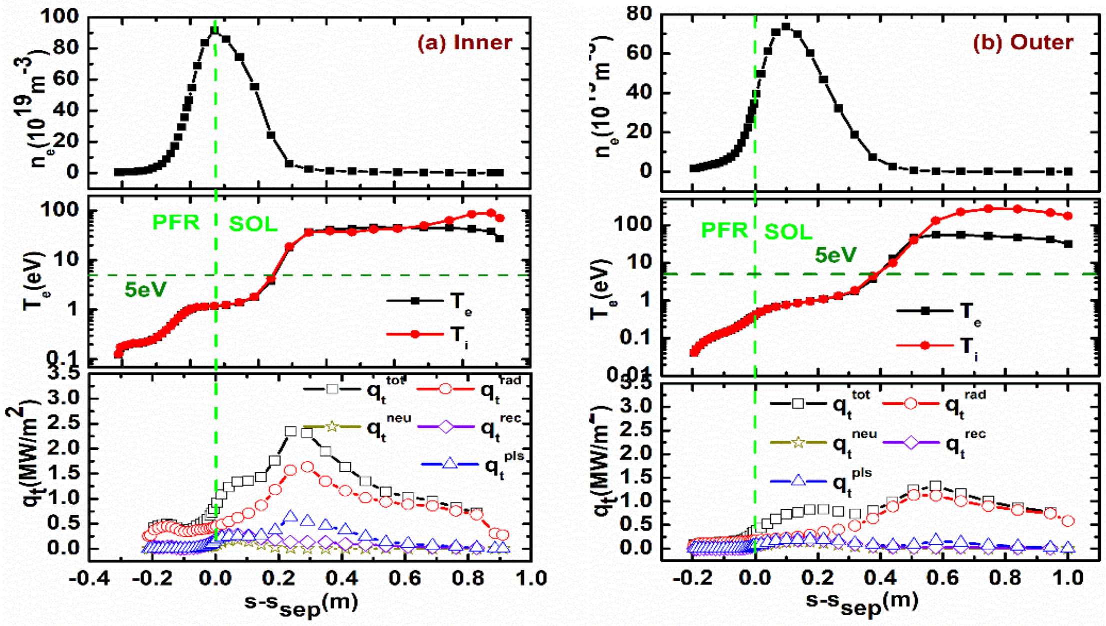
By Lei Liu using TokSys code

Large heat flux onto divertor targets can be mitigated by impurity seeding.

- **V-shape divertor**
- **Neon seeding**
  - Modeled by SOLPS 5.0 and SOLPS-ITER
  - Partial detachment at inner and outer targets
  - Heat flux < 3 MW/m^2
  - $Z_{\text{eff,ped}} < 3$
- **Tungsten erosion mitigated by D_2 puffing at upstream**
  - Modeled by DIVIMP
  - Puffing rate 2x10^{23}/s is enough to reduce tungsten erosion rate to satisfy the lifetime requirement.

*Liu, X. J., et al. 2020 Physics of Plasmas, 092508



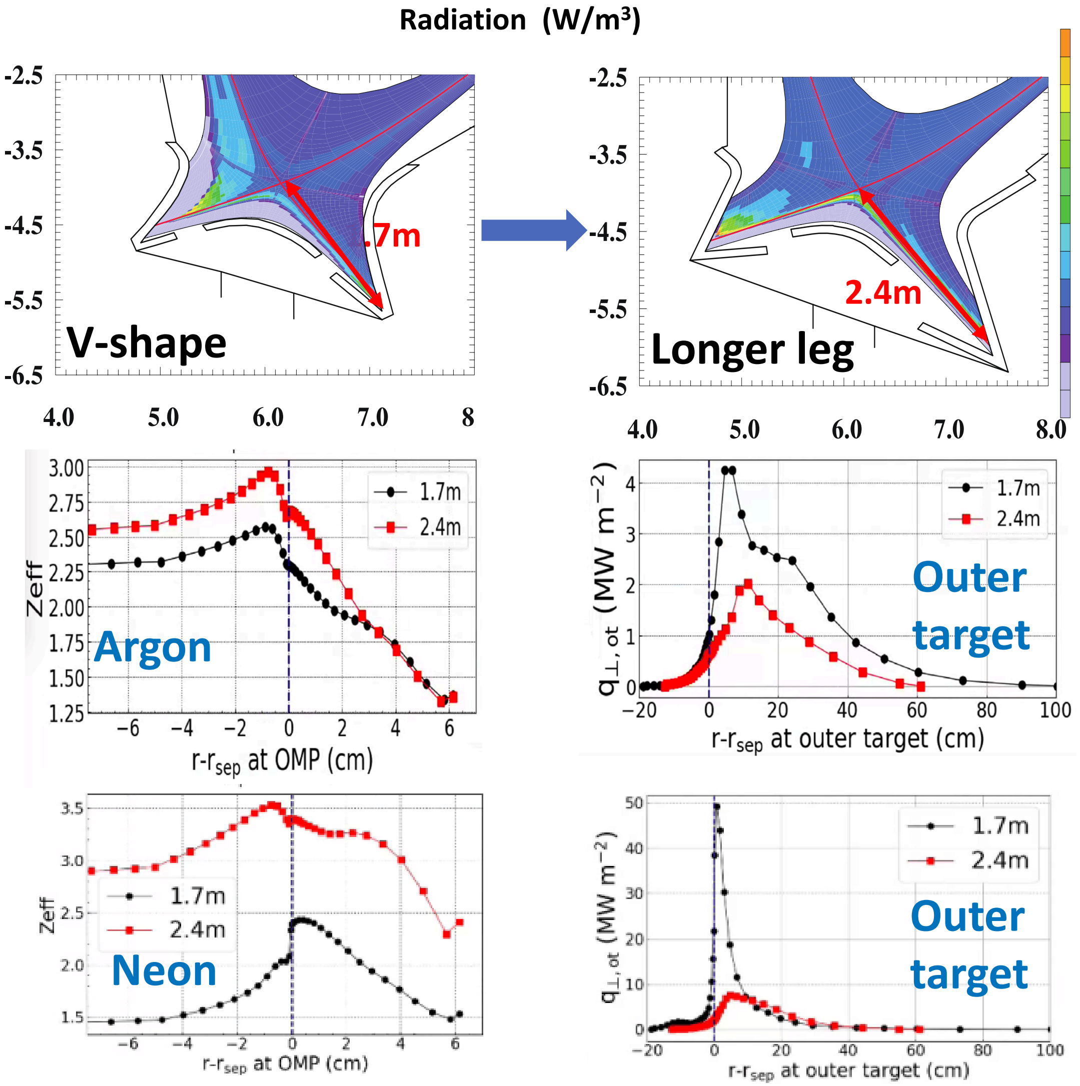


Neon seeding rate: 1x10^{20} s^{-1}

Argon seeding can be better than Neon seeding in longer leg configuration.

- **Longer leg configuration beyond V-shape divertor**

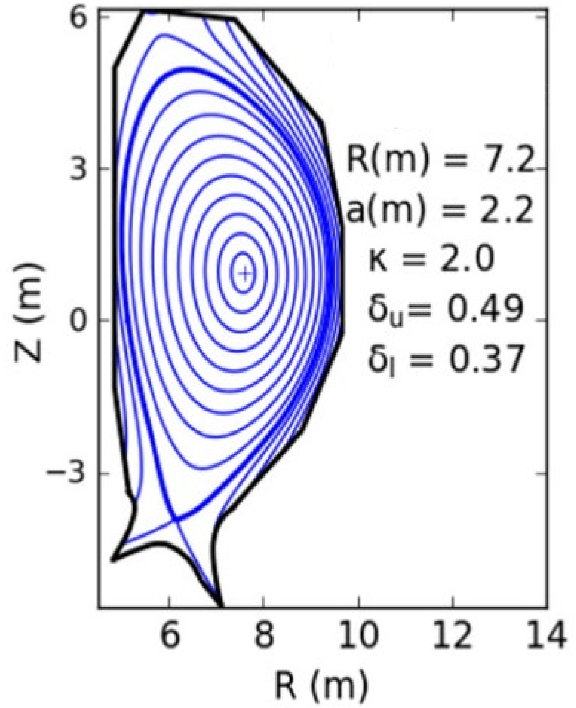
- **Argon seeding can be better than Neon seeding:**
  - Stronger radiation
  - Lower $Z_{eff\text{-}ped}$ (more compatible with the optimized condition for core plasmas)



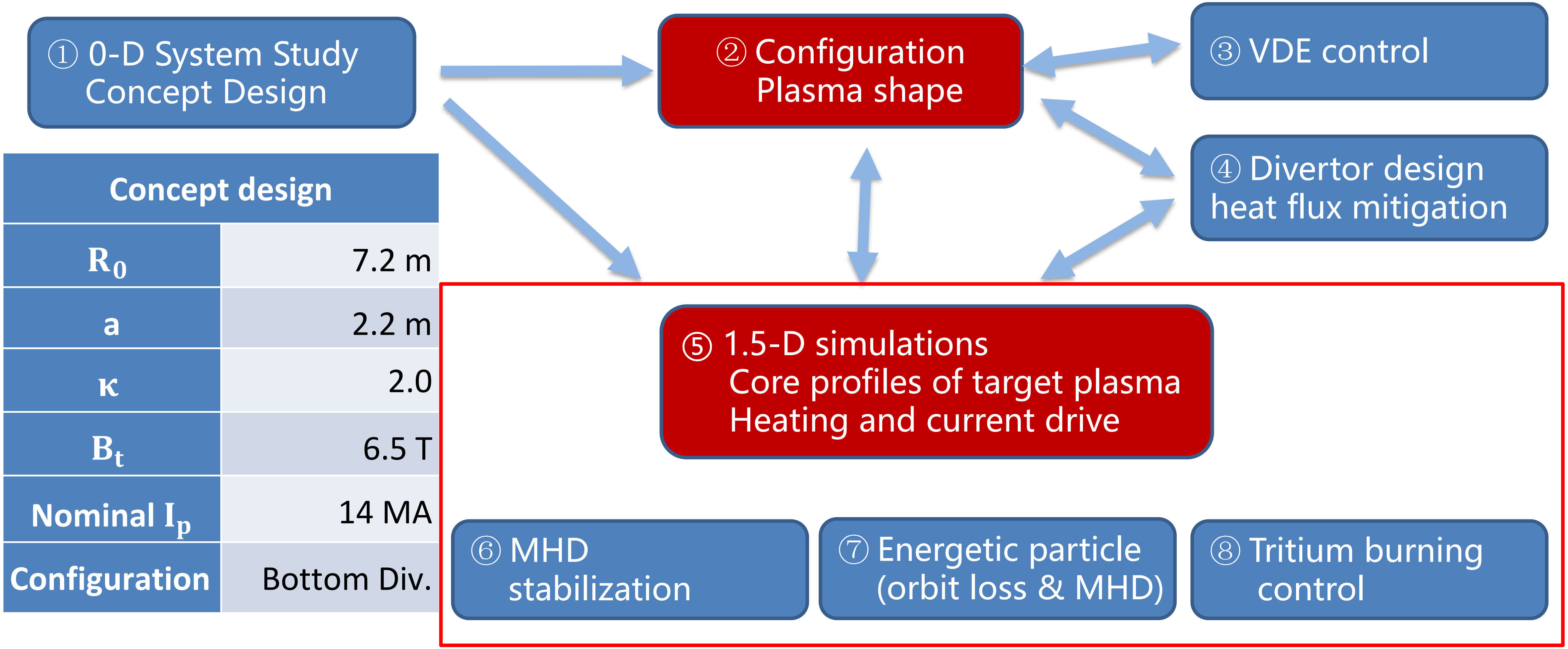
By Chaofeng Sang using SOLPS code

Summary on configuration design

- **Configuration design has matched the requirements proposed by the 0-D system study.**
    - High elongation
    - Lower power exhaust
- **Constraints on 1.5-D simulations for core plasma:**
    - SND configuration with moderate triangularity
    - Including seeding impurity (e.g. Argon)



Top-down physics design with multiple task forces



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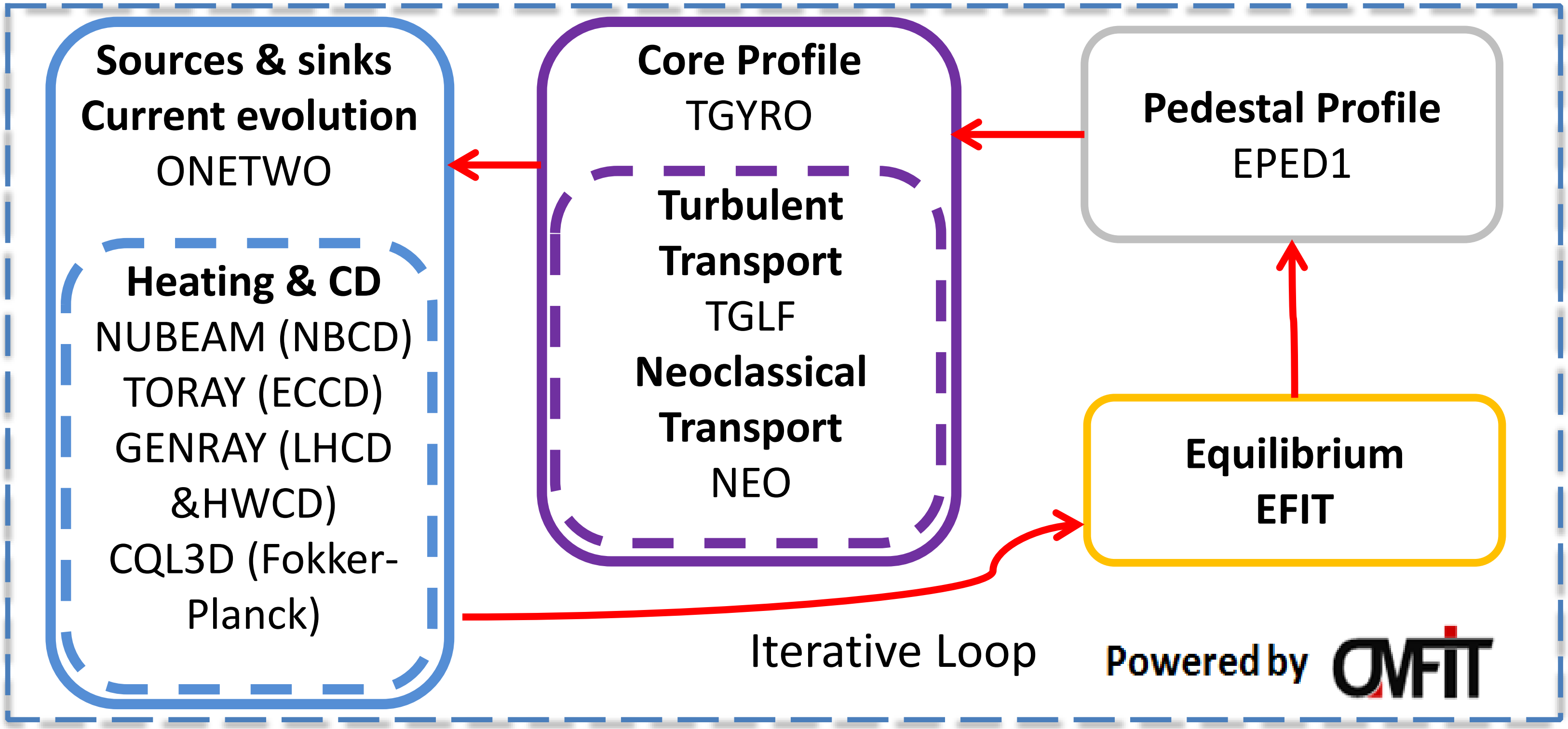
1.5-D simulations using physics based models for target plasma at flattop phase with self-consistent H&CD

- **Workflow including the coupling between core and pedestal for the modeling of plasma profiles**

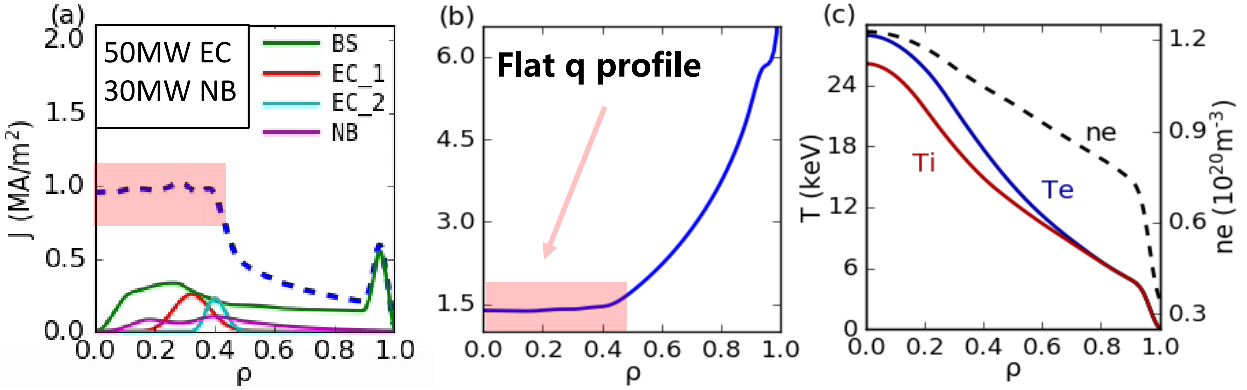


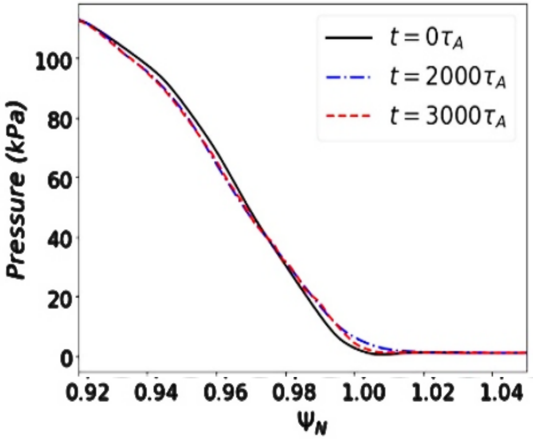
*Based on the similar workflow reported in Meneghini, O., et al. 2016 Physics of Plasmas 042507

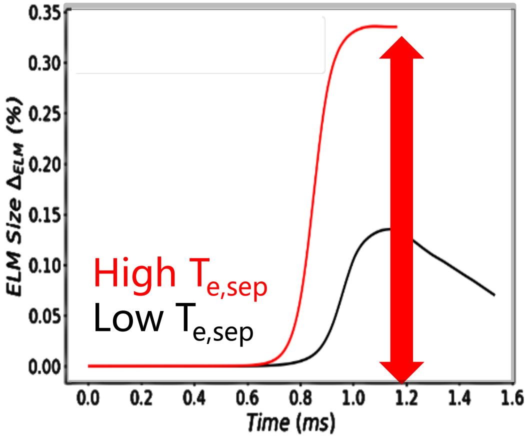
Baseline case for hybrid scenario

- **Neutral beams and EC waves**
  - 1 MeV beams
  - 250 GHz EC waves
- **Enhanced confinement**
  - Flat q profile in core
  - Including EM stabilization effect
- **Grassy ELMy pedestal**
  - Nonlinear BOUT++ simulations#：

    ELM induced power loss < 0.4% pedestal energy







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*Chen, J., et al. 2021 Nuclear Fusion 046002

Li, Z. Y., et al. 2021 Plasma Physics and Controlled Fusion 63(3) 10

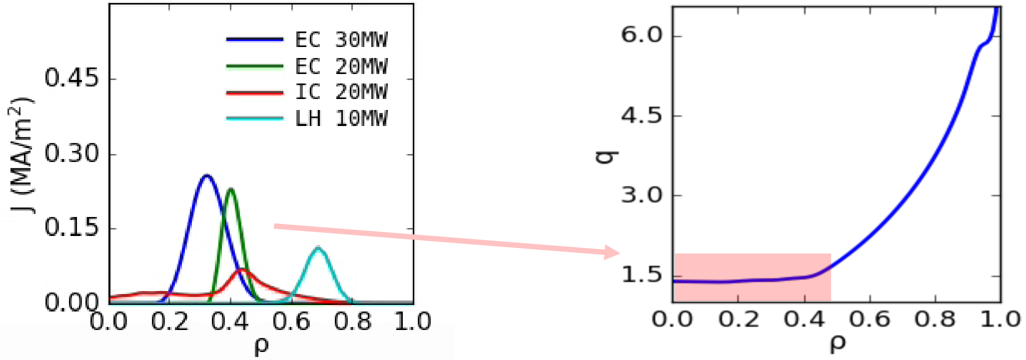
Replacement of ECCD by ICCD or LHCD yielding performance degradation

Comparison between different H&CD

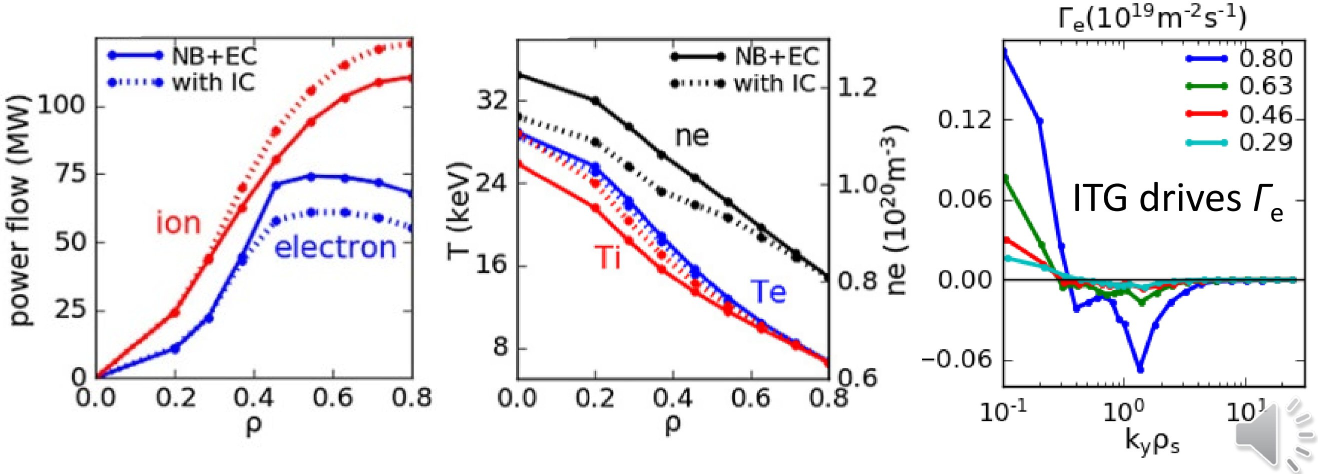
Case Note	Baseline(EC)	LHCD	ICCD
P_{NB} (MW)	30	30	30
P_{EC} (MW)	50	↓40	↓30
P_{LH} (MW)	0	10	0
P_{IC} (MW)	0	0	20
f_{bs}	0.45	0.41	0.4
H_{98y2}	1.14	1.12	1.11
P_{fus} (MW)	952	↓819	↓788
Φ_{ohm} (VS)	250	↑284	↑322
$n_{e,line}(10^{20}/m^3)$	1.01	0.98	0.96

*Chen, J., et al. 2021 Nuclear Fusion 046002

- **Only the ECCD can be localized in deep core region (r/a ≤ 0.4) to flatten *q* profile effectively.**



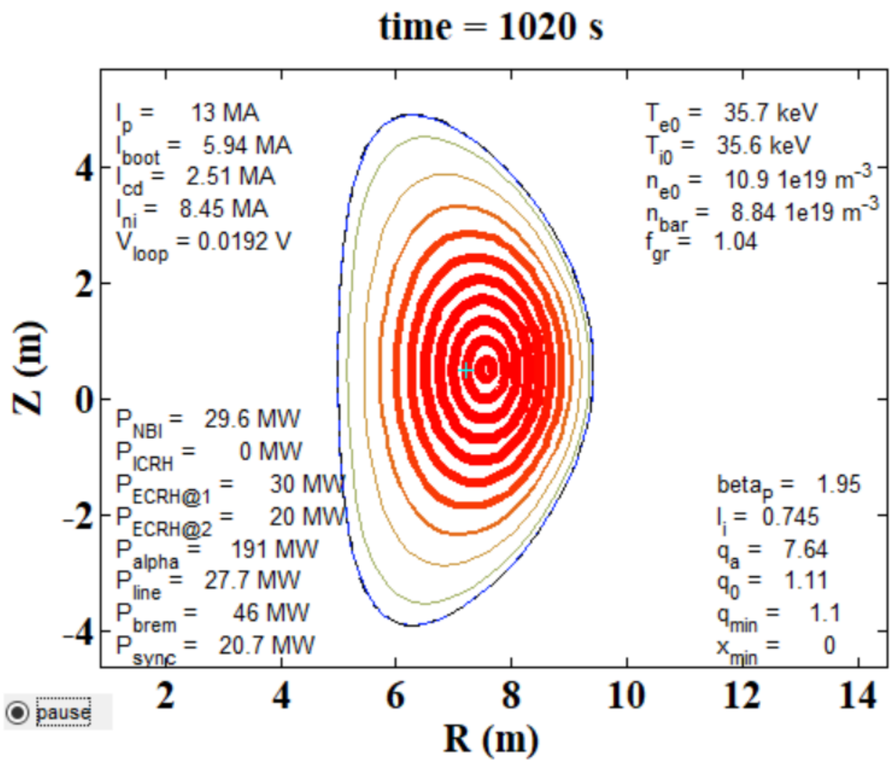
- **Lower particle confinement with more ion heating**



Baseline case verified by time-dependent simulations using METIS+CRONOS

Param.	OMFIT	METIS	CRONOS
PF(GW)	0.95	1.0	0.86
Q	11.9	12.5	10.9
IP(MA)	13	13	13
Betan	2.3	2.35	2.1
fbs	0.45	0.44	0.45
H98	1.17	1.23	1.08
Ne0(^19)	12.2	12.1	10.4
Ti0/Te0 (keV)	26/29	30/30	30/35.5
$<n>/n_{Gr}$	1.04	1.00	1.02
q0	1.38	1.42	1.35
q95	5.8	5.5	5.9
Zeff	2.2	2.2	2.2
Pec(MW)	50	50	50
Pnbi(MW)	30	30	30

By Shaoyong Chen



I_p = 13 MA
I_{boot} = 5.94 MA
I_{cd} = 2.51 MA
I_{ni} = 8.45 MA
V_{loop} = 0.0192 V

T_{e0} = 35.7 keV
T_{i0} = 35.6 keV
n_{e0} = 10.9 1e19 m^{-3}
n_{bar} = 8.84 1e19 m^{-3}
f_{gr} = 1.04

P_{NBI} = 29.6 MW
P_{ICRH} = 0 MW
$P_{ECRH@1}$ = 30 MW
$P_{ECRH@2}$ = 20 MW
P_{alpha} = 191 MW
P_{line} = 27.7 MW
P_{brem} = 46 MW
P_{sync} = 20.7 MW

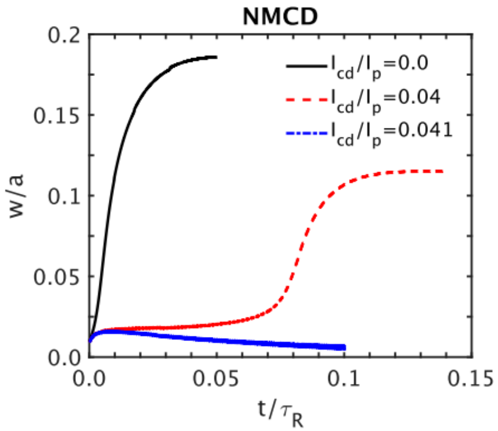
$beta_p$ = 1.95
l_i = 0.745
q_a = 7.64
q_0 = 1.11
q_{min} = 1.1
x_{min} = 0

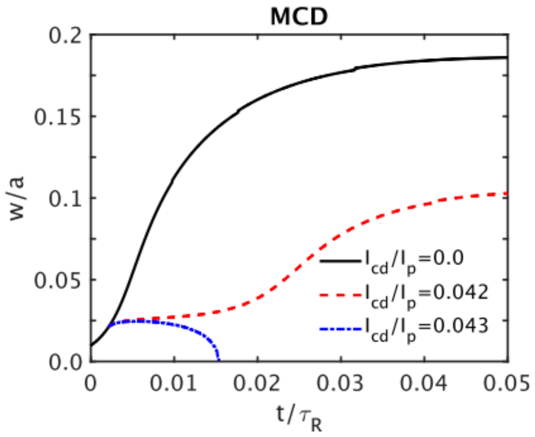
- 0.5-D METIS → 1.5-D CRONOS
- Particle density profile is based on assumptions.

Improving NTM stabilization efficiency by ECCD

- **ECCD would be used to control NTM at q=2.**

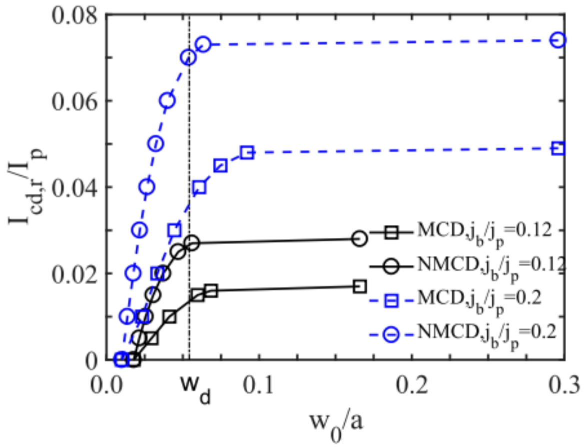
- **Modulated ECCD (MCD) is more effective than non-modulated ECCD (NMCD)**





- **ECCD at early stage of NTM reduces the required EC power for NTM stabilization**
  - Threshold I_{cd}/I_p to stabilize NTM increases with the island width w_0 at the time to apply ECCD.

Required rf current for mode stabilization vs width w_0



j_b: bootstrap current density
j_p: plasma current density

By Xiaojing Wang

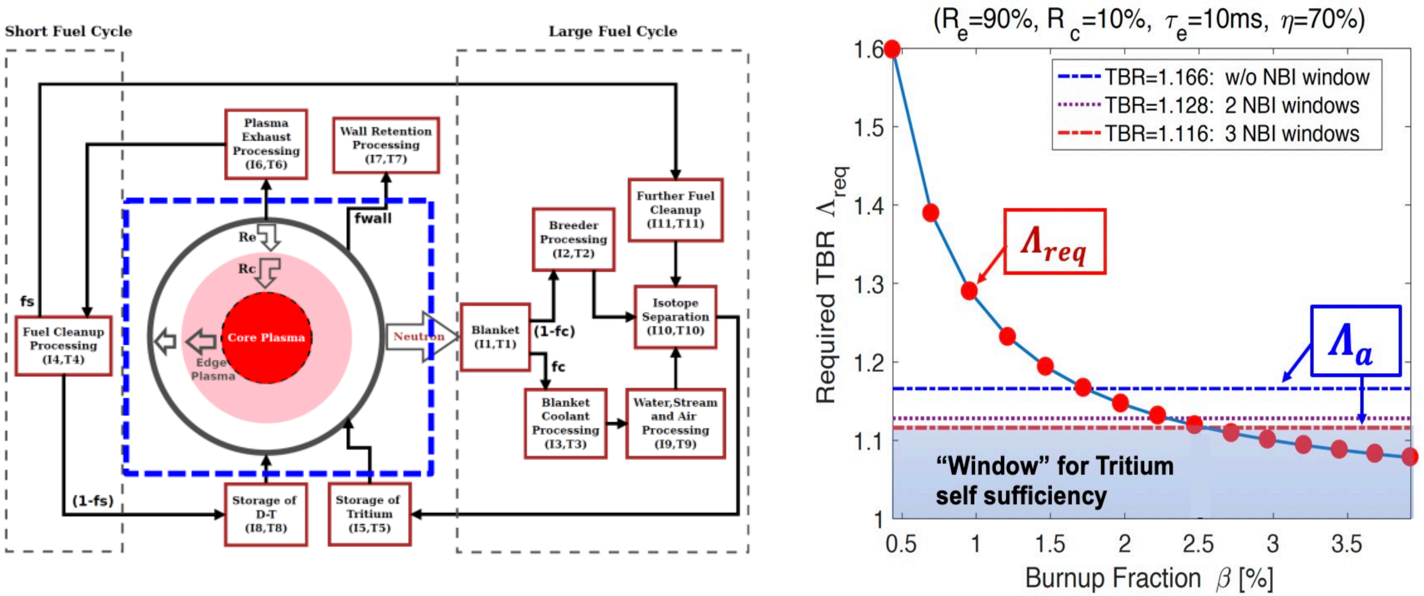
Critical TBR for tritium self-sustain depending on tritium burnup fraction

- Based on the present design of HCCB and WCCB for TBR, tritium burnup fraction for CFETR should be larger than ~3%。

Tritium self-sustain condition: $\Lambda_a \geq \Lambda_{req} > 1$

Blanket Type	H&CD occupation of ports	TBR (Λ_a)
HCCB	No	1.177
	NBI (2 toroidal modules) EC (3 poloidal modules) IC (3 poloidal modules) LH (1 poloidal modules)	1.140
WCCB (including Divertor region)	No	1.224
	NBI (2 #2 and 2 #3 modules) EC (3 #4 modules) IC (2 #5 modules) LH (1 #5 modules) Diag (3 #2 and 3 #2 modules	1.107

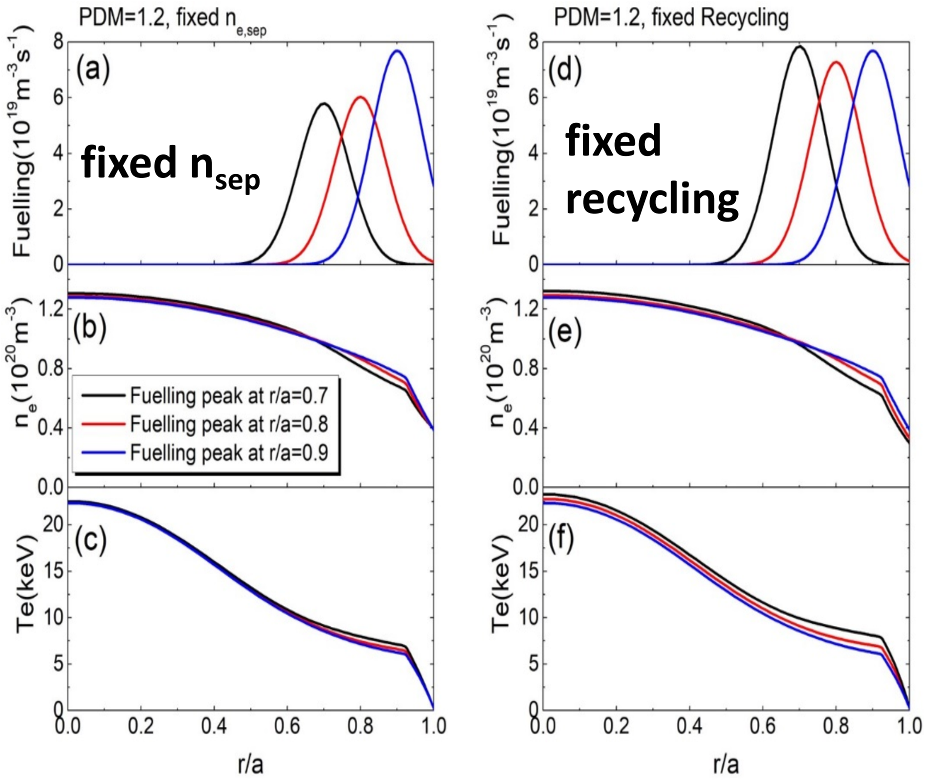
Model of tritium fuel cycle for TBR requirement Λ_{req}



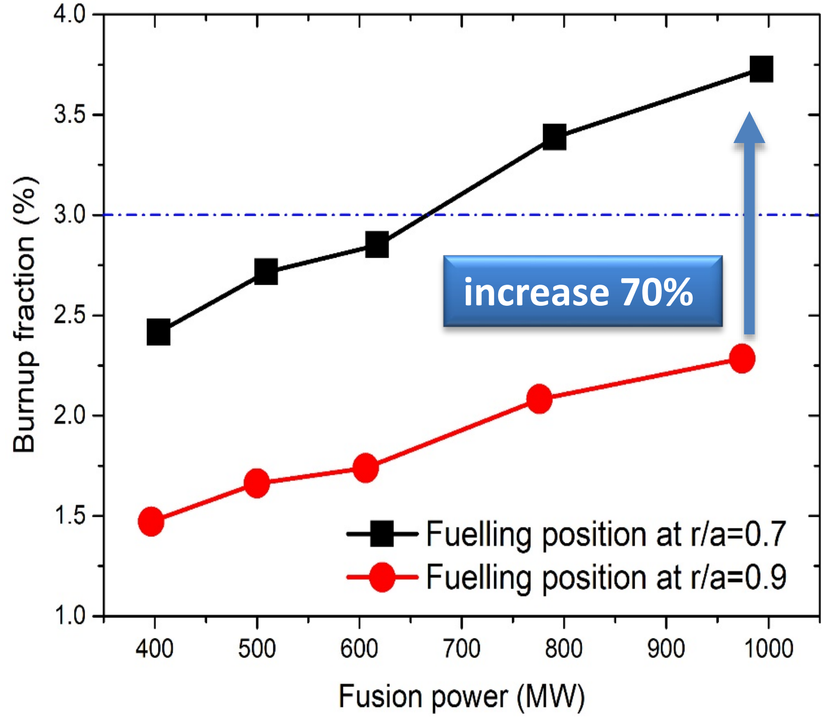
By Songli Liu, Xiaoyu Wan and Defeng Kong

Tritium burnup fraction increasing with fueling depth

- **Plasma profiles with pellet fueling are simulated by COREDIV#.**
- **Fueling at r/a=0.7 in high fusion power plasma yields burnup fraction about 3.9%.**



Burnup fraction f_{burnup} with different fueling depth and target fusion power



*Xie, H., et al. 2020 Nuclear Fusion 046022

#COREDIV uses a simple transport model but the transport coefficients are calibrated with previous core-pedestal modeling.

Summary on hybrid scenario design

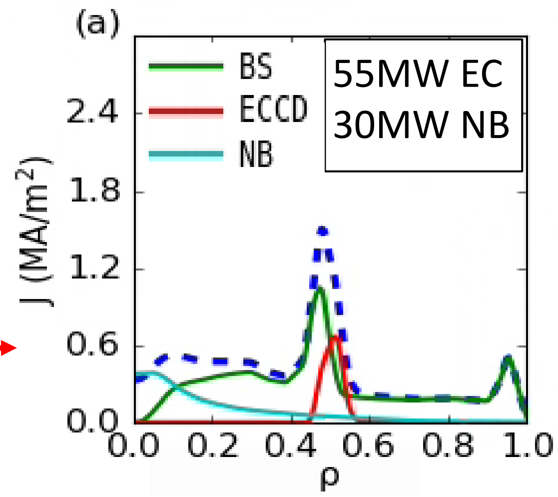
- **Target plasma at flattop phase is modeled by 1.5-D simulations based on physics theories.**
  - The *q* profile in the deep core region is flatten by the combination of NBCD and ECCD.
  - Grassy ELMy characteristic is verified by nonlinear BOUT++ simulations.
- **Time-dependent simulations have verified the target plasma parameters.**
- **Comparison of H&CD on plasma performance: ECCD by ICCD or LHCD yields performance degradation.**
- **Additional ECCD should be used to stabilize 2/1 NTM and the stabilization efficiency can be improved by applying modulated ECCD as early as possible after the onset of magnetic islands.**
- **Deep fueling (up to r/a=0.7 for P_{fus}=1GW) can increase tritium burnup fraction to satisfy the TBR requirement >~3%.**

Target plasmas at flattop phase for steady-state scenario

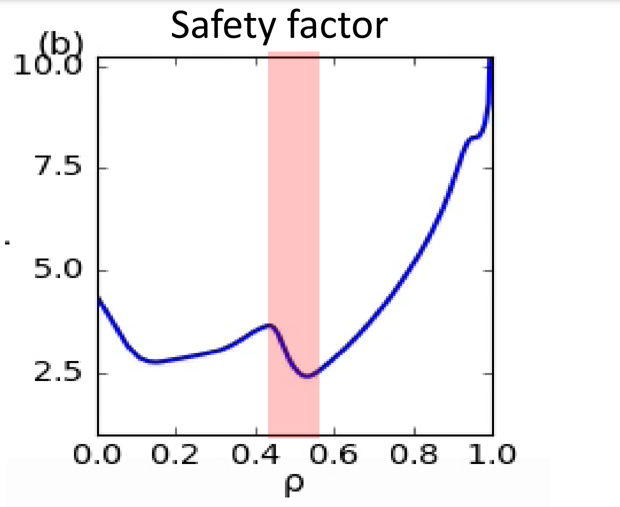
- **Neutral beams and EC waves**
  - Similar with the baseline case for hybrid scenario
- **Local reversed shear controlled by ECCD**
  - Enhanced confinement ITB*

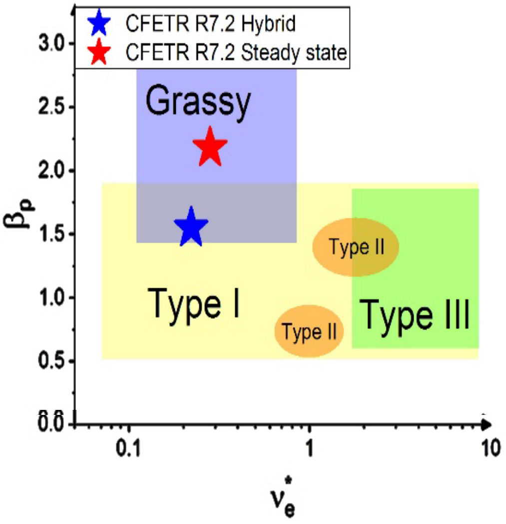
P_{fus} (GW)	H_{98y2}	β_N/β_P	f_{bs}/l_i	I_p (MA)
1.0	1.33	3.0/2.5	0.78/0.8	10.5

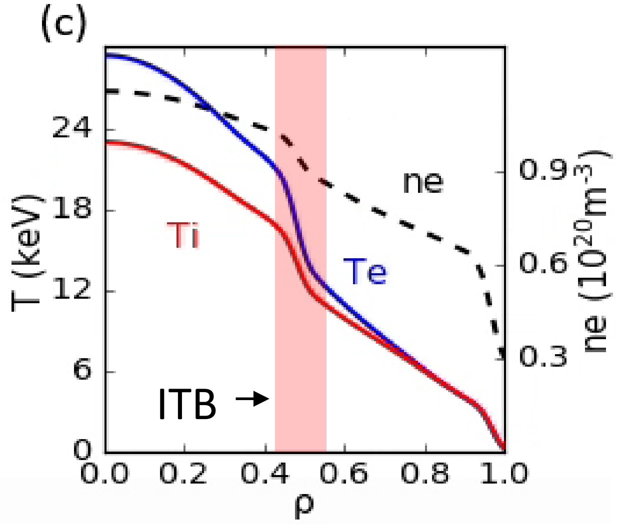
- **Operating point at the center of grassy ELMy regime**



Safety factor







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

Ideal MHD instability

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

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

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

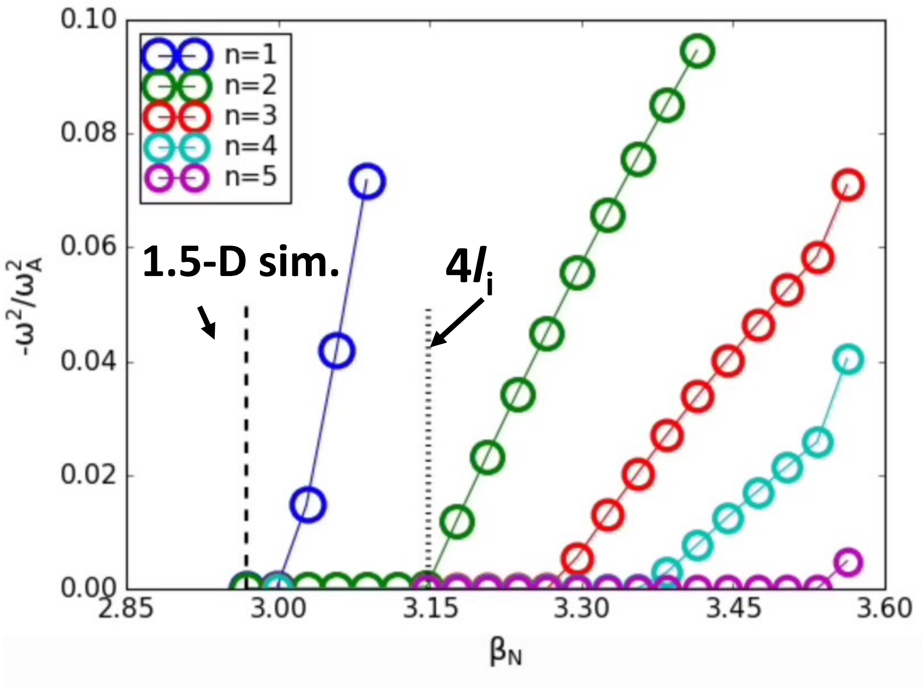
- The present 1.5-D case has a small margin:

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

- Ideal MHD code confirms that all the low n ideal modes are stable for the latest SS case.

- More verification is necessary.

Ideal no-wall MHD instability growth rate by GATO



New model is developed to predict the relaxation of alpha particle profile due to the toroidal Alfvén eigenmodes.

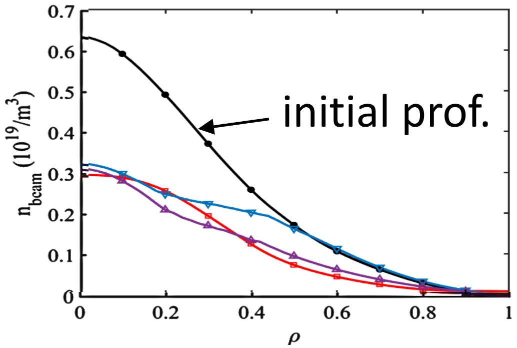
- **New Model**
  1. An upgraded critical gradient model （CGM） considering dynamic variation of EP density profiles (namely TAE induced transport)

$$\frac{a}{L^{th}_{n\_EP}} = \frac{k_1}{n_{EP}} + k_2$$

  2. **Successive** orbit loss# after the TAE induced transport.

Experimental validation of new model

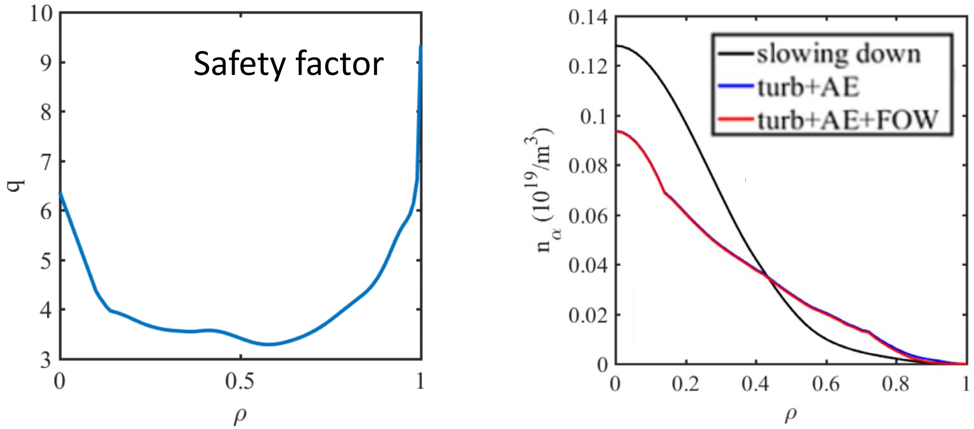
TAE on DIII-D



beam particle loss (%)	
Old Sim.	23.9
New model	48.8
Experiment	51.7

- **For the preliminary CFETR steady-state scenario***
  - **Only 6.6% alpha particle is lost since the regions for TAEs and orbit loss are separated.**
  - n = 6~10 TAEs dominate at 0.3 < r/a < 0.5.
  - Loss cone for orbit loss is at 0.7 < r/a.

Alpha particle profile relaxation by the new model for preliminary CFETR steady-state scenario



- **In the latest steady-state scenario there is no EP-driven TAEs. (future work)**

By Yunpeng Zou

#Orbit loss considered here is only that due to the finite orbit width effect (FOW)

*Zhuang, G., et al 2019 Nuclear Fusion 112010

Summary on steady-state scenario design

- **1.5-D simulations produce target plasma profiles with ITB.**
  - Local reversed shear is controlled by localized ECCD.
- **Ideal MHD code based on energy principle shows that all the destructive low-n modes are stable.**
- **Ripple induced alpha particle loss is at an acceptable level.**
- **TAEs induced alpha particle loss could be small if there is a clear separation between TAE induced transport region and the loss cone for the orbit loss.**

Future work relevant with scenario development

1. **Verification of the transport modeling in core plasmas for hybrid and steady-state scenarios**
2. **Coupling core-pedestal modeling and edge modeling as well as validating with experiments**
    - Impurity seeding and gas puffing in the edge region may cause some dilution of the tritium in the core.
3. **Studies on pellet fueling with high magnetic field**
4. **Studies on the effects of alpha particle induced modes on plasma performance**

Acknowledgement

This presentation is based on the work by the CFETR physics team leaded by Prof. Vincent Chan. The efforts and contributions by the members and the international partners are greatly appreciated.

Thanks!

Backup

- **6.6% alpha particle is lost for the preliminary CFETR steady-state scenario***
  - n = 6~10 TAEs dominate at 0.3 < r/a < 0.5.
  - Loss cone for orbit loss at 0.7 < r/a

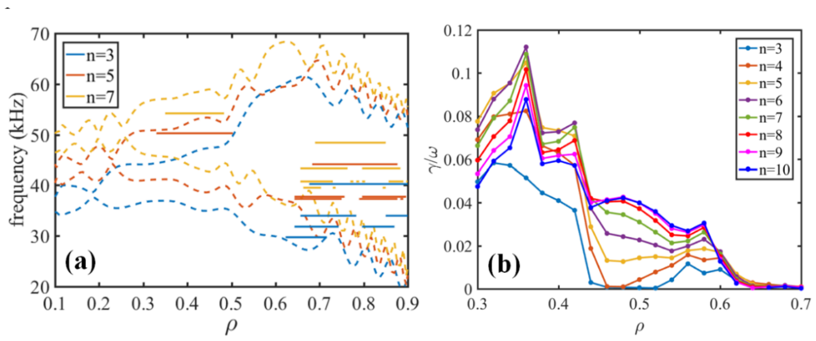


Figure 11 **(a)** n=3, 5, 7 continuum and AEs location. The mode with the lowest frequency for n=3 is an RSAE. The frequency of TAE gap has a Doppler shift by considering plasma rotation. **(b)** The growth rate of TAEs with n=3-10 as a function of minor radius calculated by TGLFEP

Table 1 Comparison of density and loss fraction between various predictions

Curve	Description	Density on axis (10^{19} m^{-3})	Loss fraction (%)
Black	classical slowing down	0.186	/
Green	only turbulence	0.158	0.7
Yellow	only FOW	0.186	1.0
Blue	turbulence + AE	0.124	3.8
Pink	turbulence + FOW	0.144	2.5
Red	turbulence +AE + FOW	0.110	6.6

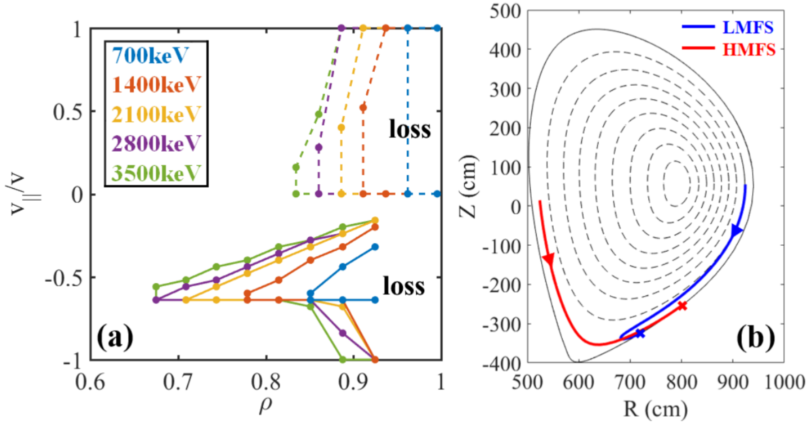


Figure 12 **(a)** Loss boundary in pitch angle space as a function of poloidal flux ψ with different energies distinguished by colors. The solid curves depict initial EPs at the outside mid-plane, and dash curves depict initial EPs at the inside mid-plane. (b) Trajectories of lost particles with initial EPs at the outside mid-plane (blue) and inside mid-plane (red).