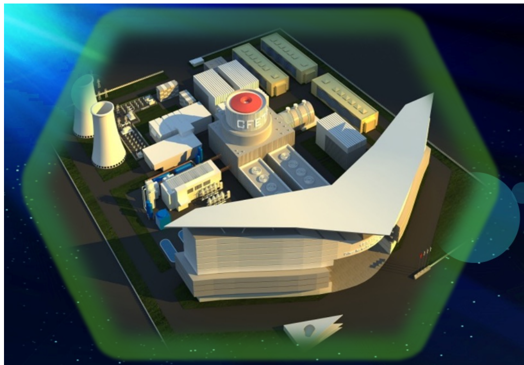
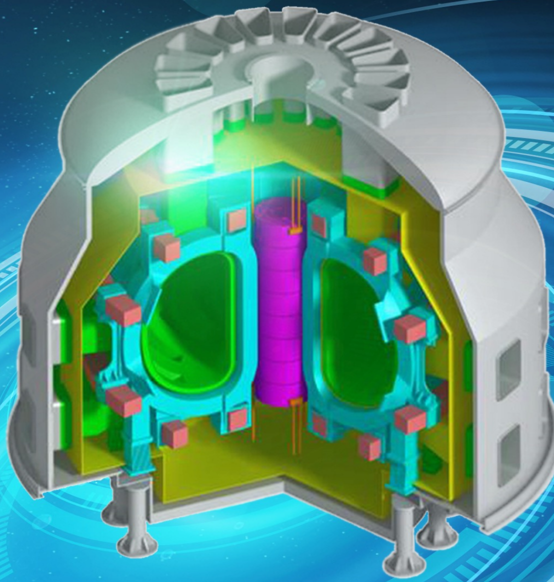


EU – China collaboration on CFETR and EU-DEMO
Reactor Design
4th Technical Exchange Meeting

Overview of CFETR Physics Design



Vincent Chan and the CFETR Physics Team

19-21 March 2024, KIT, Karlsruhe, Germany

CONTENTS

Outline

- ❖ Introducing CFEDR (China Fusion Engineering Demo Reactor) – a logical evolution of CFETR

- ❖ Establishing key physics basis
  - ➢ High confinement factor at high f_{GW}
  - ➢ Handling transient and steady-state heat load
  - ➢ Stable operation at high β_N
  - ➢ Maximizing alpha heating
  - ➢ Achieving tritium self-sufficiency

- ❖ BEST as an essential step for CFEDR – collaboration opportunities

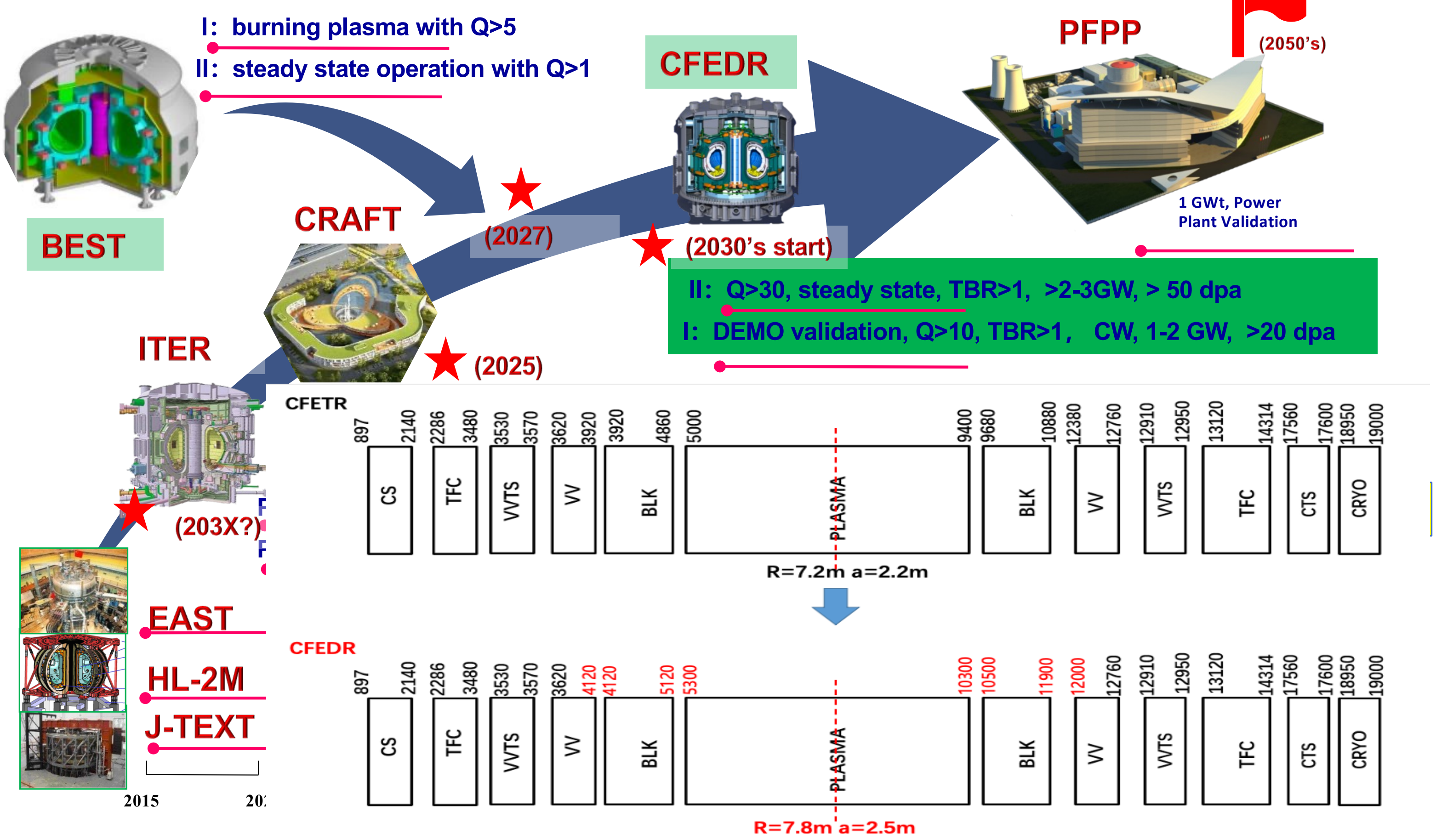
Burning plasma
Experimental
Superconducting
Tokamak

New China MCF Roadmap （2022）

What to fill the gap? A new tokamak!

Technical readiness

- **EAST**
  Steady-state long-pulse physical operation
- **ITER**
  Near 20 years' R&D experience
- **CFETR**
  The engineering design completed
- **CRAFT**
  The construction launched in 2019



I: burning plasma with Q>5

II: steady state operation with Q>1

II: Q>30, steady state, TBR>1, >2-3GW, > 50 dpa

I: DEMO validation, Q>10, TBR>1, CW, 1-2 GW, >20 dpa

CFEDR Mission Remains the Same as CFETR

High fusion power at FPP relevant level with high gain

1. P = 2000-3000 MW
2. Q = 20, physics and technology SS
3. Q = 20-30 hours-FPP long-pulse/SS
4. High energetic a heating

Approaching DEMO

Steady-state operation and high duty factor >0.5

5. SSO (Ext H&CD + Higher f_b)
6. Hybrid (OH+BS+CD)
7. PSI on the first wall
8. Heat & particle exhaust on Div.

Demonstrating T self-sufficiency

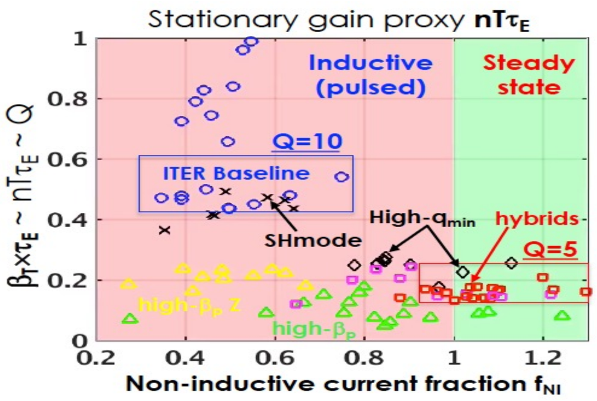
9. T-breeding by blanket
10. T-plant: extract & reprocessing
11. Materials & components
12. Reliable and quick RH
13. Licensing & safety

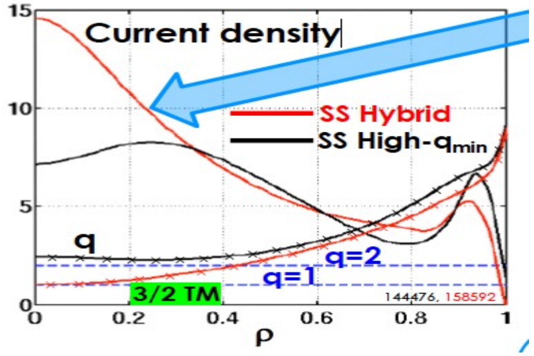
0D Predictions of CFEDR Steady-State and Pulsed Scenarios

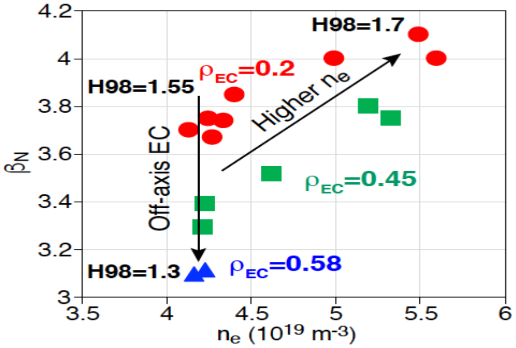
CFETR fully non-inductive A=3.12,a=2.5m, R=7.8m, κ=1.65		A.3 2GW SS EC+IC	C.4 3GW Pulsed EC+IC
fusion power(MW)	Pf	2043	2721
Pfusion/Paux	Qplasma	20.4	27.2
Neutron Power at Blanket(MW/m2)	Pn/Awall	1.97	2.62
toroidal beta	BetaT	0.026	0.030
normalized beta	BetaN	3.25	3.25
betaP	BetaP	1.89	1.64
bootstrap fraction	fbs	0.75	0.65
H factor over ELMY H_net	HITER98Y2	1.63	1.44
Ohmic fraction	fohm	0.0	0.18
current drive power(MW)	Pcd	86(EC) 14(IC)	78(EC) 22(IC)
plasma current(MA)	Ip	13.0	15.0
field on axis(T)	Bo	6.5	6.5
Ion/electron Temperature(KeV)	Ti(0)/Te(0)	35/35	35/35
Electron Density(E20/m3)	n(0)	1.08	1.24
Ratio to Greenwald Limit	nbar/nGR	1.30	1.30
Zeff	Zeff	2.45	2.45
Power per unit Major Radius(MW/m)	P/R	27.6	35.5
q95 Iter	q95_iter	5.25	4.55

- **Both scenarios are advanced modes**
- **Both require $f_{GW}>1$**

Experimentally Validated Candidates for High Confiement Core – hybrid & high β_p mode

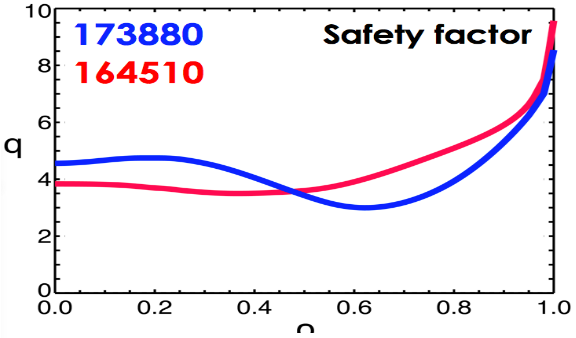




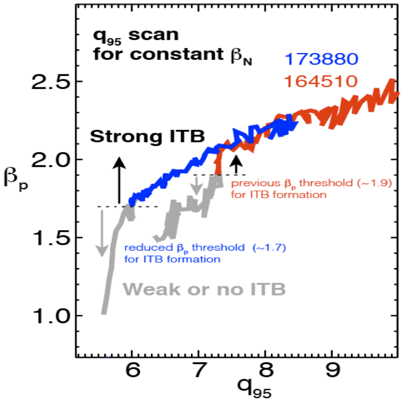


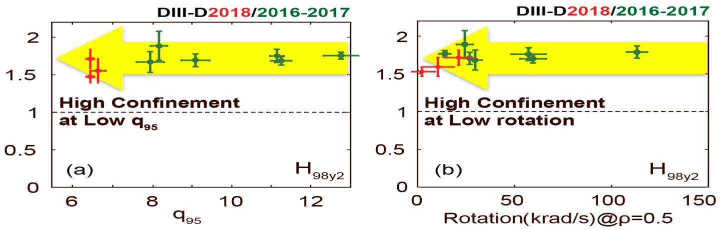
Hybrid mode lower q_{95}, extended to high density

F. Turco, APS 2020



High β_p higher q_{95}
Local RS lowers q_{95}

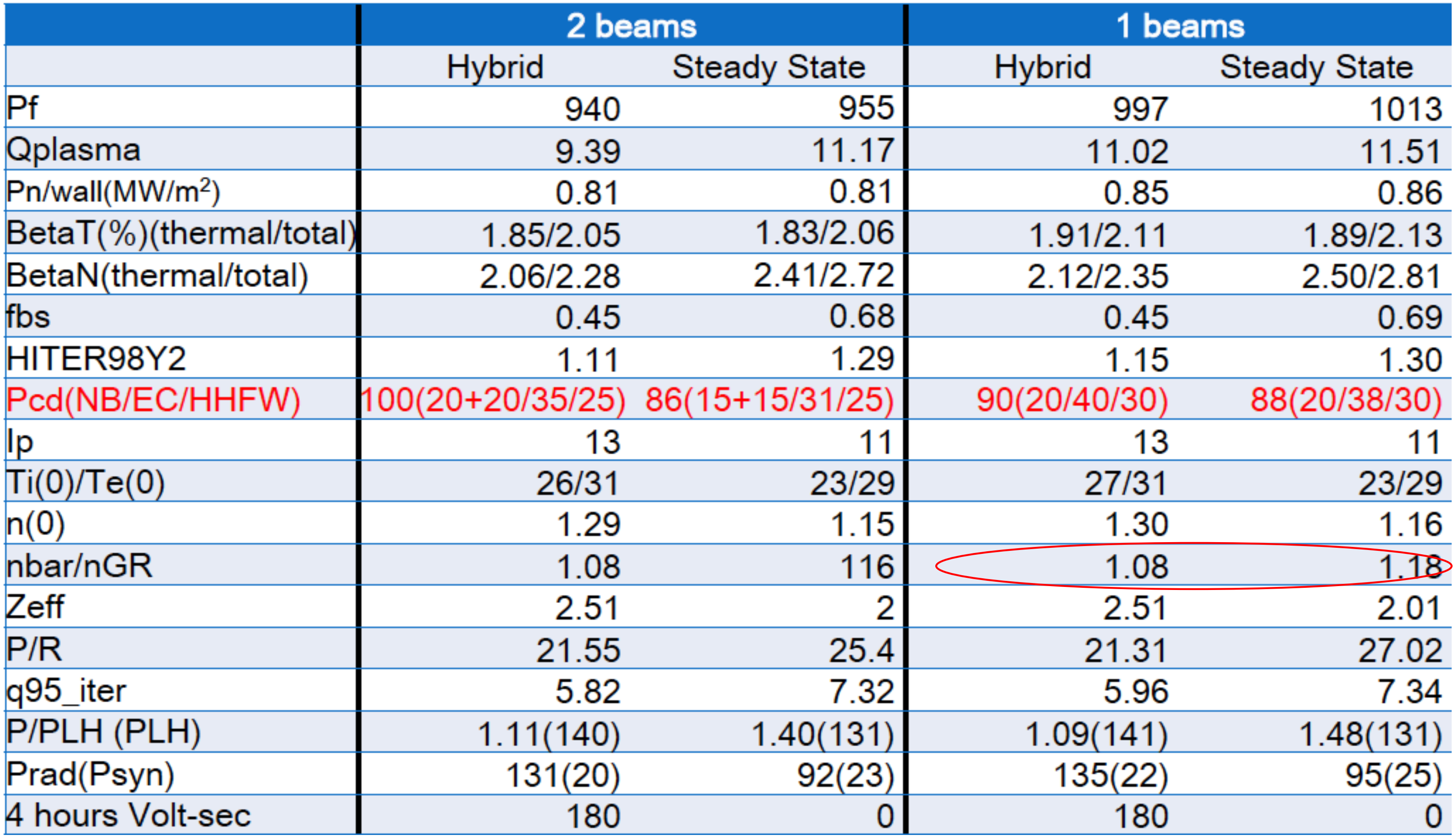




High β_p achievable with low torque

EAST/DIII-D collaboration
J. Huang, NF 2020

Physics Analysis Based on CFETR 1.5D Design (2020)



	2 beams		1 beams	
	Hybrid	Steady State	Hybrid	Steady State
Pf	940	955	997	1013
Qplasma	9.39	11.17	11.02	11.51
Pn/wall(MW/m^2)	0.81	0.81	0.85	0.86
BetaT(%)(thermal/total)	1.85/2.05	1.83/2.06	1.91/2.11	1.89/2.13
BetaN(thermal/total)	2.06/2.28	2.41/2.72	2.12/2.35	2.50/2.81
fbs	0.45	0.68	0.45	0.69
HITER98Y2	1.11	1.29	1.15	1.30
Pcd(NB/EC/HHFW)	100(20+20/35/25)	86(15+15/31/25)	90(20/40/30)	88(20/38/30)
Ip	13	11	13	11
Ti(0)/Te(0)	26/31	23/29	27/31	23/29
n(0)	1.29	1.15	1.30	1.16
nbar/nGR	1.08	116	1.08	1.18
Zeff	2.51	2	2.51	2.01
P/R	21.55	25.4	21.31	27.02
q95_iter	5.82	7.32	5.96	7.34
P/PLH (PLH)	1.11(140)	1.40(131)	1.09(141)	1.48(131)
Prad(Psyn)	131(20)	92(23)	135(22)	95(25)
4 hours Volt-sec	180	0	180	0

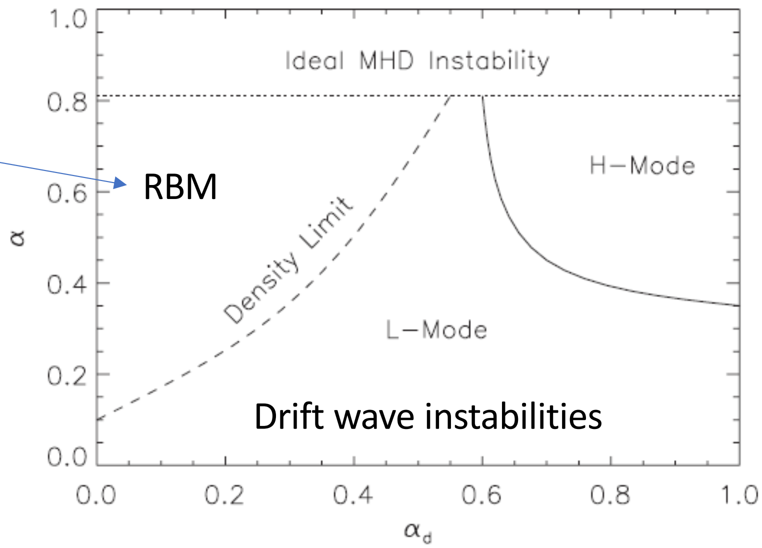
Use dimensionally similar analysis to project from existing experiments to BEST/CFEDR

J.L. Chen

Theoretical Basis for a Tokamak Density Limit

Theory	Linear or nonlinear	Model	Cause of density limit
Rogers & Drake	linear	Braginskii equations	RBM set the limit
Giacomin	Linear	Drift-reduced Braginskii equation	Resistive interchange mode
Diamond	Nonlinear	Hasegawa-Wakatani equation	Edge shear layer collapse

$$n_{\mathrm{lim}} \sim A^{1/6} P_{\mathrm{SOL}}^{10/21} R_0^{1/42} B_T^{-8/21} (1+\kappa^2)^{-1/3} \frac{I_p^{22/21}}{a^{79/42}} .$$



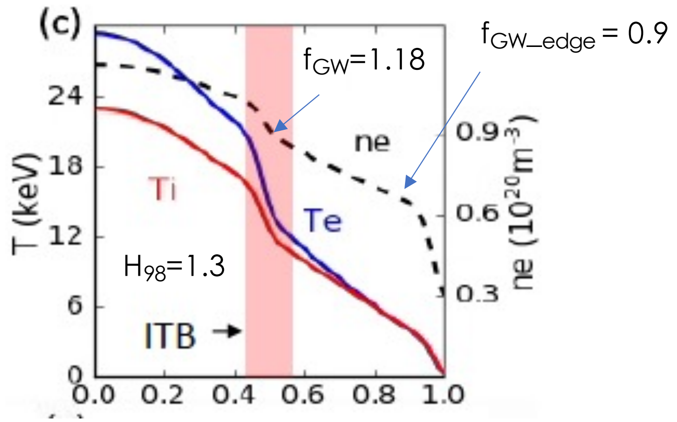
$$\alpha_d = \frac{\rho_s C_s t_0}{L_n L_0}$$

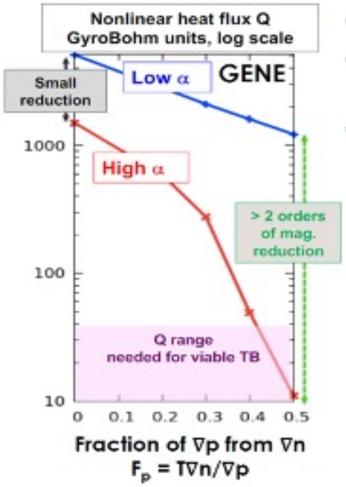
$$t_0=\frac{(RLn)^{0.5}}{C_s}, L_0 = 2\pi q(\nu_e R \rho_s/2\Omega_e)^{0.5}$$

- **All focus on edge instabilities**
- **None identifies f_{GW}=1 as the critical limit**

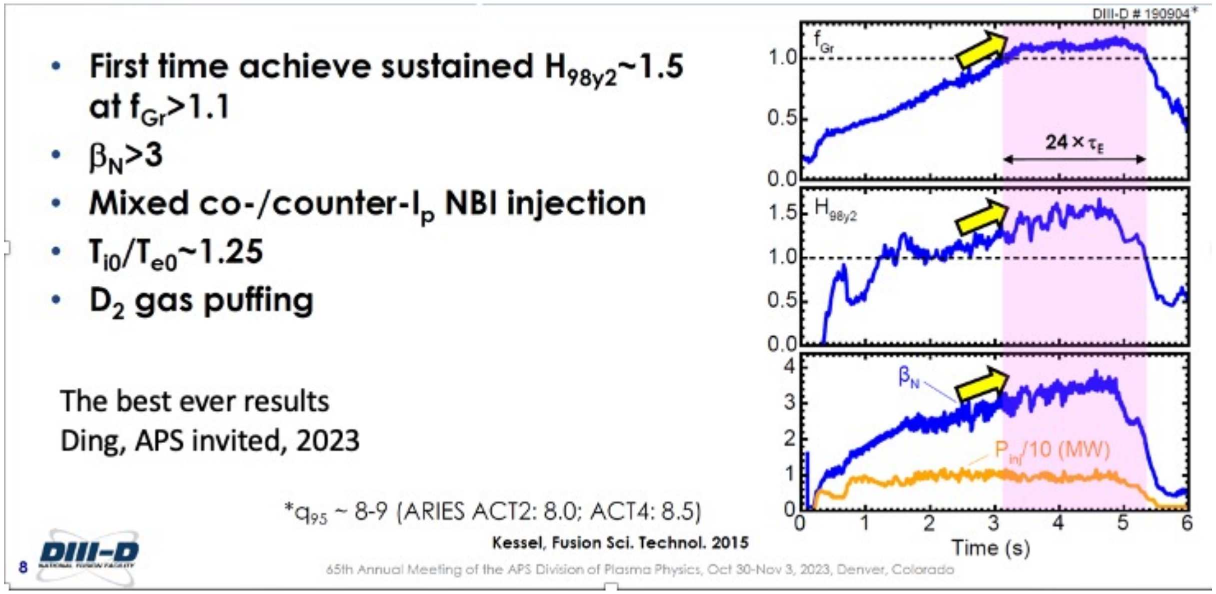
A Plausible Strategy for High H_{98} is to Keep f_{GW_edge}<1

CFETR Steady-State





- f_{GW}=1.2 is not the upper limit
- Efficient core fueling is essential



- First time achieve sustained H_{98y2}~1.5 at f_{Gr}>1.1
- β_N>3
- Mixed co-/counter-I_p NBI injection
- T_{i0}/T_{e0}~1.25
- D_2 gas puffing

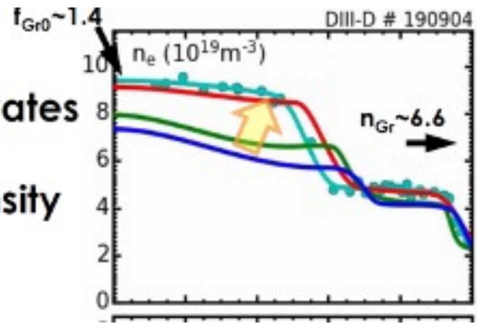
The best ever results
Ding, APS invited, 2023

*q_{95} ~ 8-9 (ARIES ACT2: 8.0; ACT4: 8.5)
Kessel, Fusion Sci. Technol. 2015

8 DIII-D

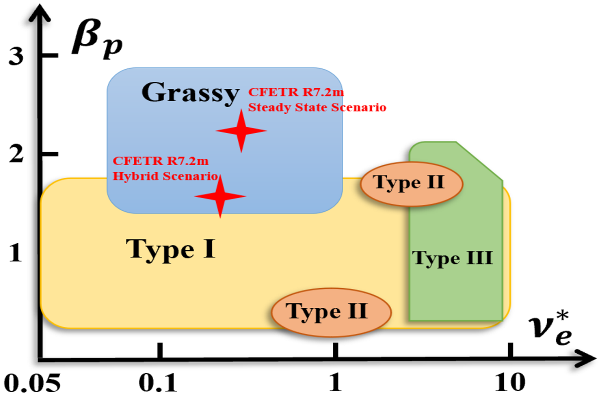
65th Annual Meeting of the APS Division of Plasma Physics, Oct 30-Nov 3, 2023, Denver, Colorado

- Strong density ITB elevates core density, while keeping pedestal density below n_{Gr}
  - $f_{Gr,ped}$~0.7, $f_{Gr,0}$~1.4



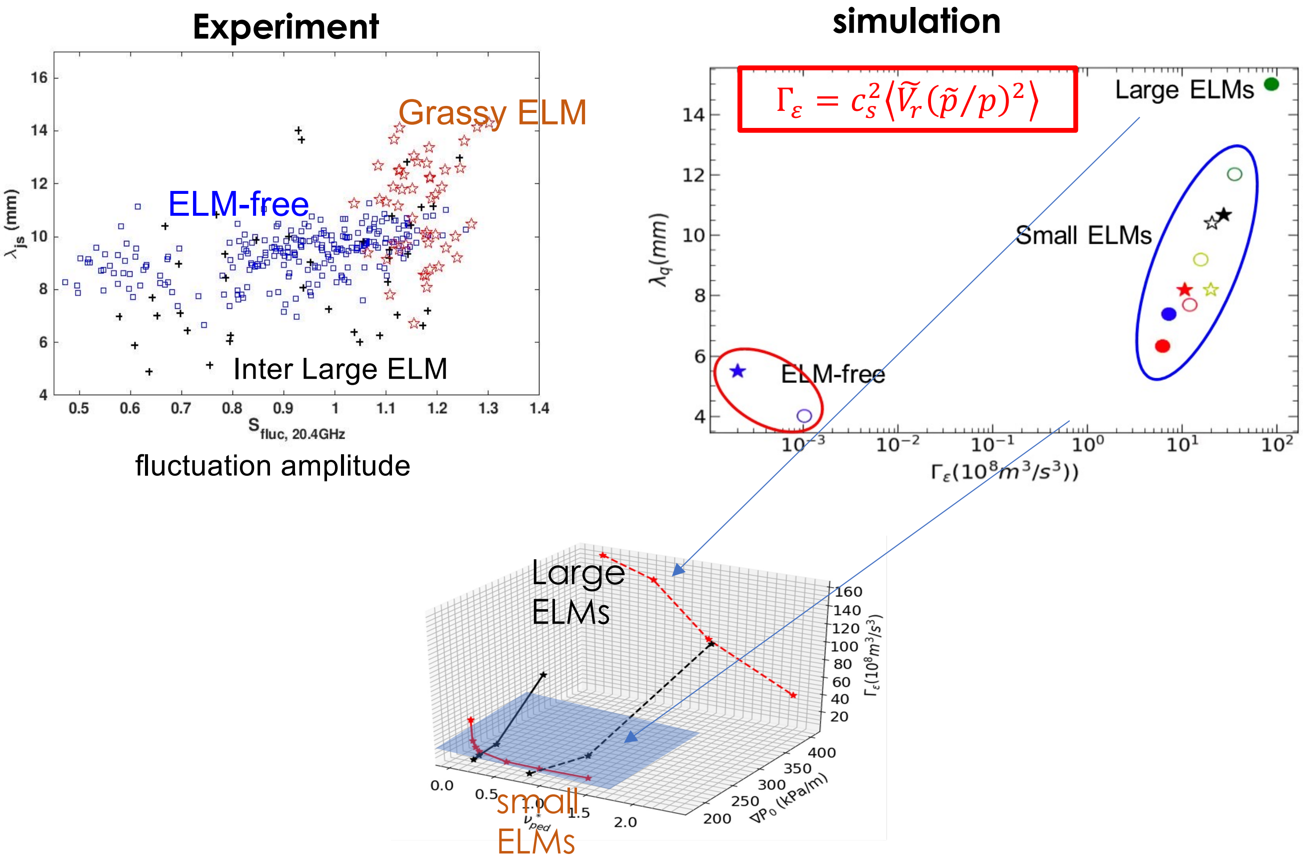
Mitigating Transient Heat Load on PFC
- Grassy ELM Operation has Many Advantages for CFETR

- ✓ **Lower transient heat flux to the first wall (requires $\Delta W/W_{ped}$<<1%)**
- ✓ **Beneficial impurity cleansing effect**
- **Broadening of λ_q**
- **High β_p and intermediate ν^* (f_{GW_edge}<1) compatible with high confinement, high bootstrap fraction and divertor solution**



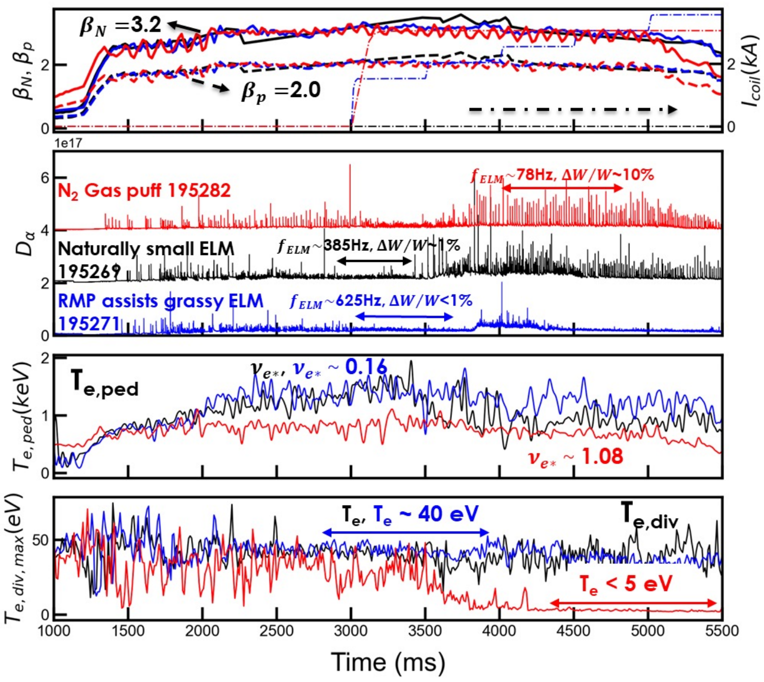
From CFETR simulation

EAST experiments: grassy ELMs show broader heat flux width due to fluctuation energy density flux

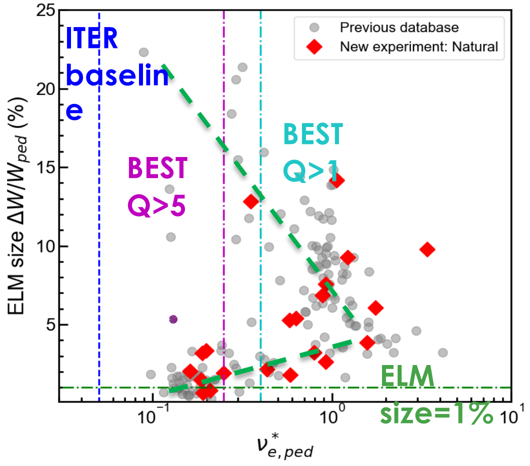


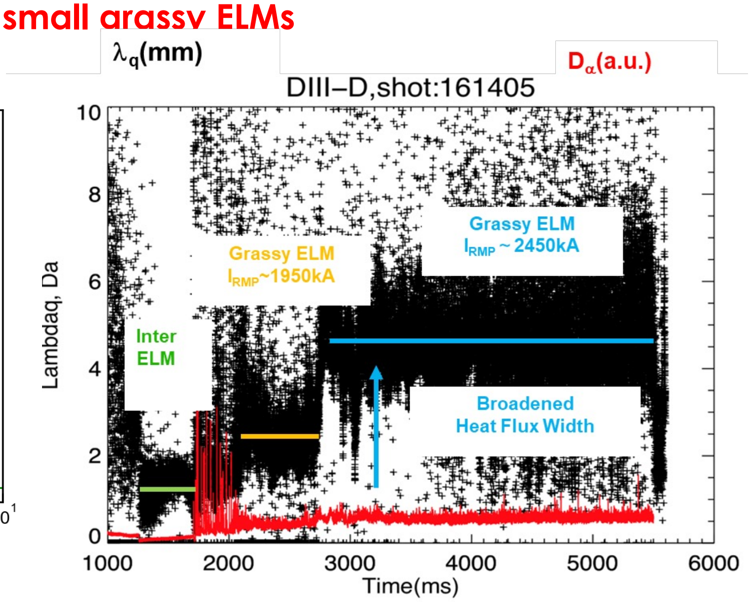
DIII-D Achieved Small/Grassy ELM with High-Performance core

ZY Li



- Small/grassy ELMs achieved with the steady-state high-performance hybrid core
  - β_N>3, β_p~2, low collisionality
  - Naturally small ELM (~300 Hz)
  - RMP assists grassy ELM (~600 Hz)
- Divertor detachment is achieved with N_2 injection
  - Not yet tested with small grassy ELMs





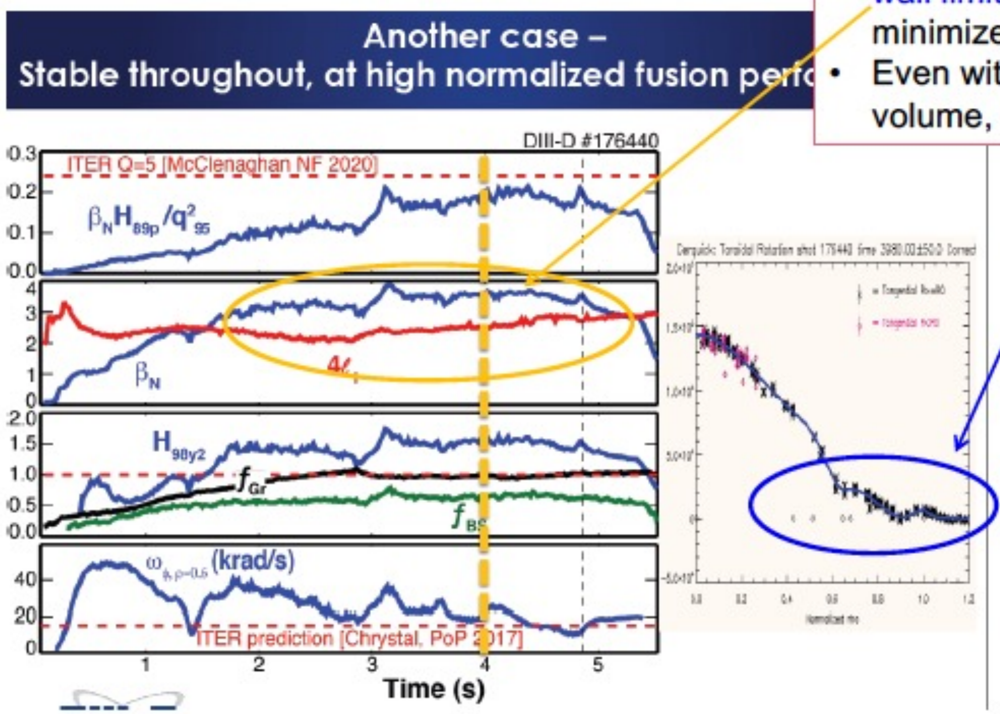
* X.Q. Xu H.Q. Wang, et al, IAEA FEC 2020

- Operating in H-mode with small/grassy ELMs will solve two critical problems:
  - reducing ELM size
  - broadening SOL width

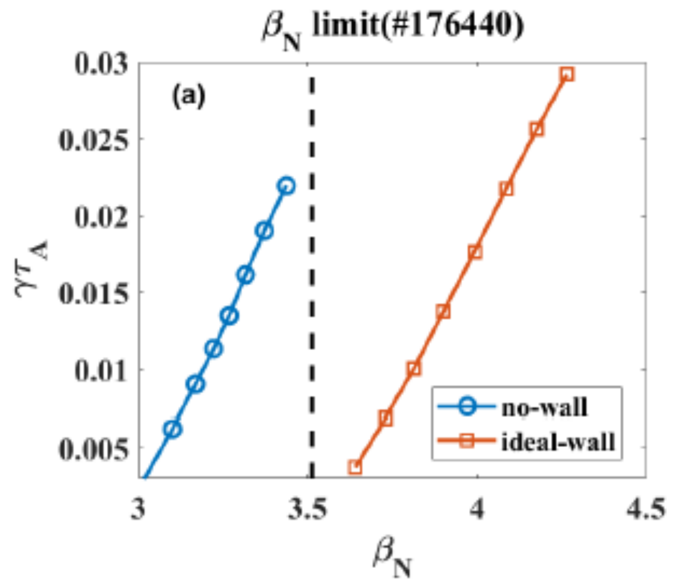
Experiments Demonstrated Stable Operation Above No-Wall β Limit

➤ **Discharge 176440 @ 4200 ms**

- DIII-D routinely operates with β_N above the empirical no-wall limit(~4li), as long as existing error fields are minimized.
- Even with low toroidal rotation for half of the plasma volume, RWM is still stable in experiment.

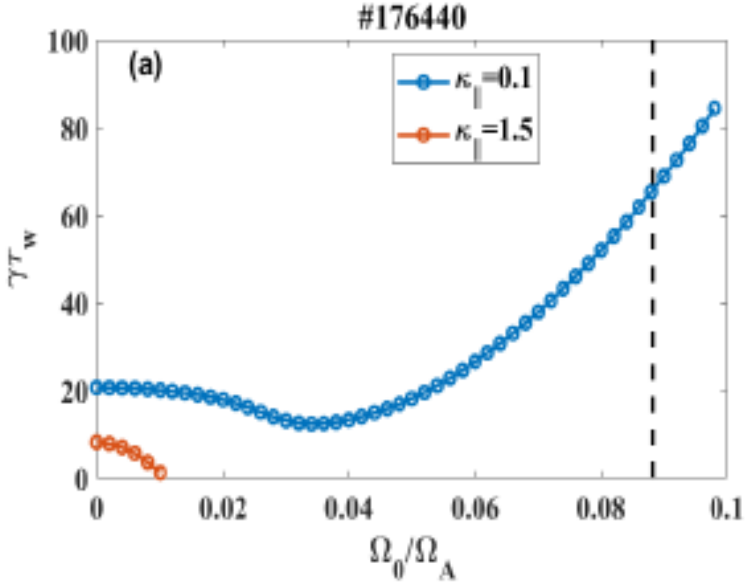


Another case –
Stable throughout, at high normalized fusion perf



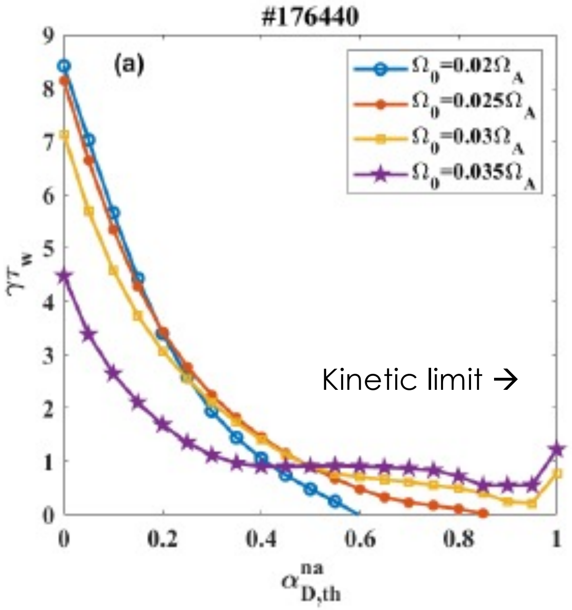
EK & RWM are Stabilized by Viscosity and Kinetic Damping

MARS-F



At high rotation, mode is stabilized at high viscosity $\kappa_{//}$ (Landau damping)

MARS-K



Kinetic limit →

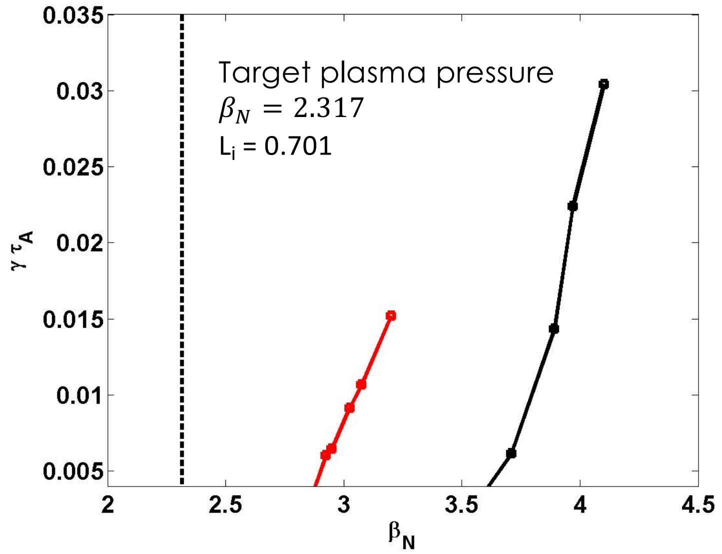
At low rotation, mode is stabilized by precessional drift resonance damping of thermal particles alone

- Over a range of rotation frequency, EK and RWM are effectively stabilized by either fluid or kinetic damping
- Error field minimization and staying before the ideal-wall limit are essential

YF Zhao

Ideal MHD Stability of CFETR Scenarios from MARS-F Code

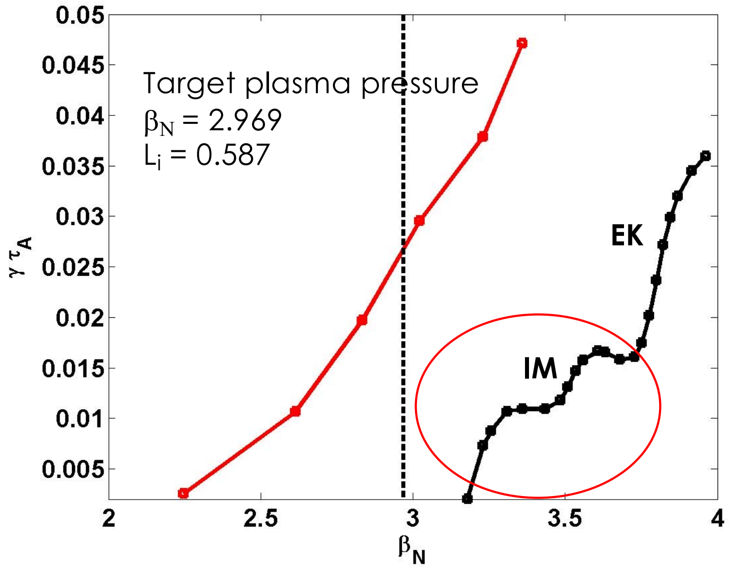
CFETR hybrid mode



Fixed q_a=7.07, scan β_N w/o plasma rotation

- No-wall beta limit: $\beta_{NW} = 2.85$
- Ideal-wall beta limit: $\beta_{IW} = 3.6$

CFETR steady-state



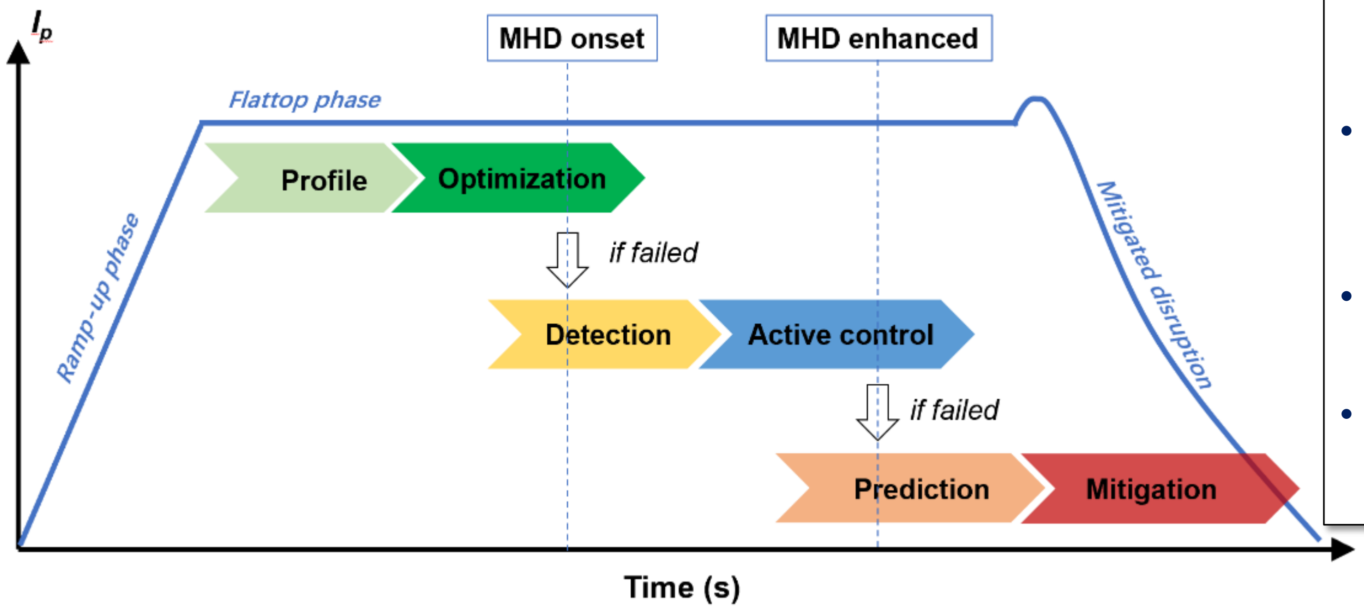
Fixed q_a =10.955, scan β_N w/o plasma rotation

- No-wall beta limit: $\beta_{NW} = 2.25$
- Ideal-wall beta limit: $\beta_{IW} = 3.15$

Based on DIII-D analysis, CFETR steady-state scenario should operate with robust stability above the no-wall β-limit at low rotation

L. Li

End-to-End Simulation of CFEDR Discharge for Disruption Control



- Compute time-dependent equilibrium target
- Compare with RT equilibrium /or AI prediction
- Evaluate key disruption parameters
- Apply control decision

- **Prevention:** keep discharge away from disruptive stability boundaries
- **Avoidance:** instability event detection and control to avoid disruption
- **Mitigation:** machine protection for an unavoidable disruption

New Approaches for Fusion Energy R&D with AI Technology

- Base on AI/ML technology, new approaches are developed in establishing plasma simulation, state/parameter estimation models and advanced plasma control algorithms, which accelerate discharge numerical simulation and improve robustness, safety of plasma operation for future fusion reactors.

☐ Data-driven plasma modelling

✓ Surrogate model of simulator, PDE solver, response model

☐ Plasma state/parameter estimation

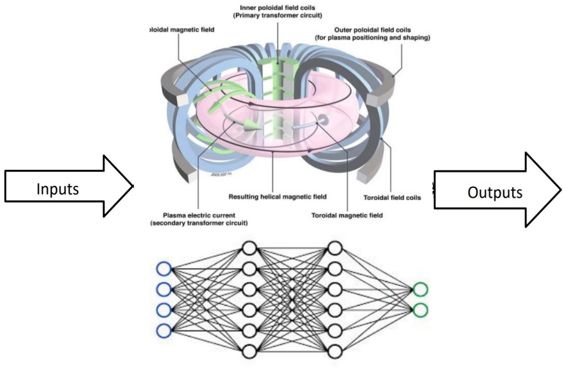
✓ Disruption prediction

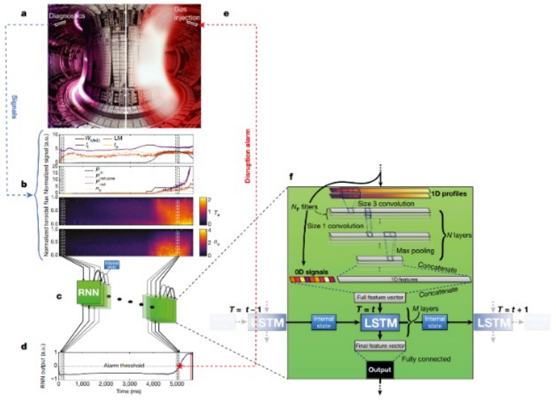
✓ MHD mode recognition

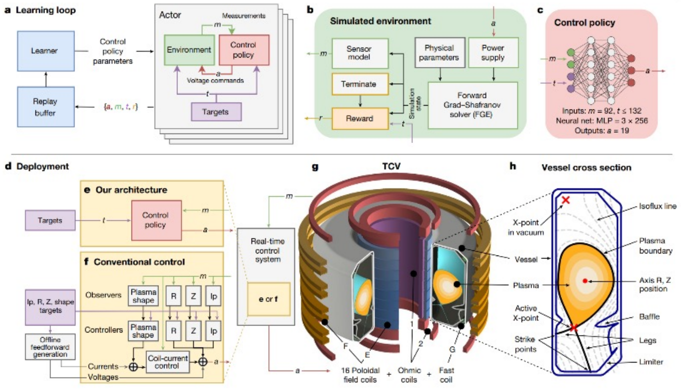
☐ Advanced control algorithms

✓ Reinforcement learning models

✓ Self-adaptive control

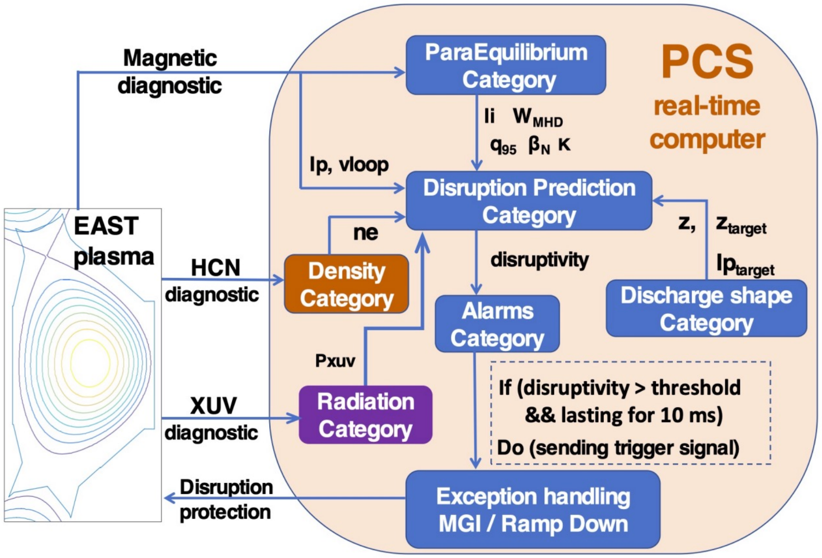






EAST Density Limit Disruption Prediction and Experimental Validation based on Random Forest

Random Forest Disruption Predictor (DPRF)



PCS
real-time computer

EAST plasma

Magnetic diagnostic

HCN diagnostic

XUV diagnostic

ParaEquilibrium Category

li W_{MHD} q_{95} β_N K

Ip, vloop

ne

Density Category

Pxuv

Radiation Category

Disruption Prediction Category

z, z_{target} Ip_{target}

Discharge shape Category

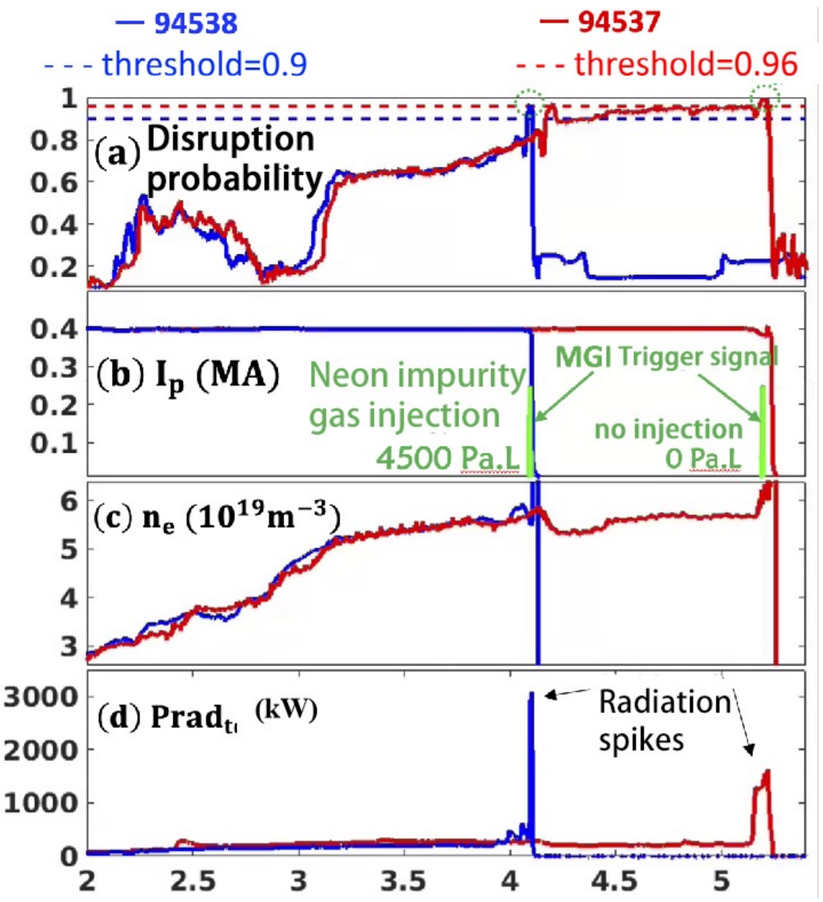
disruptivity

Alarms Category

If (disruptivity > threshold
&& lasting for 10 ms)
Do (sending trigger signal)

Exception handling
MGI / Ramp Down

Disruption protection

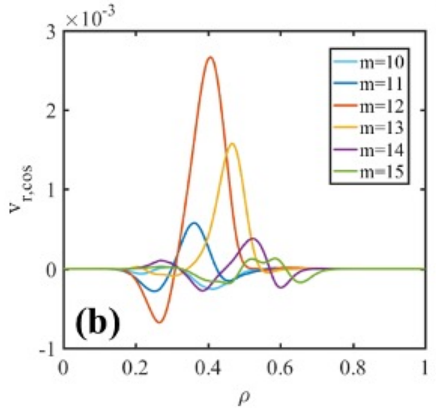


- Calculation time of DPRF is 200~300μs and satisfy the real-time disruption prediction.
- Real-time disruption warning triggers the MGI system, effectively reduces the damage caused by disruptions.

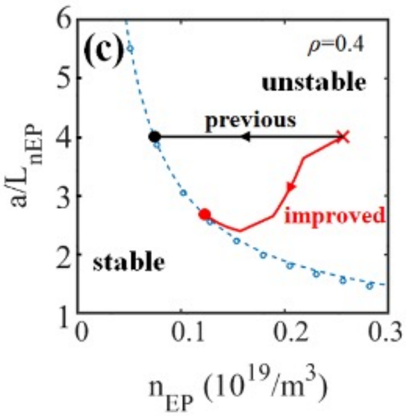
W.H. Hu et al 2021 Nucl. Fusion 61 066034

Alfven Eigenmode Induced Energetic Particle Transport Can Impact Global Energy Confinement and achievable Q_{plasma}

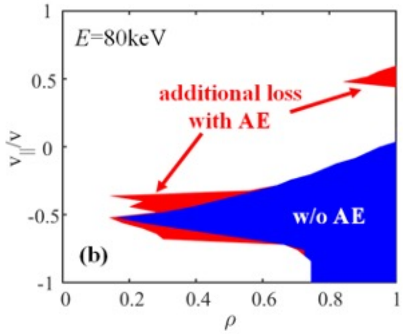
Unstable AE



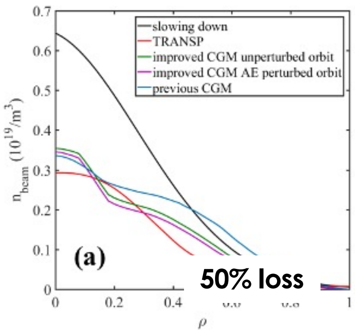
Critical gradient



FOW loss cone



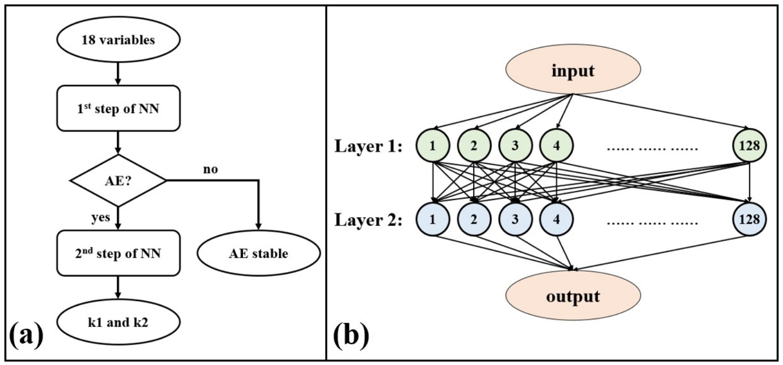
DIII-D



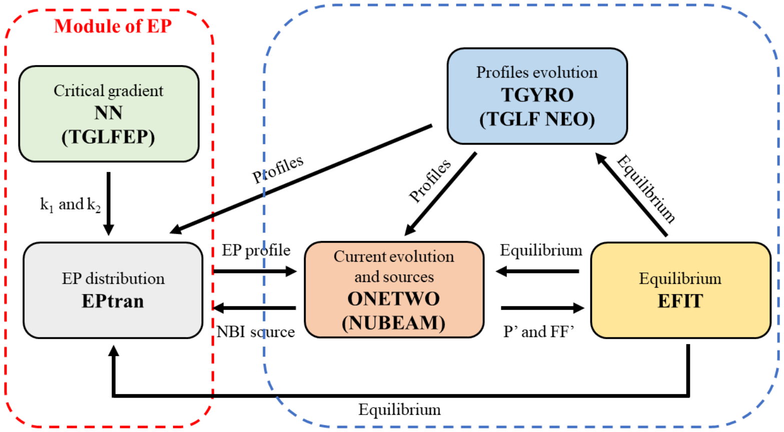
50% loss

In CFETR, large R and high B leads to separation of unstable AE region and loss cone => significantly reducing EP loss ~7%

NN module



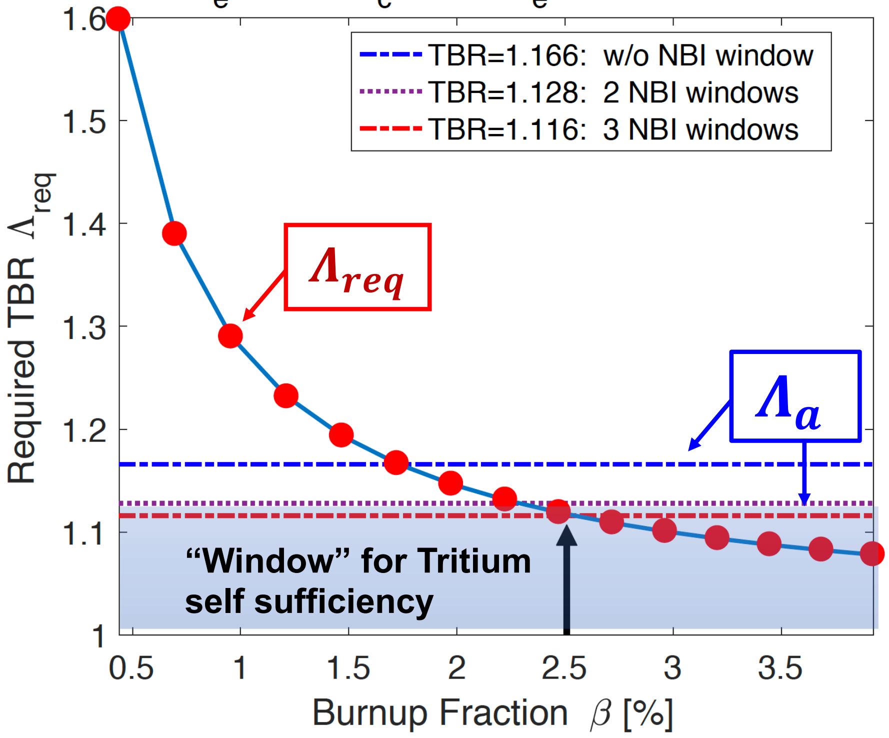
- Calculating CG is time consuming
- NN module developed to speed up computing
- Ready for integration to core modeling to evaluate τ_E



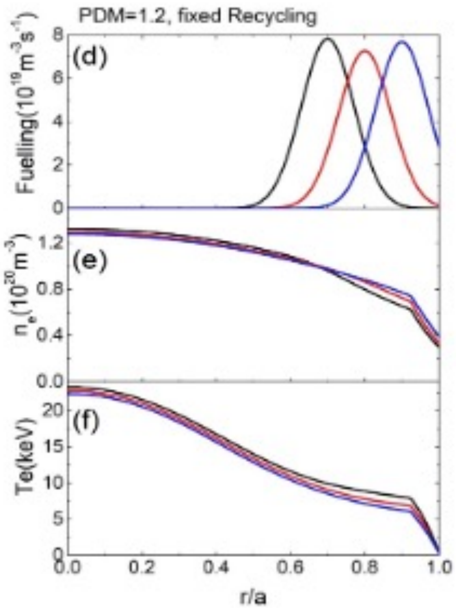
Tritium Self-Sufficiency Imposes Fueling Requirement for High Tritium Burnup Fraction

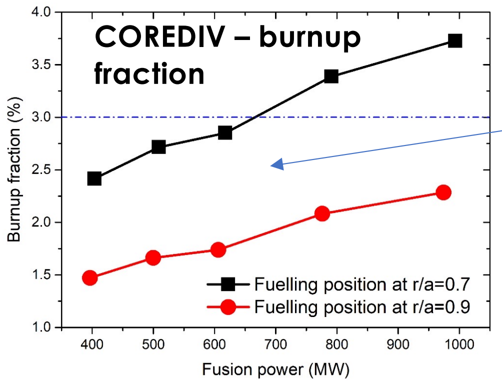
$self-sufficiency\text{:}\ \Lambda_a \geq \Lambda_{req} > 1$

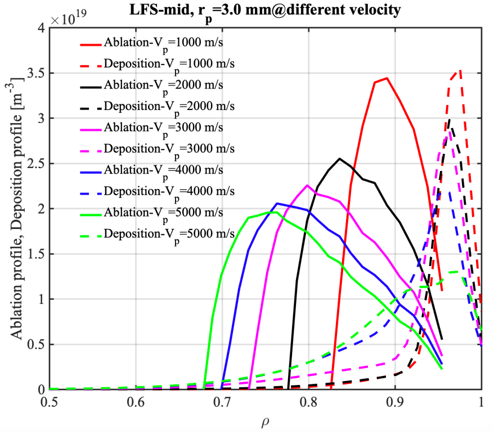
(R_e=90%, R_c=10%, τ_e=10ms, η=70%)

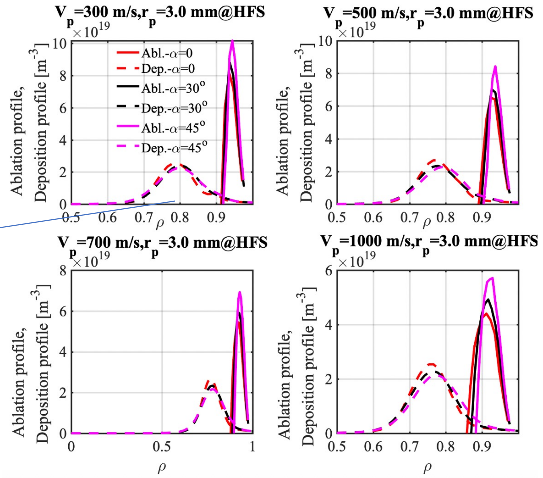


HPI2 modeling of CFETR hybrid mode pellet penetration



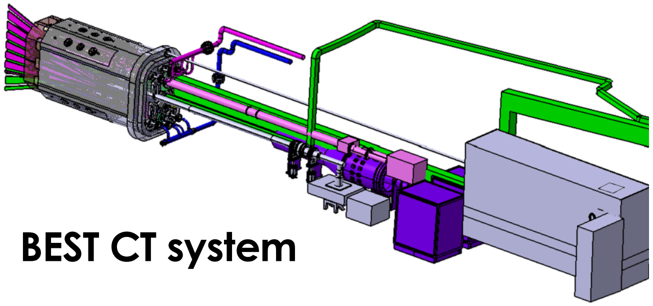






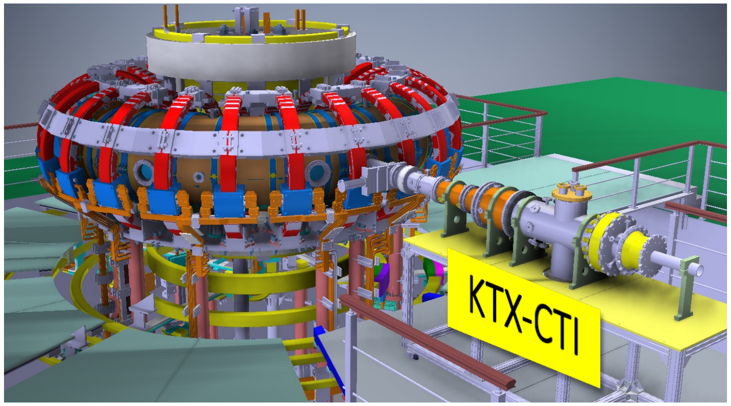
Compact Toroid Injection System under Development for BEST/CFEDR

- A numerical code has been developed to calculate the CT trajectory in tokamaks based on Xiao's model [C. Xiao et al 1998 NF 38 249]
- The code is applied to calculate CT trajectory in KTX and ITER
- Code predictions:
  - CT can penetrate beyond KTX plasma with designed parameters (consistent with experimental observations)
  - CT can penetrate beyond ITER magnetic axis with its designed parameters



BEST CT system

Number of injectors	1
CT diameter	0.2 m
CT density (D+T, 7:3)	4×10^{22} m^{-3}
CT mass	> 1 mg DT
N_{CT}/N_{BEST}	2.7 %
Fueling rate (D+T)	5 Pam^3/s
Fueling frequency	5 Hz
CT injection speed	400 km/s
Gas trapped in CT	75%
Total CT length	14 m



KTX designed CT velocity is 240 km/s

For penetration to ρ=0.2, BEST designed CT velocity > 400 km/s

CT system to be installed on EAST for testing.

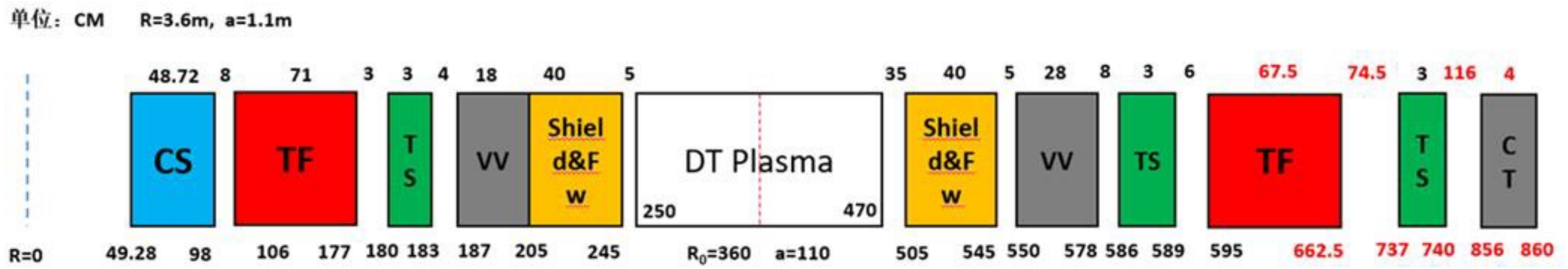
Mission of BEST

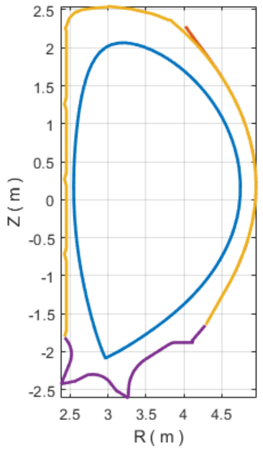
Burning plasma steady-state operation

Burning plasma physics

Tritium breeding and cycling technologies

- **Q~1 for 100-1000s long-pulse, P_{fus}=20-40MW, steady-state operation**
- **Q=5-10 for ~10s short pulse, P_{fus}=100-200MW, α-dominant heating**
- **Q~0.3 for 1-4h, P_{fus}=10-20MW, Tritium breeding and cycling technologies**





CS：HTS hybrid，TF：LTS

CS: 55Vs，up to I_p~7.5MA，B_{t0}~6.15T，reaching q_{95}~4.0

BEST can Significantly Mitigate the Risks for CFEDR

Issue	BEST	CFEDR
Achieving high H_{98} at high f_{GW}	√	
Solving heat exhaust problem with a conventional ITER-like radiative divertor	√	
Operating in a robust ideal MHD and VDE stable regime	√	
Effective removal of helium ash and impurities while retaining tritium in plasma	√	√
Minimizing EP loss due to AE transport at high α fraction	√	√
SSO PSI under full metal wall at high heat/particle flux condition (low recycling, retention)		√
T burning rate (deep fueling) > 1% (better >3%) for T self-sufficiency		√
Burning plasma physics at Q=10-30		√

OPPORTUNITIES FOR COLLABORATION

- **Projection from existing devices to support accessibility of high confinement** – need more experiments with W-wall, gyrokinetic modeling of turbulent transport
- **Small/grassy ELMs with high performance** – confirm robust parameter windows, compatibility with detached divertor
- **Robust divertor detachment with low W erosion and efficient pumping** – impurity control, impact of impurity on core performance
- **End-to end discharge simulation in progress** – cross-machine validation of AI/machine learning, integration of diagnostics in simulation platform
- **Prediction of AE driven EP redistribution and other EP losses** – alpha and background interaction on global τ_E, ripple loss and EP hot spots on first wall, high and low q_{95} operation
- **BEST can test strategy for optimizing tritium burnup fraction** – pellet fueling requirements, CT
- **Reliability of auxiliary heating system design** – efficient RF coupling versus protection of first wall, impurity generation by RF antennas, near-field absorption and EP production

Backup Slides

Physics Design has to Target Key Mission Elements

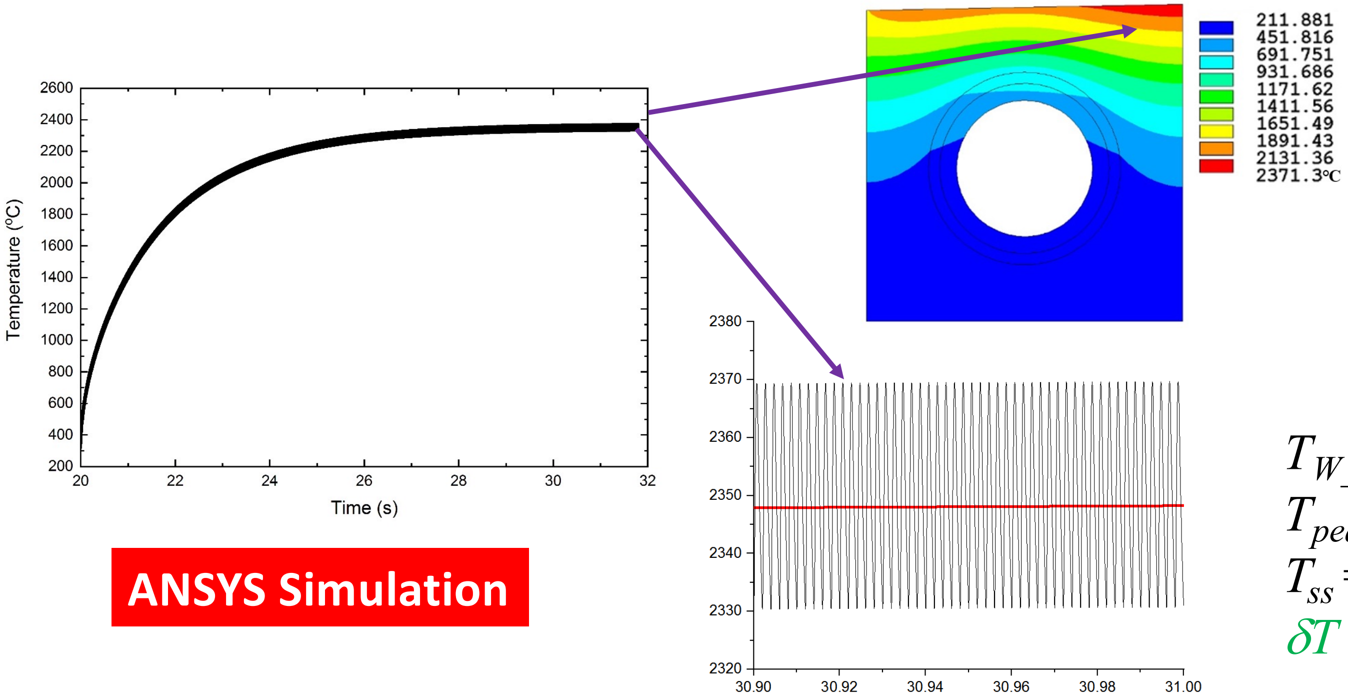
For CFETR/CFEDR

- **High performance** - Simultaneous achievement of Q=30 and P_{fusion}=3000 MW
- **Stable, robust operation** - with low disruptivity and tolerance to steady-state and transient heat load
- **Optimizing design for tritium self-sufficiency**
- **Anticipating alpha particle impact on achieving high confinement and high gain**

ELM Effect on Material Lifetime of CFETR 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%



ANSYS Simulation

$T_{W\_melt} = 3400$ °C

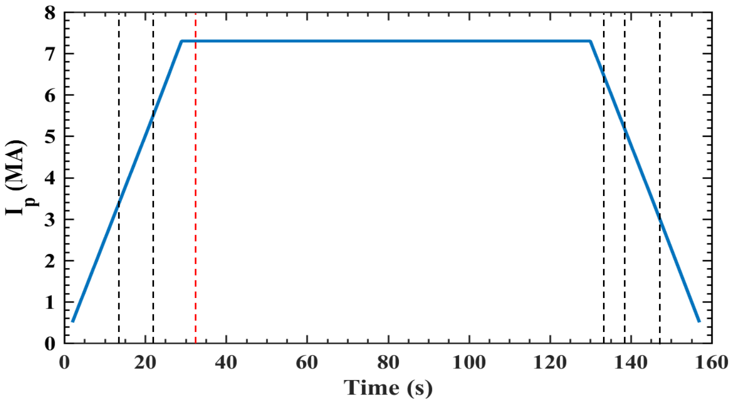
$T_{peak} = 2371$ °C

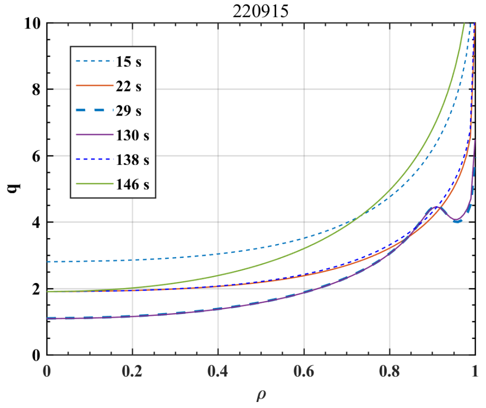
$T_{ss} = 2348$ °C

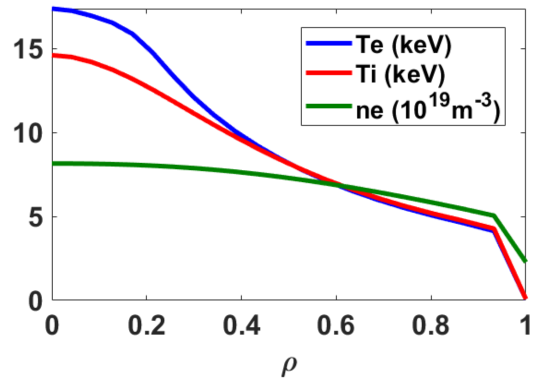
$\delta T \approx 20$ °C

GL Xu

Conventional Method for Designing Stability Control

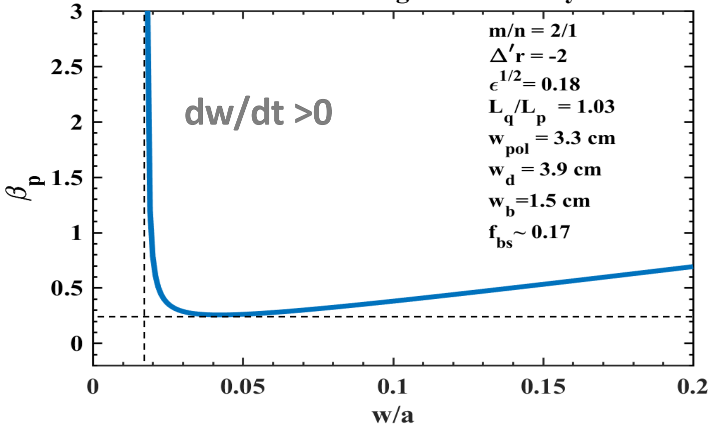






- **Use METIS+TEQ to produce equilibrium evolution with time**
- **In ramp-up, perturb equilibria under worst condition to design VDE feedback control**
- **In flat-top, identify margin from stability boundary and apply correction, e.g., for NTM use error field correction to minimize W_{seed} or ECCD feedback.**

NTM onset marginal boundary



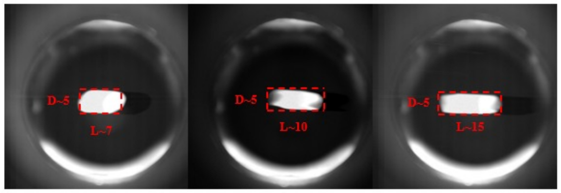
NTM could be unstable if W_{seed} > 2cm and $\beta_{p,s}$ > 0.26

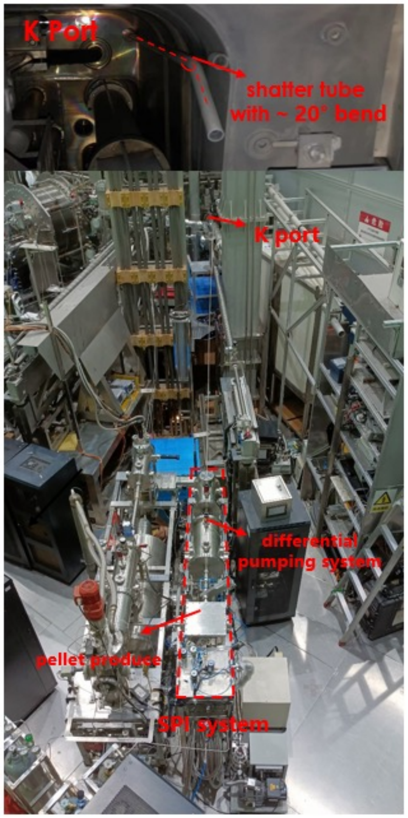
Plasma Disruption Mitigation Systems(DMS) in EAST

☐ **MGI system:** response time: less than 0.15ms, 2 injection positions

☐ **SPI system in EAST** was developed in 2022

- **pellet parameters:** D*L=5×5-15mm, <400m/s;
- **position:** middle K port, (R,Z)=(2.5m, 0.38m);
- **More effective disruption mitigation than MGI;**





plasma parameters: I_p~400kA, B_t~2.7T, $P_{heating}$~5.1MW, W_{dia}~155 kJ, Ne_{SPI}~9.4Pa·m³, v_{pellet}~280 m/s, Ne_{MGI}~10Pa·m³, v_{gas}~610 m/s