Time-dependent SOLPS-ITER simulation for actuator design and system identification

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Time-dependent SOLPS-ITER simulations were performed to address dynamic problems

✓ **Most SOLPS-ITER simulations focus on steady-state B2.5 plasma solutions**
- B2.5 plasma state converges with global particle balance achieved
- Quasi steady-state (QSS) EIRENE schemes are used

→ This approach cannot deal with dynamic problems (both plasma and neutral dynamics)

❑ **Examples of dynamic problems in the boundary of tokamaks**

1) Abrupt target flux drop (cliff type [1-2]) induced by strong X-point radiation with time scale of few tens of ms, observed in KSTAR experiment
2) System identification with time-varying gas injection signal
3) Design of actuators for real-time control
   e.g., Louvre (neutral conductance regulator) → requires time-dep. neutral solver

❑ **Two types of time-dependent SOLPS-ITER simulations to address above problems**

1) Full time-dependent simulation (both B2.5 & EIRENE)
2) QSS time-dependent simulation (only B2.5, QSS EIRENE scheme)
   → Both requires time-dependent settings in B2.5 side
   (w/o numerical acceleration or relaxation, etc.)

[1] Eldon, D., *et al*. 2017 Nucl. Fusion **57** 066039

[2] McLean, A. G., *et al.* 2015 J. Nucl. Mater. **463** 533-536

Summary

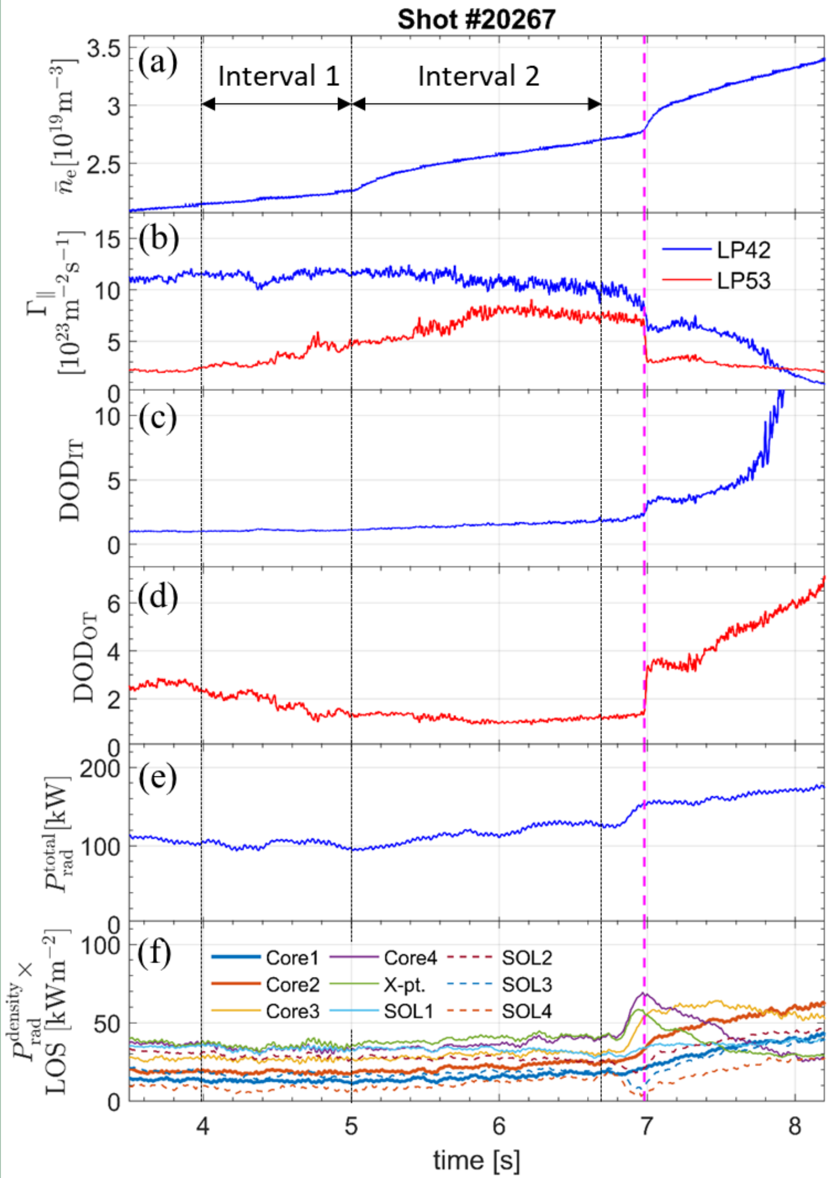
❑ Time-dependent SOLPS-ITER simulations were performed to address dynamic problems:

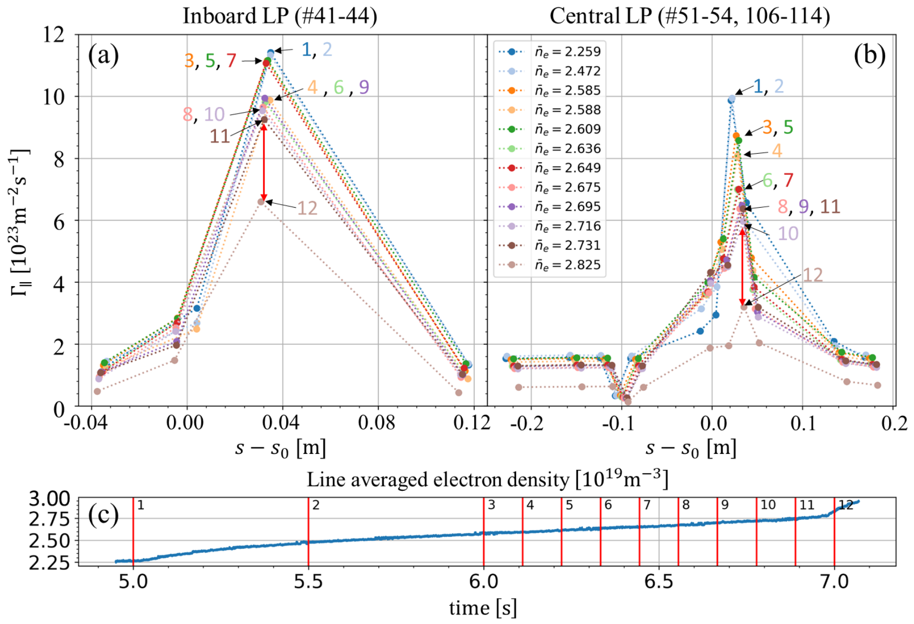
1) **Bifurcation-like KSTAR target flux drop**
   - Unstable branch solutions can be obtained which qualitatively reproduced measured target flux, radiation and density trends
   - Simultaneous penetration of carbon radiation and ionization front towards the core region across X-point by excessive cooling of the fluxtube with D2 gas injection
   - Both the ionization front and radiation front are strongly coupled to the T_{e} (5eV front)
   - T_{et} characterizes $T_{\mathrm{e}}(s_{\parallel})$ for both inner/outer divertor SOL

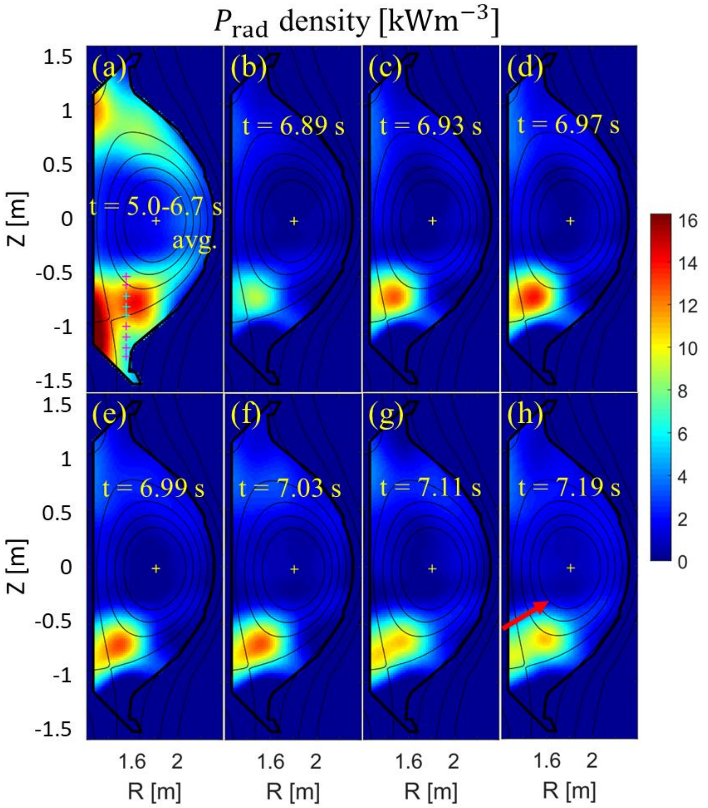
2) **System identification with time-varying gas puff**
   - Phase space ($n_{\mathrm{e,sep}}$ vs. T_{et}) represent system characteristic: by time-dep. throughput scan
     a) Clearly demonstrates hysteresis and directional properties on the phase space
     b) T_{et} determines threshold of KSTAR bifurcation-like transition
   - Low density branch of SPARC shows hysteresis due to thermo-electric current

3) **Design of Louvre actuator that controls divertor neutral pressure**
   - Time-dependent SOLPS-ITER can be used to actuator design (response time)
   - Simulated neutral relaxation time scale agrees with analytic model
   - The effects of Louvre transparency and gas throughput can be equivalent in plasma away from the pump.

Bifurcation-like target flux drop coupled with X-point radiation observed in ***KSTAR density ramp experiment***







❑ Discharge condition

- $I_p = 0.6$ MA, $B_T = 2.5$ T (forward field), $P_{heat} = 0.93$ MW (mainly NB), L-mode density ramp: $\bar{n}_e = 2.0 - 3.0 \times 10^{19}$ m^{-3}

❑ Abrupt target flux drop characteristic

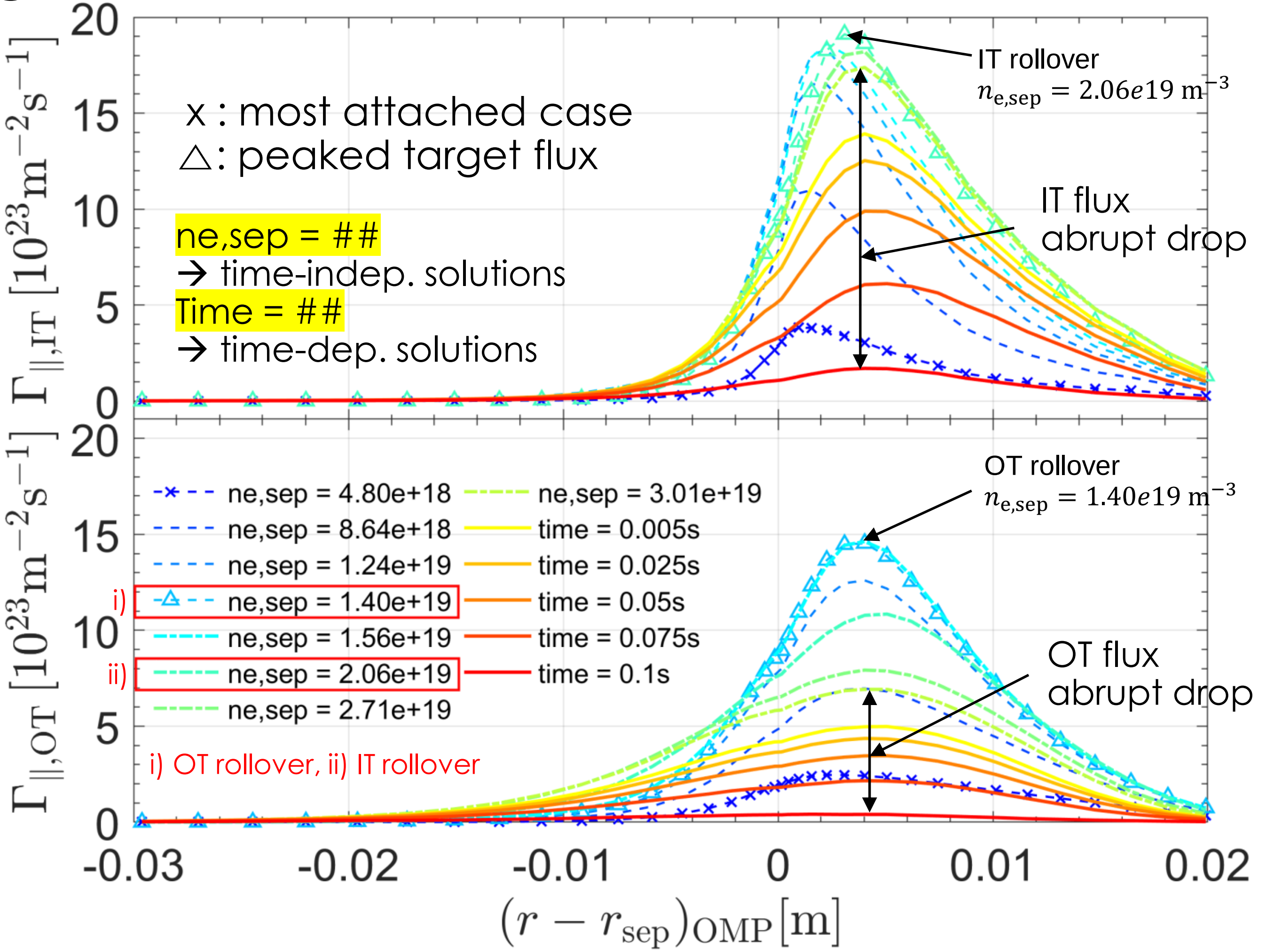
- Target flux drop when line averaged density reaches critical level
- Time scale of 20-30 ms
- Simultaneous drop for both targets, whole profile (PFR-SOL)
  → Different type of cliff from ExB Drift induced cliff in DIII-D [1]
- Considering time-scale of the drop, it may not be 'carbon oscillation' [2]

[1] Jaervinen, A. E., *et al.* 2018 Phys. Rev. Lett. **121** 075001
[2] Loarte, A., *et al.* 1998 Nucl. Fusion **38** 331

SOLPS-ITER SS (before drop) + time-dep. (during drop) solutions reproduced experimental target trend

❑ Simulation setup

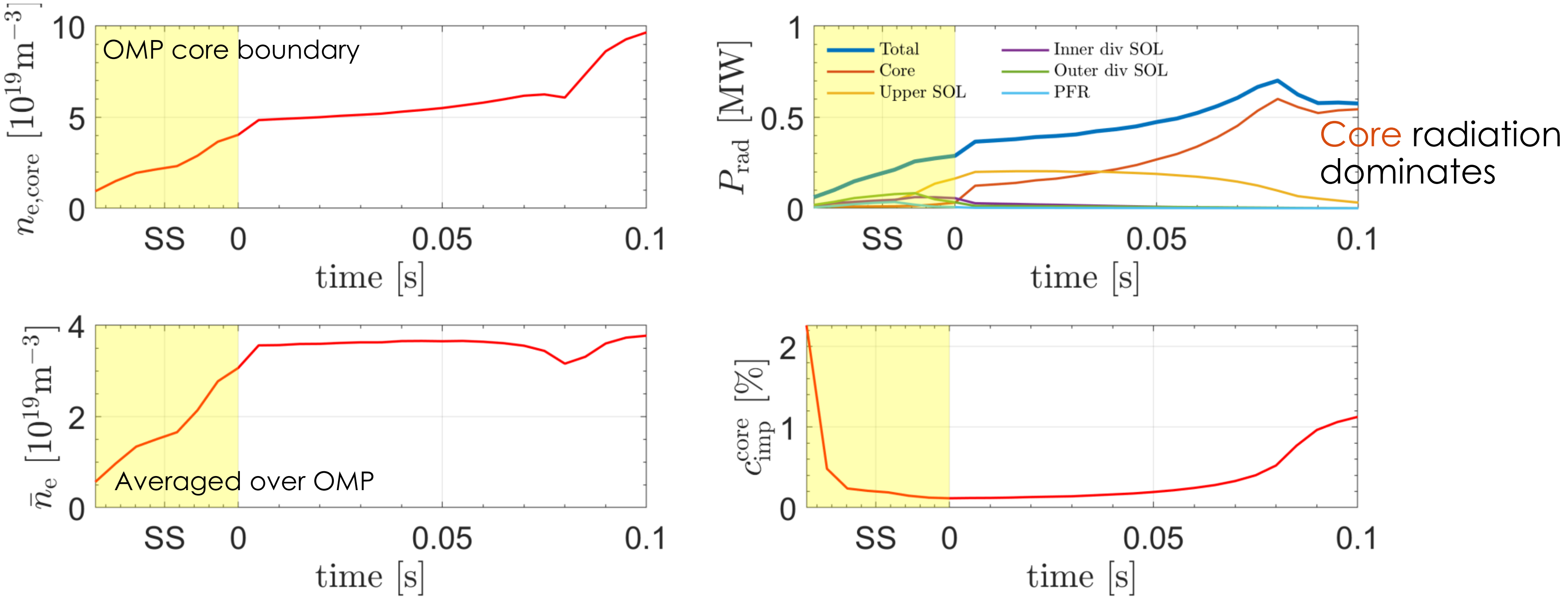
- P_{SOL} = 0.8 MW
- Species: D, C
- Core boundary particle flux (D+) = 8e19/s (neutral beam)
- Steady-state (SS) fueling throughput scans: 5e20-3e21 atom/s
- Time-dependent simulation for 4 throughputs: 3e21, 4e21, 5e21, 8e21 /s
- QSS time-dependent simulations were performed because plasma dynamics is more important for this problem



- Steady state behavior: OT rollover at lower $n_{e,sep}$ than IT (reproduced [JSPark 2018 NF 58])
- Time-dependent simulation shows that collapse of the target flux profile is continuous in time within 100 ms (collapse time scale depends on the gas throughput)

Simulated core density trend matches with measured $\bar{n}_\mathrm{e}$

- ❑ Steady-state (SS) solution + time-dependent solution: GP = 3e21, 5-100 ms (20 snapshots)



- $n_\mathrm{e,core}$ (n_e at OMP core bdy.) and $N_\mathrm{e,core}$ (total # of core ptl.) increases

→ In SOLPS-ITER, 'core region' only covers core periphery so lack of core coverage gives $\bar{n}_\mathrm{e}$ trend discrepancy with experimental observation (dominant contribution of core density to $\bar{n}_\mathrm{e}$ considering monotonic profile and width)

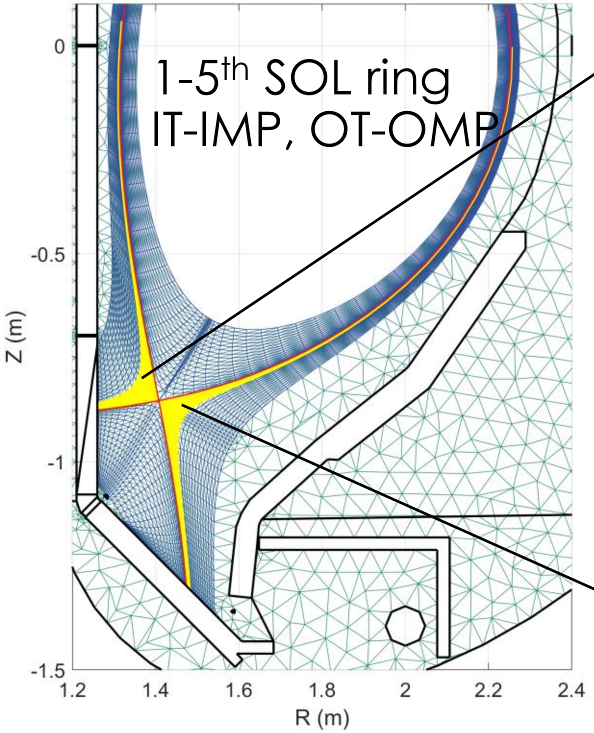
→ **However, SOLPS-ITER core density trend agrees with experimental observation**

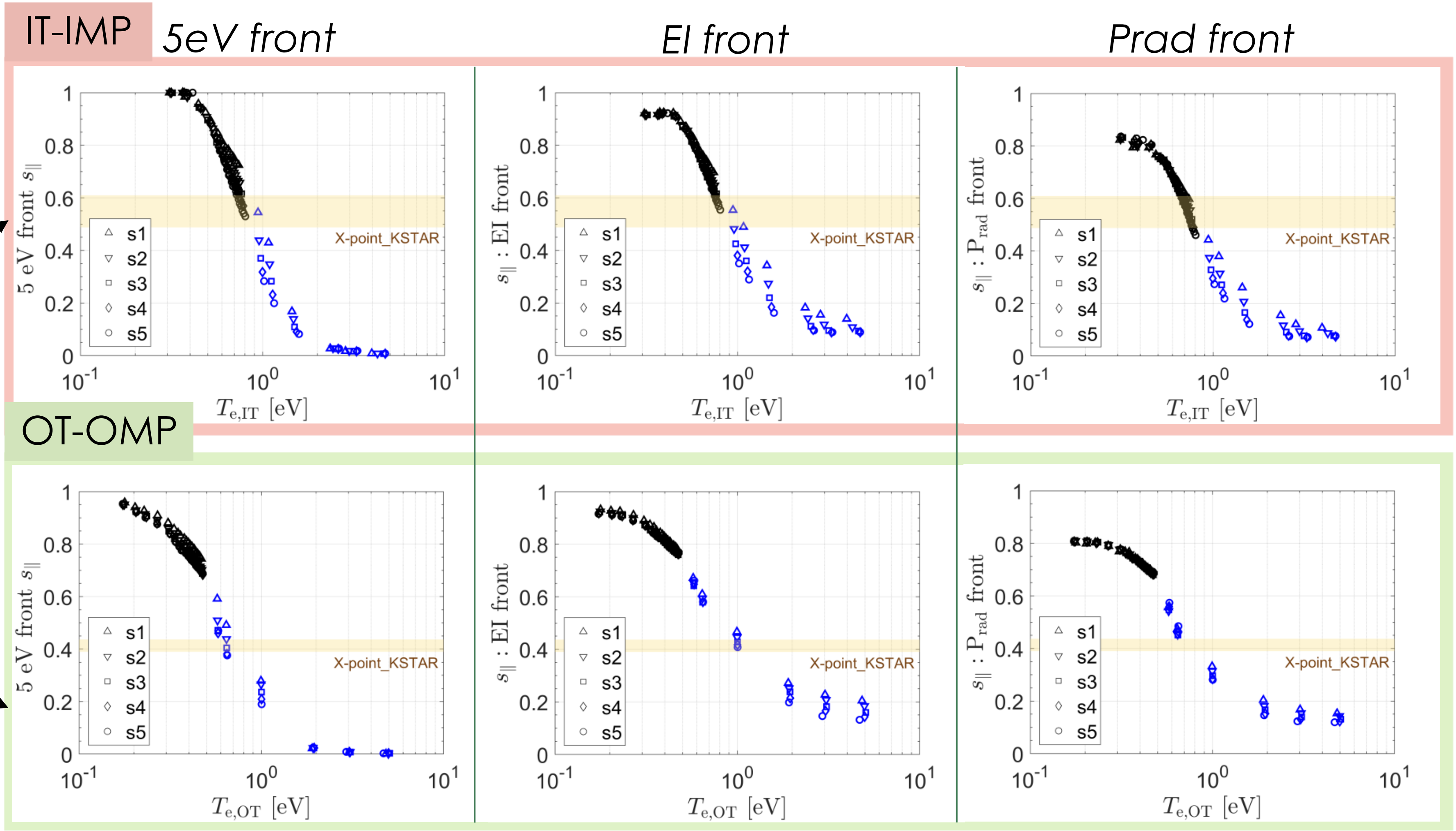
- Both the separatrix and core carbon concentration increases, and core radiation become dominant as abrupt target flux drop proceeds

EI front and Prad front coincides with 4-5 eV fronts

- 20 snapshots of time-dep solution and SS solution

- $s_{\parallel}(\text{EI front}) \equiv \frac{\int_t^u S_{na} s_{\parallel} ds_{\parallel}}{\int_t^u S_{na} ds_{\parallel}}$
- $s_{\parallel}(\text{P}_{\text{rad}}\text{ front}) \equiv \frac{\int_t^u P_{\text{rad}} s_{\parallel} ds_{\parallel}}{\int_t^u P_{\text{rad}} ds_{\parallel}}$

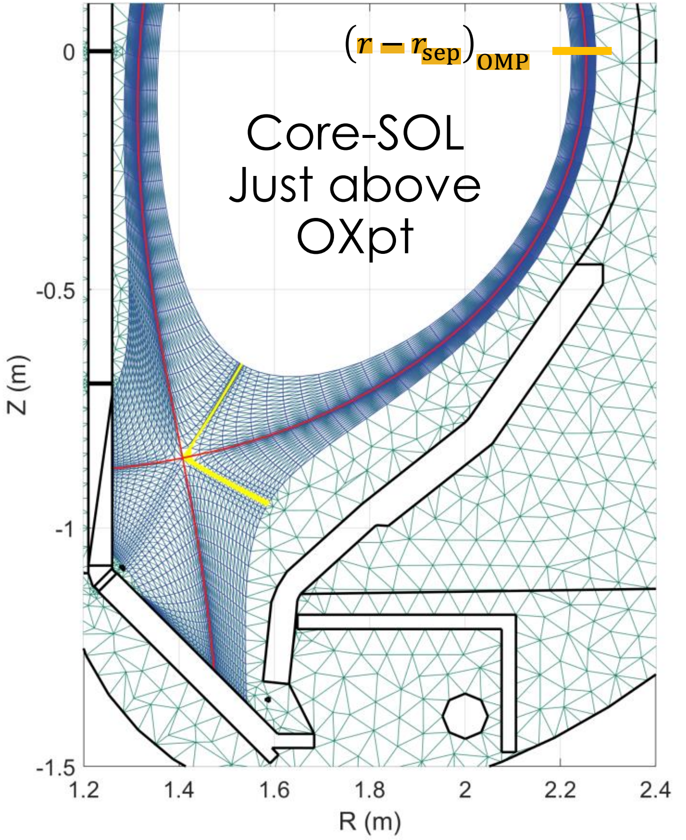


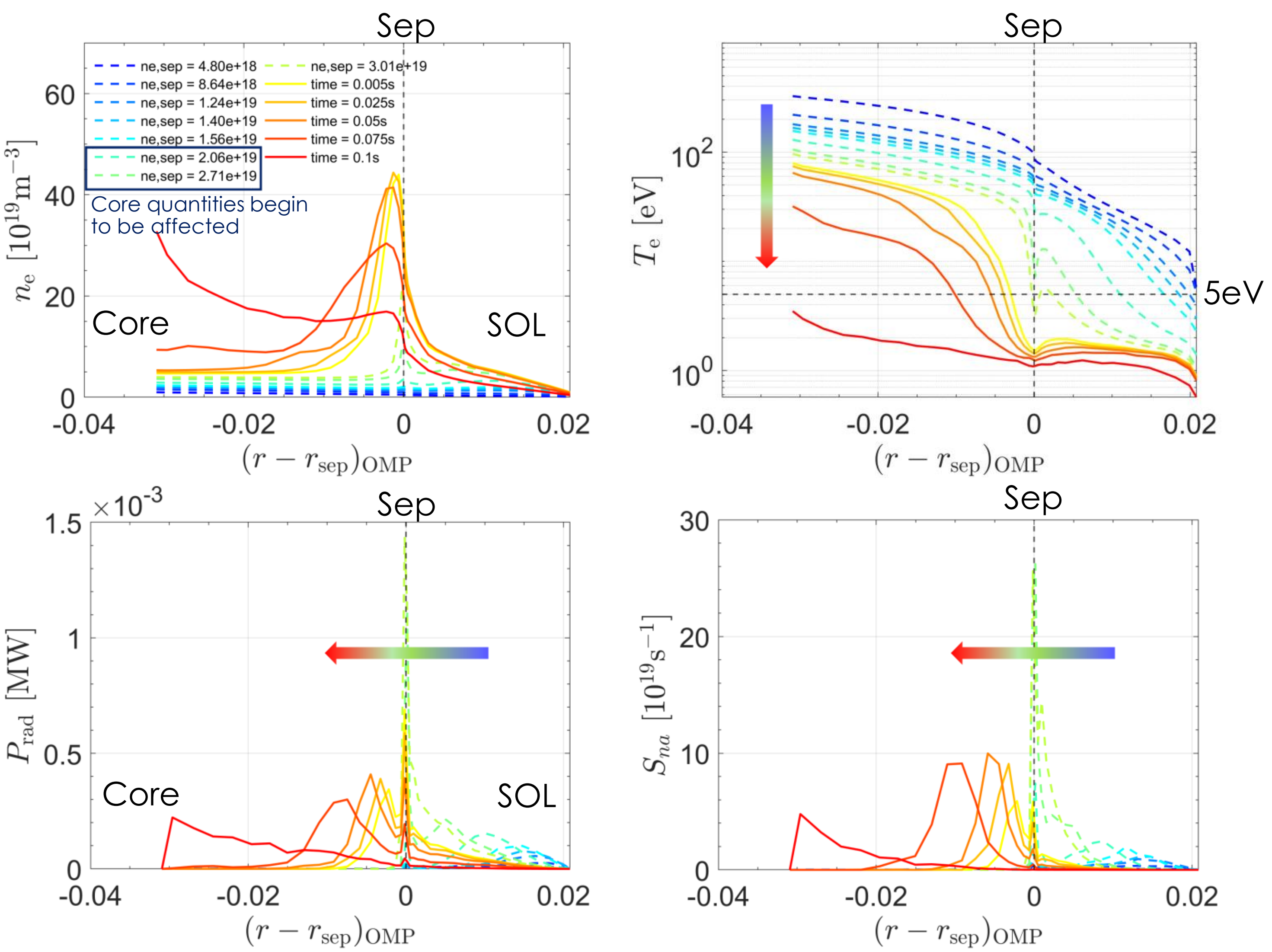


- $T_{\text{et}} \sim s_{\parallel}(5\text{ eV})$ relation can be changed by geometry or IT/OT
- However, EI front and Prad front (mainly carbon) always coincides with 5eV front
- Regardless of the flux tubes, front location is tightly coupled with T_{et}

Radial distribution of $n_e, T_e, P_{rad}, S_{na}$ just above X-pt (core – SOL)

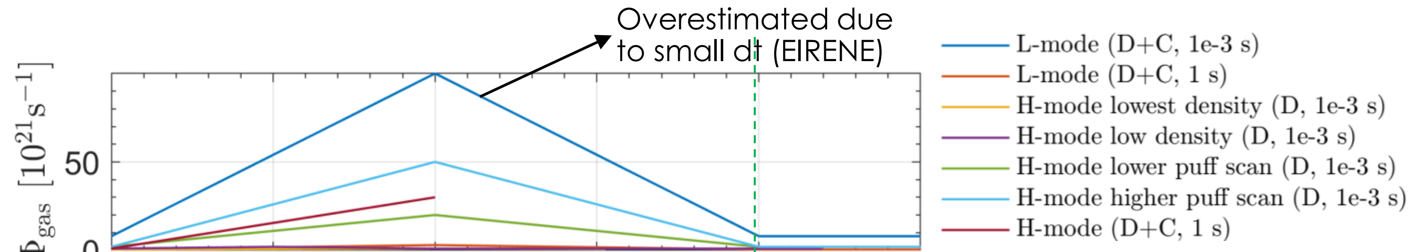
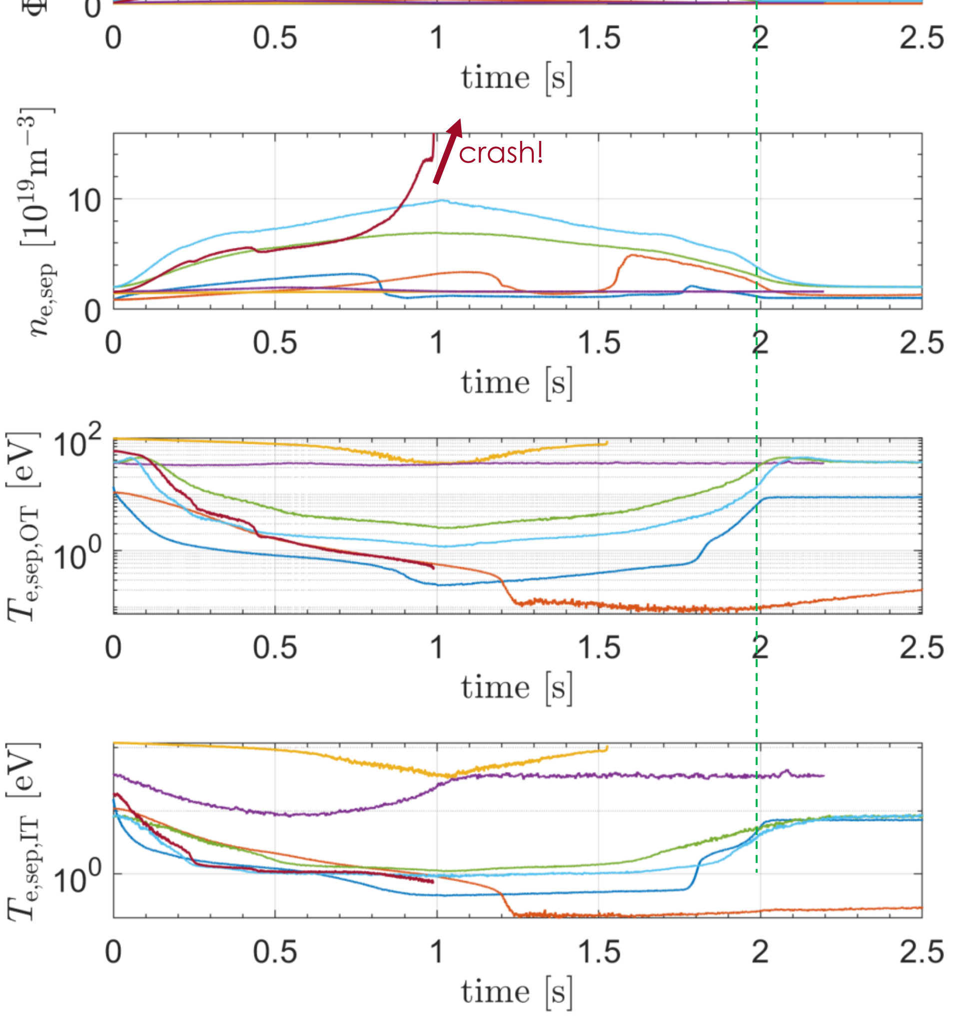
Radial coordinate w.r.t. separatrix mapped to OMP





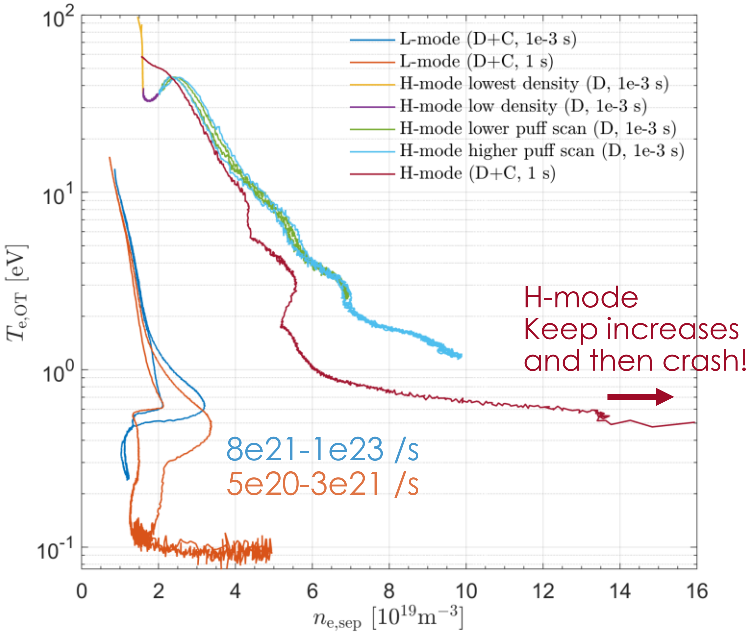
- Radiation and ionization source both peaks at the X-pt then penetrates core
- Density and ionization source peaks near the X-pt & core temperature cooled with radiation
- Strong localized radiative cooling makes T_e profile partially non-monotonic at the X-point

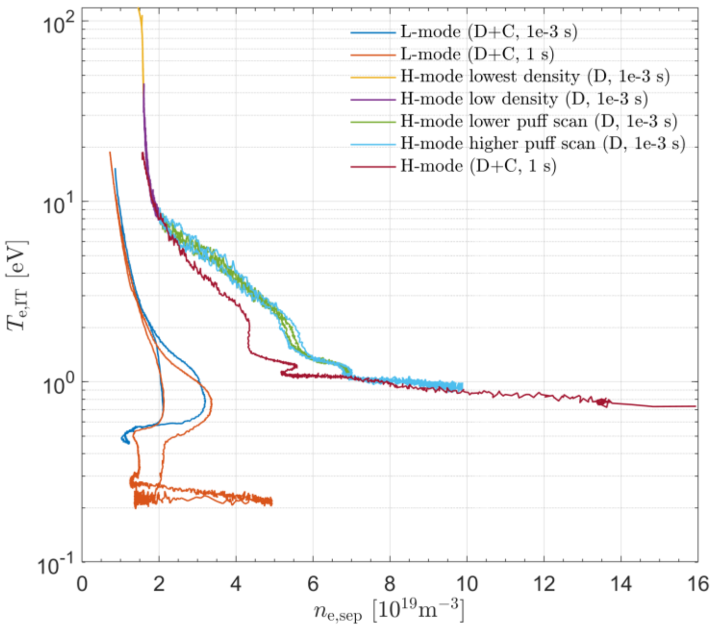
System identification of KSTAR with time-varying gas puff

❑ QSS time-dependent D_2 gas scan

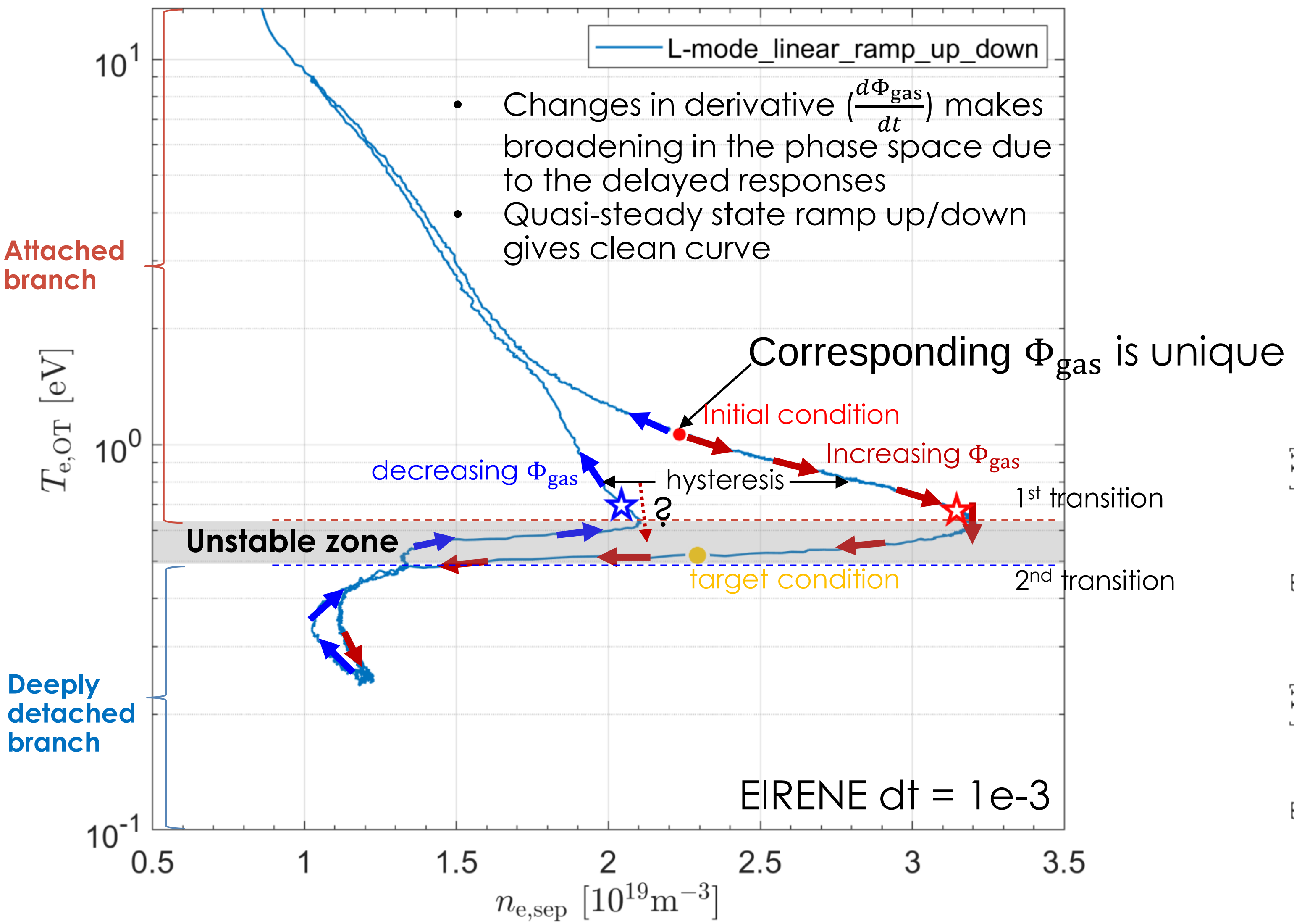
- Operation mode: L-mode / H-mode
- Species: D / D+C
- Eirene step dt: 1e-3 s / 1s

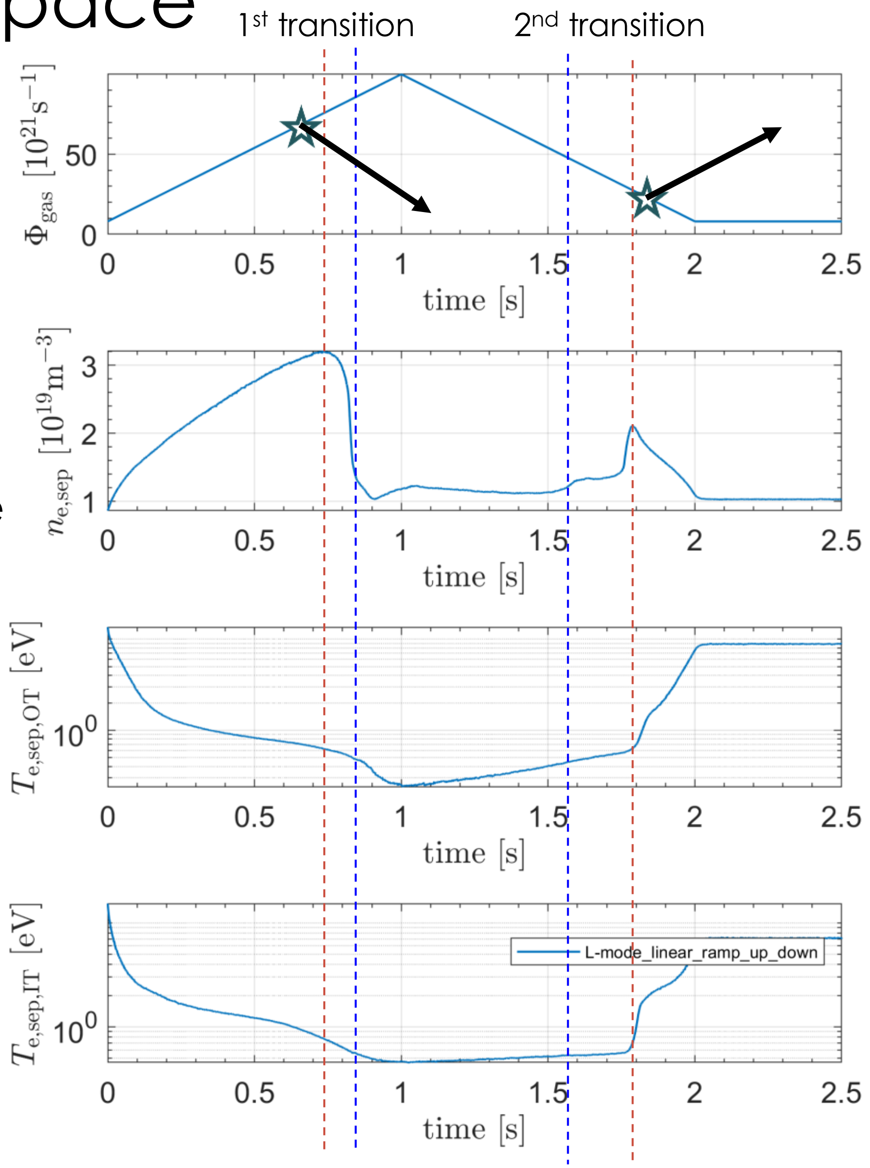




- Phase space can be obtained by GP scans for a long enough time compared to the relaxation time-scale, instead of series of the steady-state density scans
- Not long enough dt (EIRENE) overestimate gas puff but the phase space is not significantly distorted
- H-mode has higher density and temperature, so XPR induced bifurcation is not likely to be occurred (lack of T_{et} and density limit)

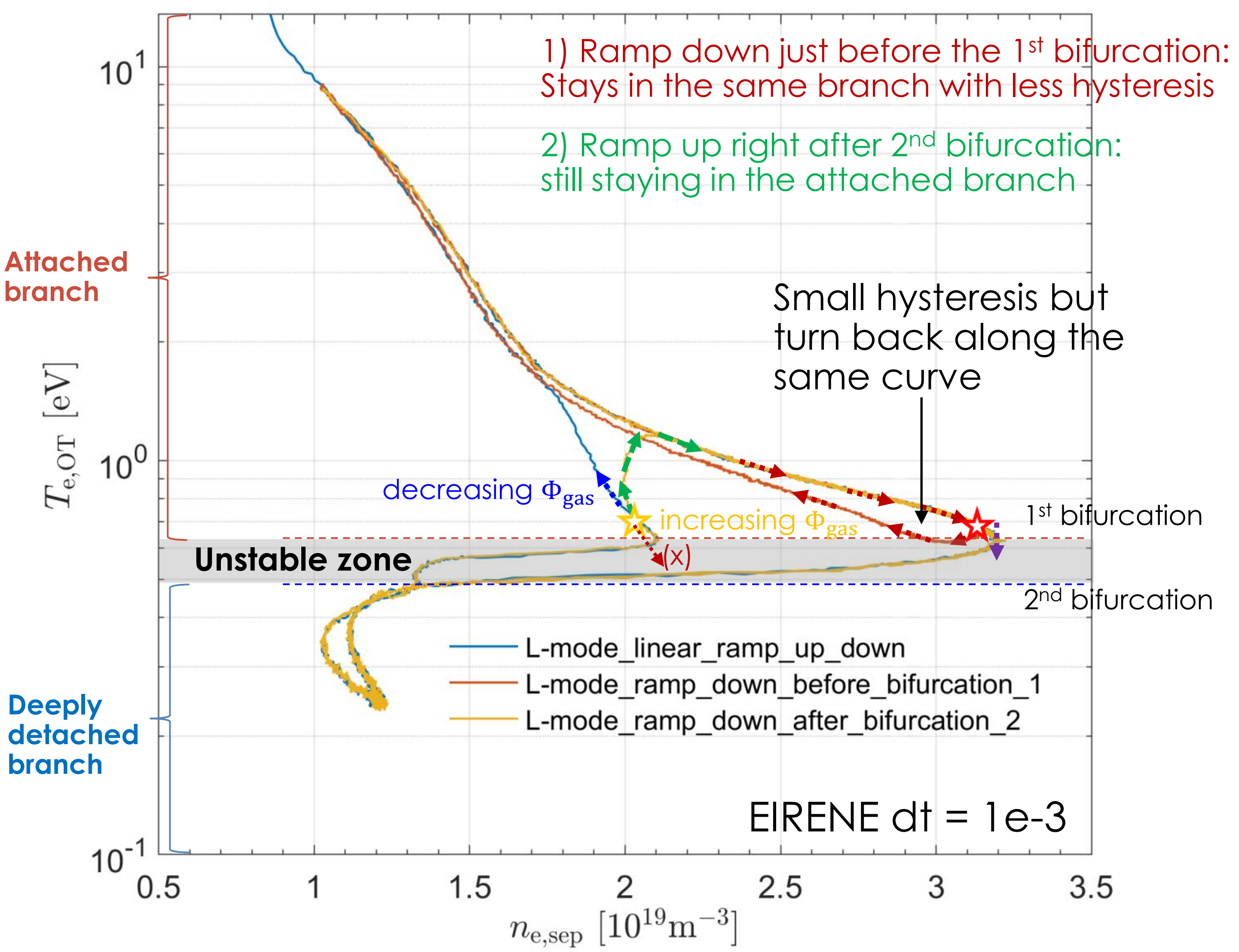
KSTAR L-mode bifurcation on the phase space

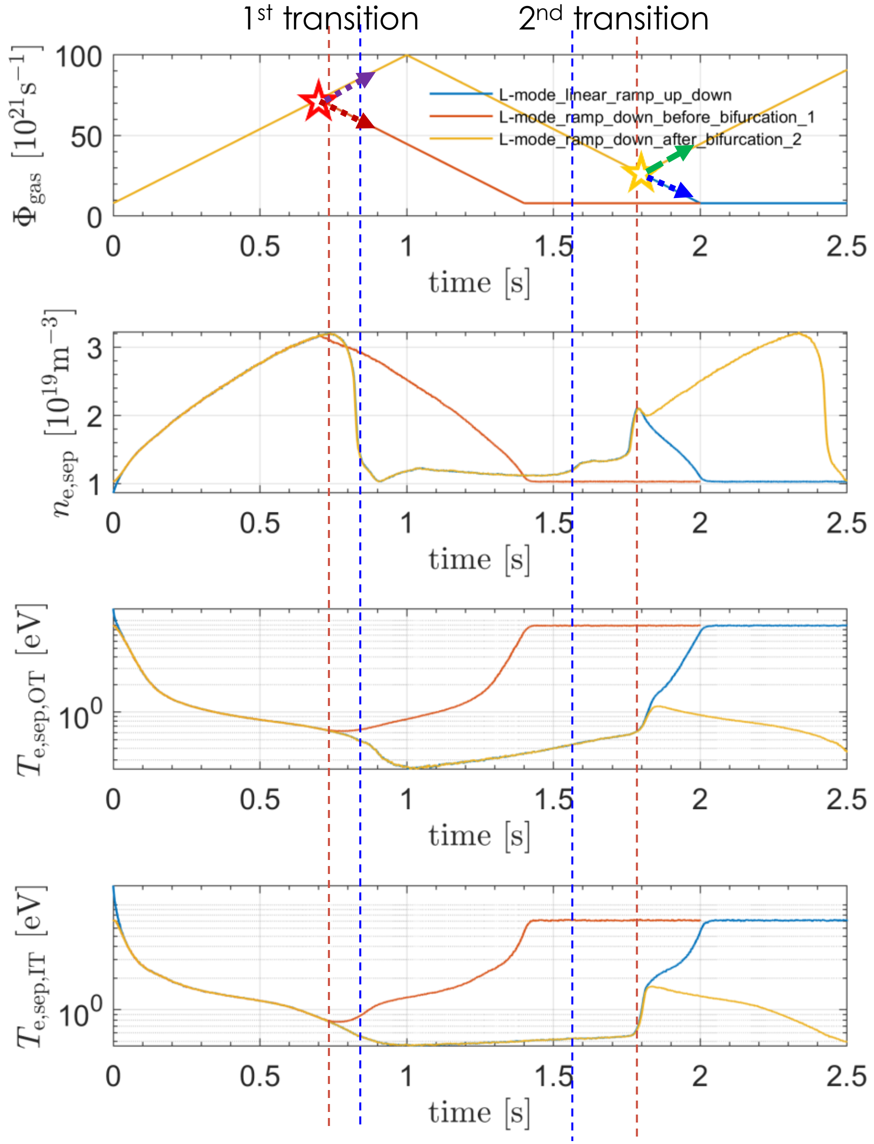




- Tet can be classification criteria of the branches: attached branch, detached branch, unstable zone (↑↓))
- Bifurcation-like transition is strongly coupled with Tet (either Te,OT or Te,IT)
- Hysteresis observed on the phase space

Directional property test on the attached branch

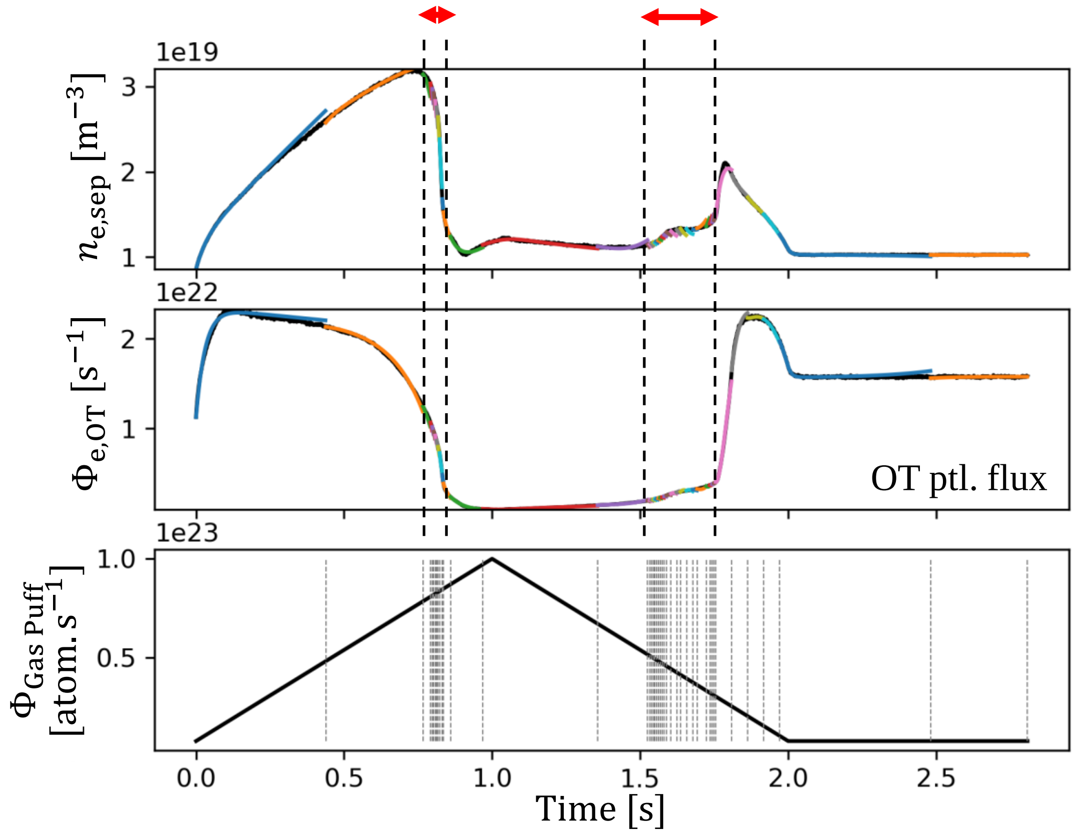


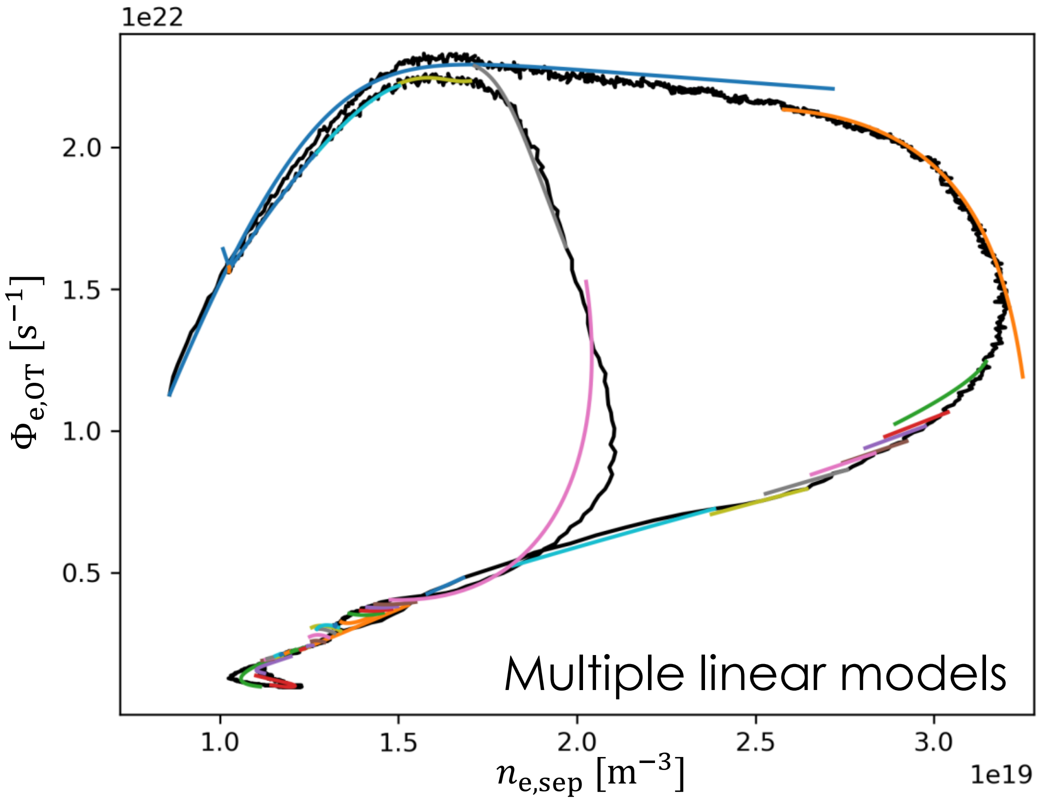


- Control of plasma state on the phase space is bi-directional in the same branch
- Crossing the branch is unidirectional: makes bifurcation (gap) on the phase space

Fully automated algorithm for system identification with bifurcation

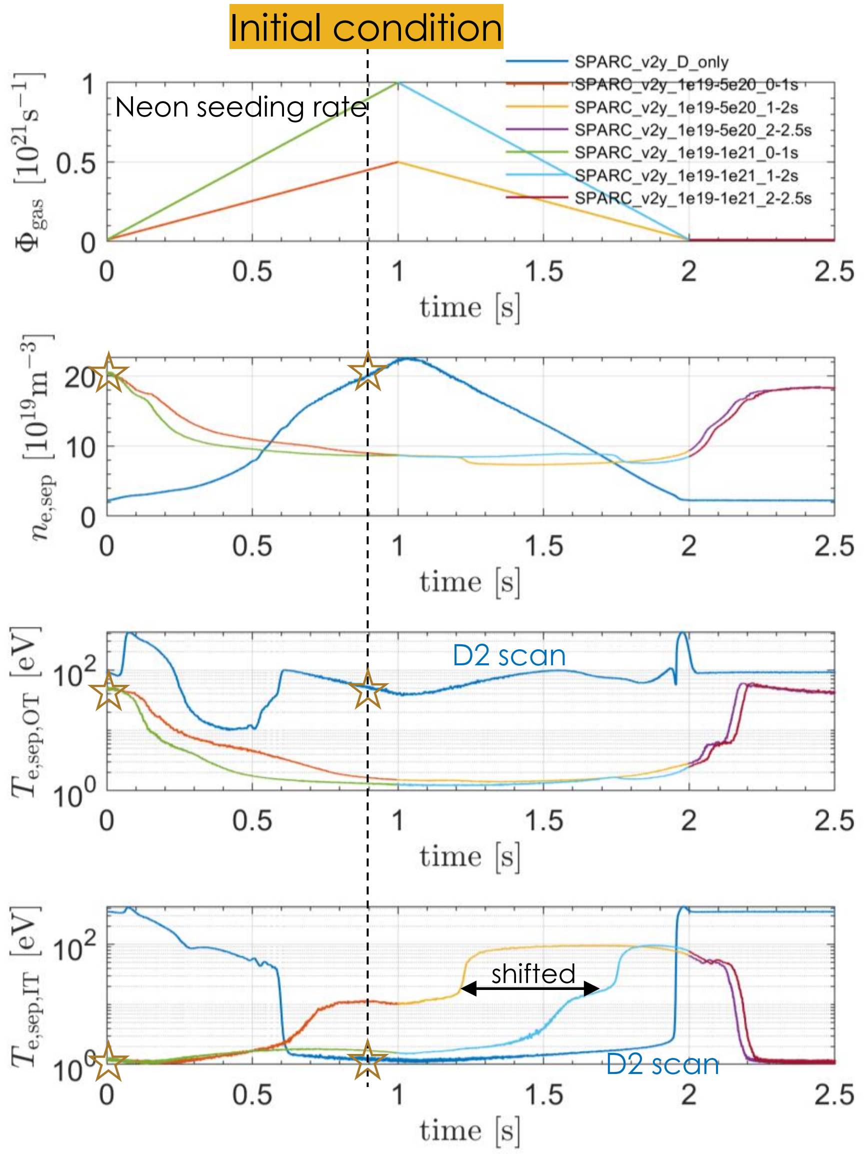
[S. De Pascuale]





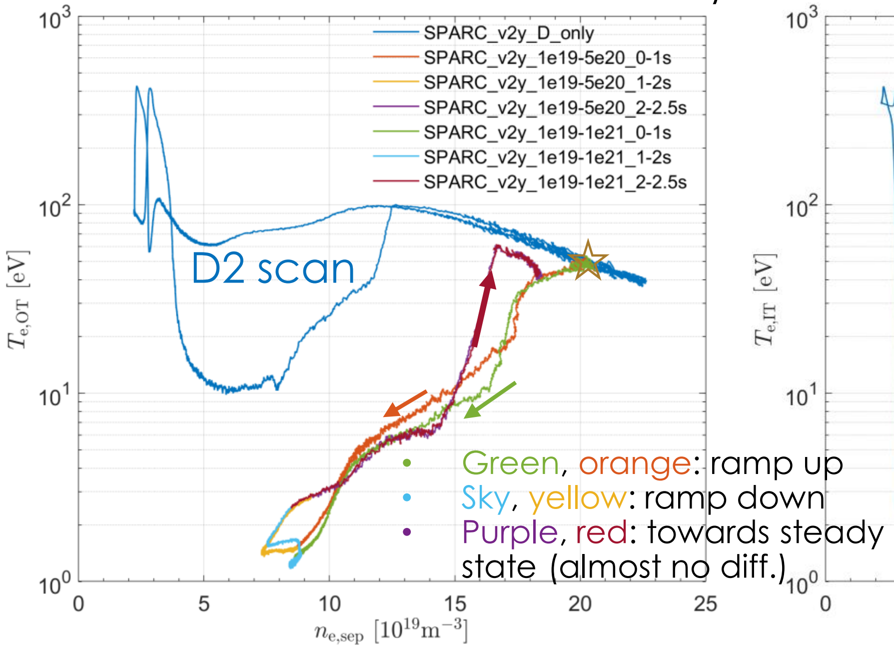
- Coupled system identification performed best with correlated variables $\Phi_{e,OT}$ and $n_{e,sep}$
- $T_{e,OT}$: serves as a threshold for bifurcation / $n_{e,sep}$: feature identified most strongly
- Phase diagram shows model turnover (--) near inflection points in slope between observed variables
- A prediction horizon of at least 500 ms is used, where e models are truncated to within 5% error threshold before retraining over a new scrolling interval. First order linear models are identified in each interval to avoid overfitting bifurcation discontinuities

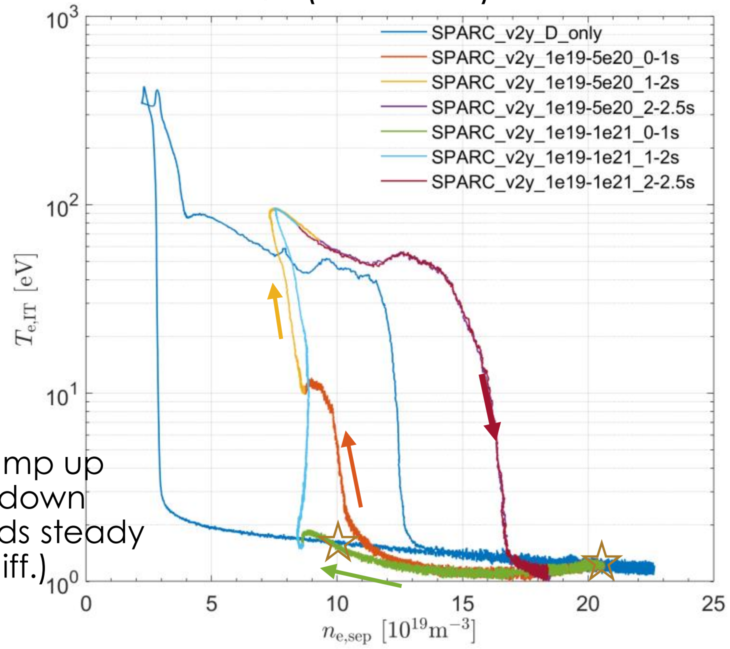
SPARC v2y operation space (time-dep Ne seeding)



Initial condition taken from D2 scan:
D2: 2.6e22 /s, Ne: 1e10
ne,sep ~ 2e20 m^-3 ☆
(no hysteresis regime)

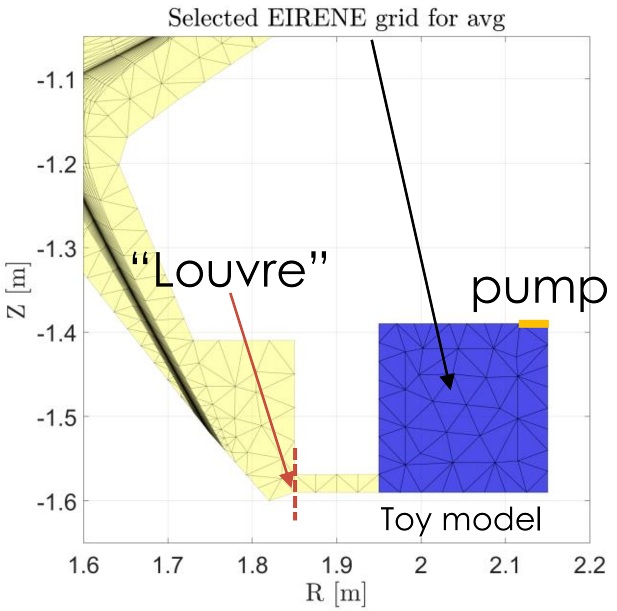
Time-dependent Ne scan
1) D2: 1e21-3e22 /s
2) Ne: 1e19-1e21 /s (high seed)
3) Ne: 1e19-5e20 /s (low seed)



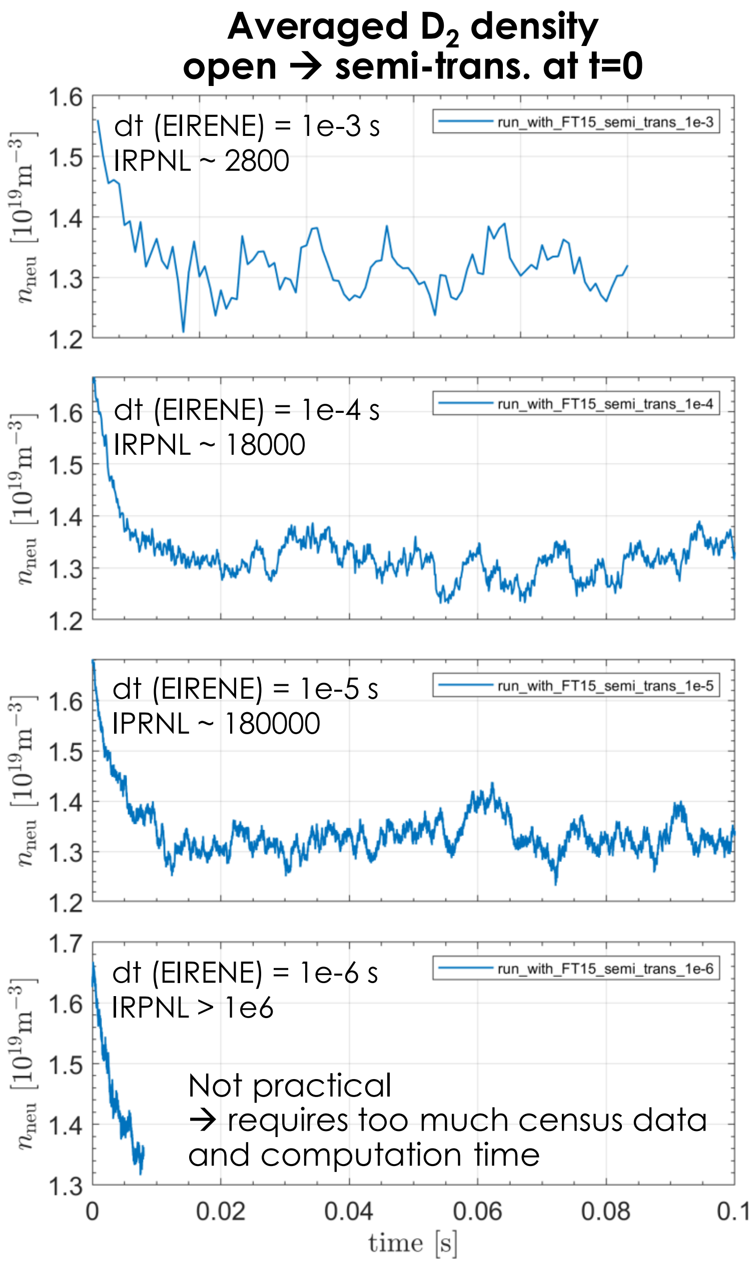


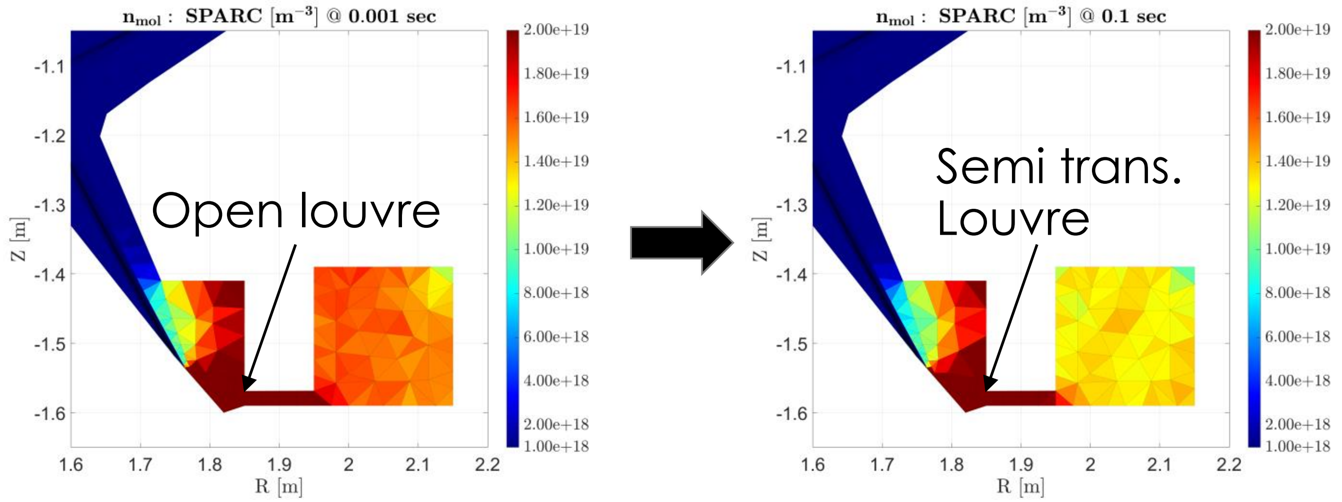
- $T_{e,OT}$ **cooling: Ne > D2,** $T_{e,IT}$ **cooling: D2 > Ne**
  → Difference in dominant cooling mechanism expected (radiation vs. pl.-neut.)
- $n_{e,sep}$, $T_{e,OT}$ not sensitive to the peak Ne seeding rate while $T_{e,IT}$ suppression behavior depending on Ne seeding rate (shifted but the same structure)
- Simultaneous suppression of $T_{e,IT}$, $T_{e,OT}$ can be only achieved for high seeding but $n_{e,sep}$ decreases → so both more puff/seed required
- Abrupt transition occurs in the phase space with opposite $T_{e,IT}$, $T_{e,OT}$ behavior due to the thermo-electric current → This is accompanied by a thermo-electric current and is presumably due to the narrow PFR geometry (future work).

SPARC "Louvre" actuator design using full time-dependent SOLPS-ITER simulation (time-dependent EIRENE)

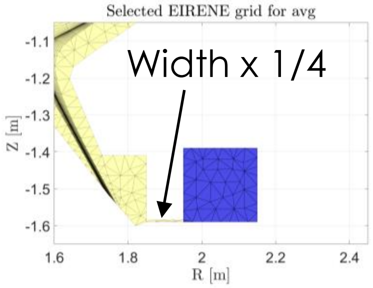


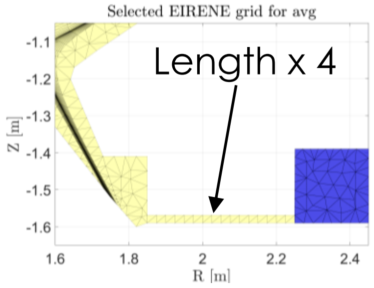
- Louvre controls neutral conductance
- 29MW pure D scenario with a toy model geometry (chamber, duct and Louvre)
- Full time-dependent SOLPS-ITER simulation with dt (B2.5) = dt (EIRENE) scans over 1e-6 to 1e-3 s
- Fixed background plasmas to check neutral relaxation time
- Saturated number of particle (IPRNL) in the census array scales with dt (EIRENE) that limits taking too small dt

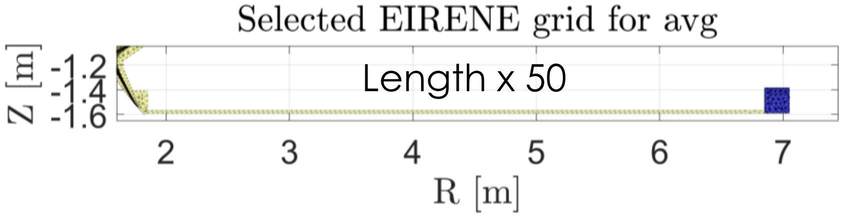




Time-scale of neutral pressure evolution is consistent with analytic model [1] and is dominated by pumping speed

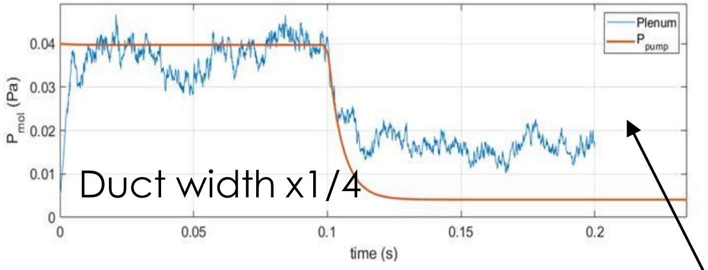


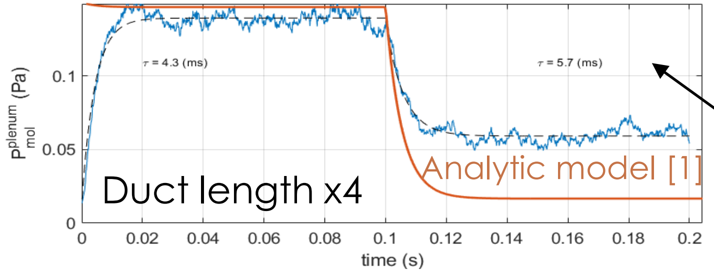


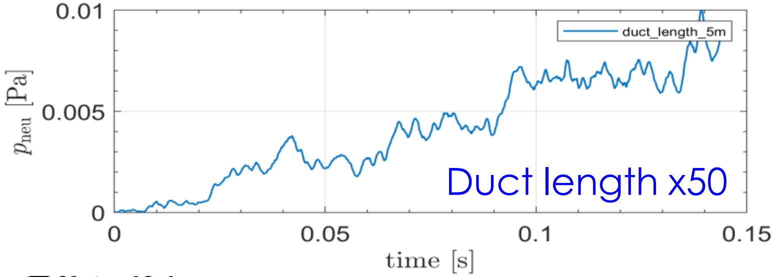


t=0: open Louvre, no neutral
t=0.1 s: 90% closed Louvre

$$V\frac{dP}{dt} = -C\Delta P + SP$$







- Only extreme changes in duct geometry (e.g., duct length 0.1 m → 5 m) affects relaxation time scale otherwise pumping speed S dominates neutral pressure evolution time
- Time scale with decreased pumping speed agrees with experimental neutral relaxation time scale (e.g., C-Mod ~ 100 ms [2])

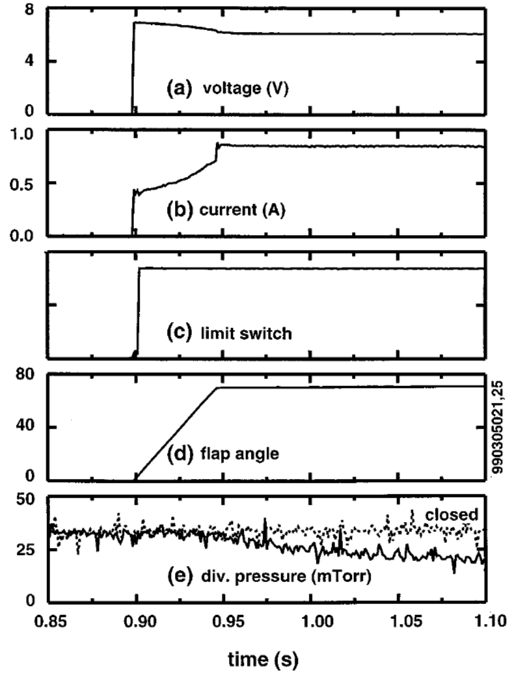
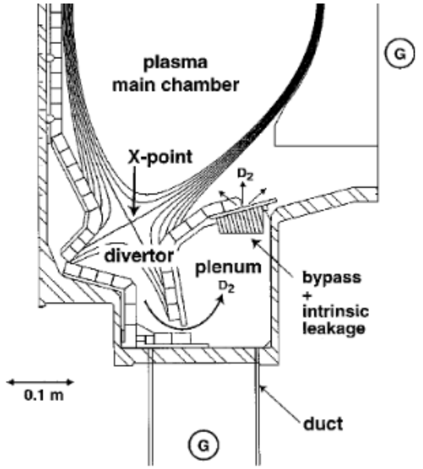
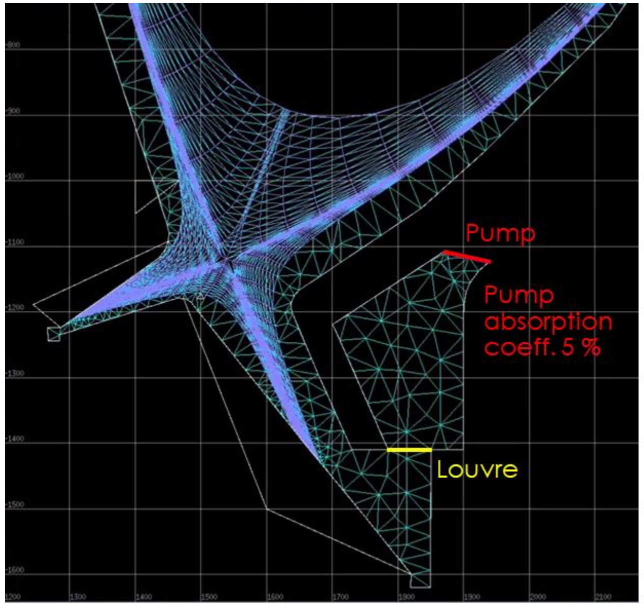


FIG. 5. Results during a discharge in Alcator C-Mod.

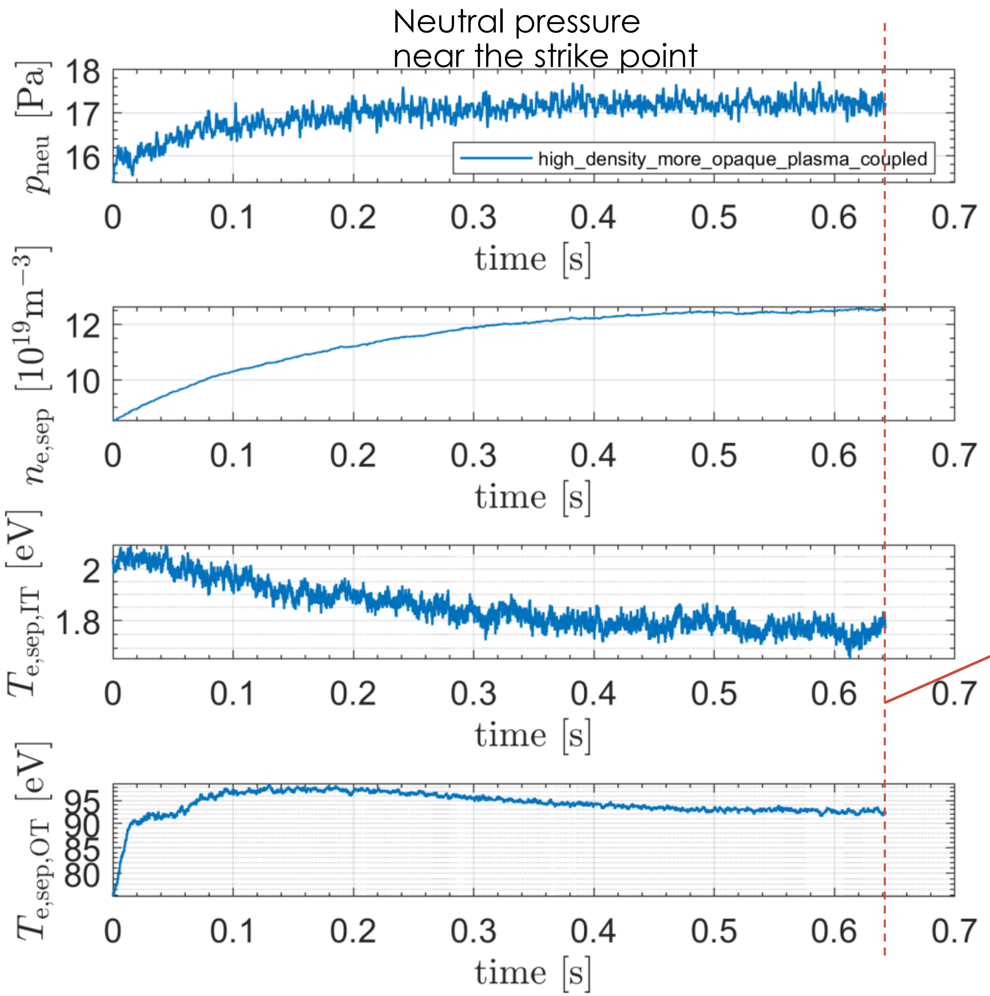


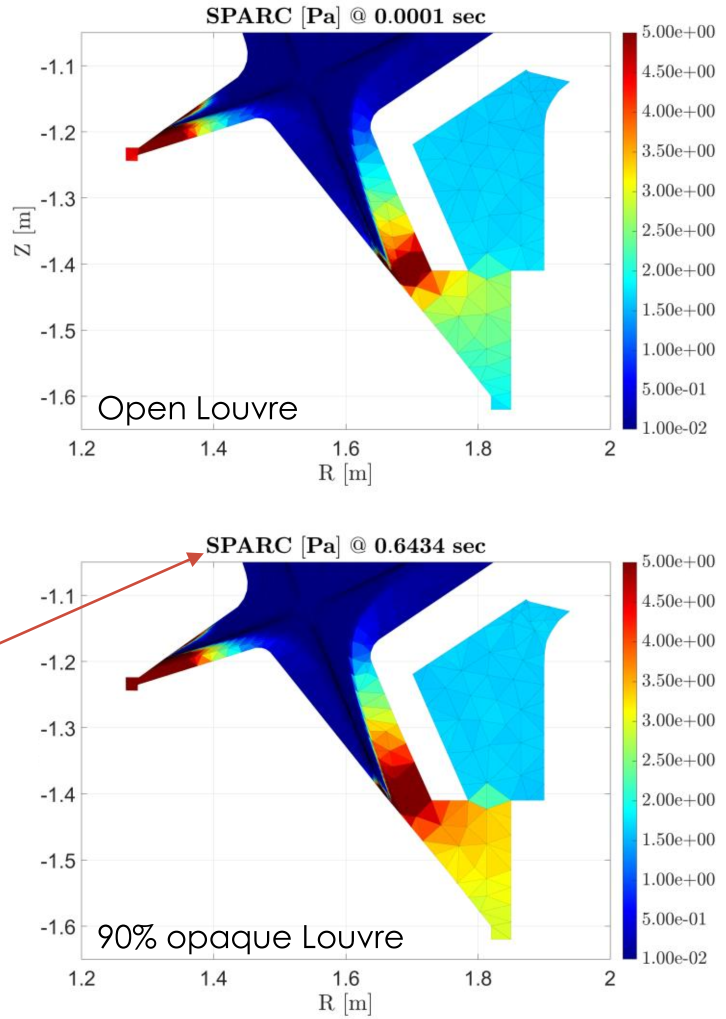
[1] J. D. Lore 2019 PPCF 61 065001
[2] C. S. Pitcher RSI 2000

Full-time dependent simulation coupled with plasma on a realistic geometry (open to 90% opaque louvre at t=0)



- ❑ Simulation setup
- Lower single null
- D only, D2 puff scan
- Input power: 10 MW (low power scenario)
- $T_{e,\mathrm{div}} \sim 50$ eV
- 'v2y' geometry
- Full time-dependent

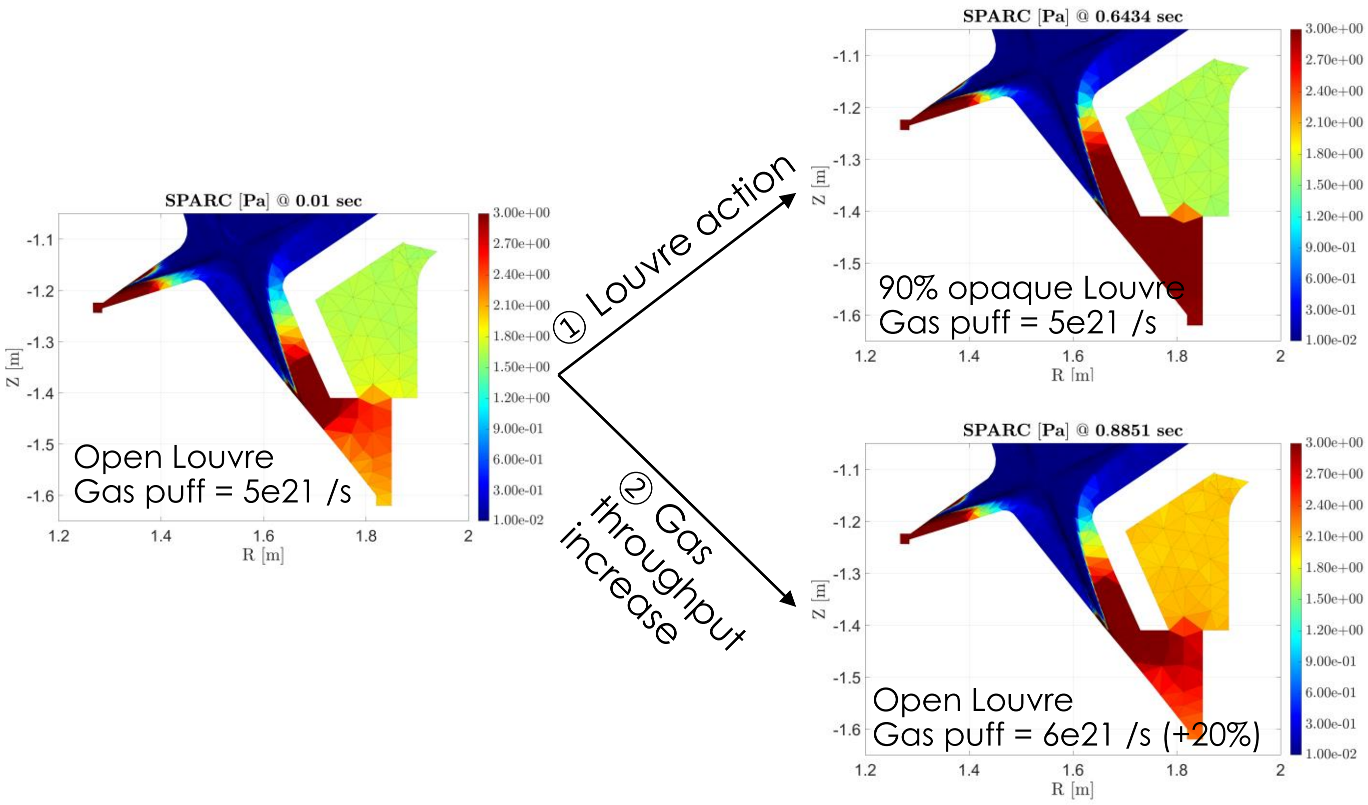




Neutral pressure

Actuator equivalence: GP throughput vs. Louvre transparency

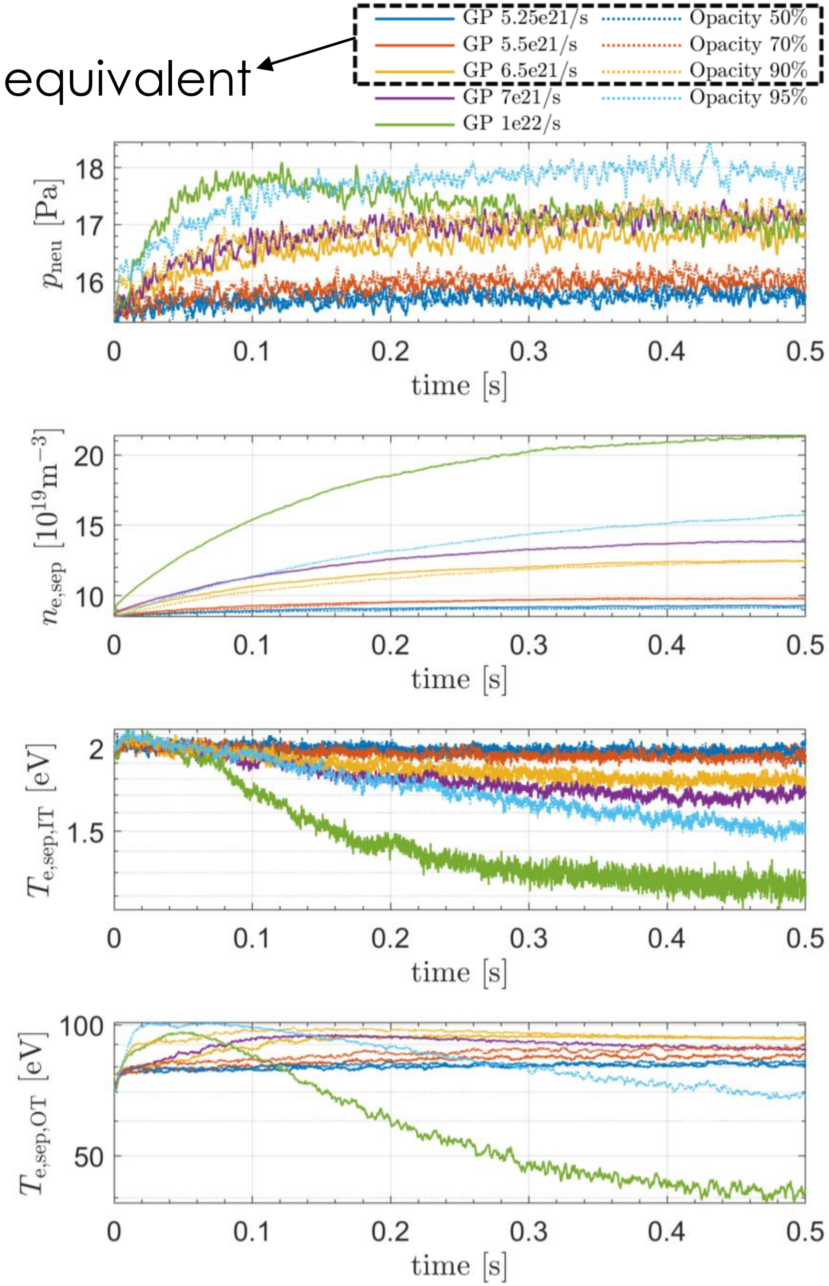
- Two actuator gives similar $p_{\mathrm{neut}}^{\mathrm{sp}}$ or $p_{\mathrm{neut}}^{\mathrm{div}}$ with different $p_{\mathrm{neut}}^{\mathrm{pump}}$



$p_{\mathrm{neut}}^{\mathrm{pump}}$ not affected

$p_{\mathrm{neut}}^{\mathrm{pump}}$ increases to achieve puff = pump (flux)

equivalent



- $\Phi_{\mathrm{pump}} = \Phi_{\mathrm{puff}}$ (pumped flux = gas throughput)
- $\Phi_{\mathrm{pump}} = p_{\mathrm{pump}} S_{\mathrm{pump}}$ (S_{pump} is pumping speed)
- $p_{\mathrm{pump}} \sim \Phi_{\mathrm{puff}}$ (S_{pump} is const. → thermalized D2 dominates)
- $p_{\mathrm{pump}} \sim p_{\mathrm{strike\ pt.}}$ (relation determined by neutral conductance, e.g., Louvre condition)

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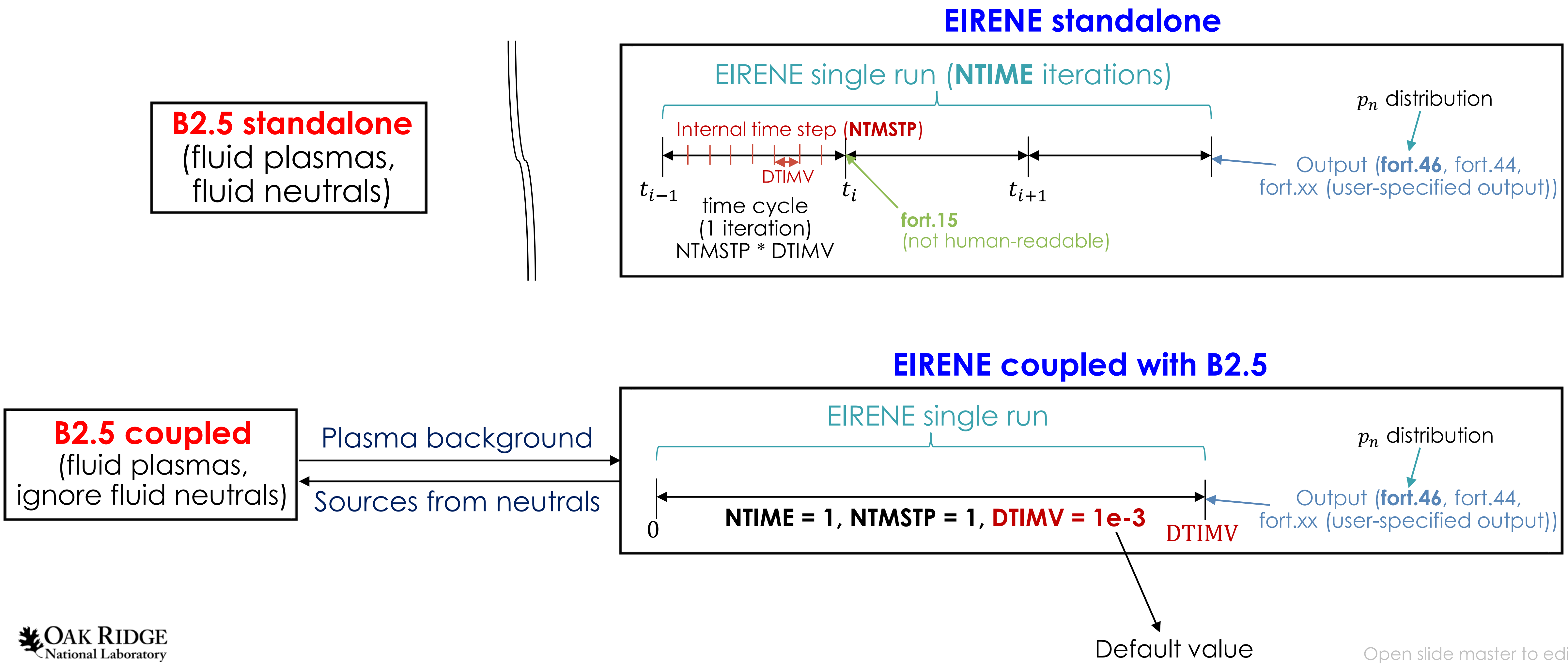
Backup Slides

Introduction - SOLPS-ITER code and B2.5-EIRENE coupling

- SOLPS-ITER: tokamak boundary plasma simulation code suite managed by ITER that includes fluid plasma solver **B2.5** + kinetic MC neutral solver **EIRENE**



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Coupling schemes "usually" assumes quasi-steady-state (QSS) neutral approximation

- Time steps
- **dt (B2.5)** = 1e-7 to 1e-4 s
- **dt (EIRENE)**: DTIMV is effectively EIRENE time step for each EIRENE calls (default = 1e-3 s)

- Two EIRENE schemes for coupled simulations

1) Quasi-steady-state (QSS) scheme
   - dt (EIRENE) = 1e-3 s (default),
   - dt (EIRENE) for ITER: large (~1e9 s) for ensuring QSS, limited by max CPU time assigned

   → Long-lived neutrals beyond dt (EIRENE) will be cut-off so neutral info can be underestimated or distorted (e.g., ionization sources distribution)

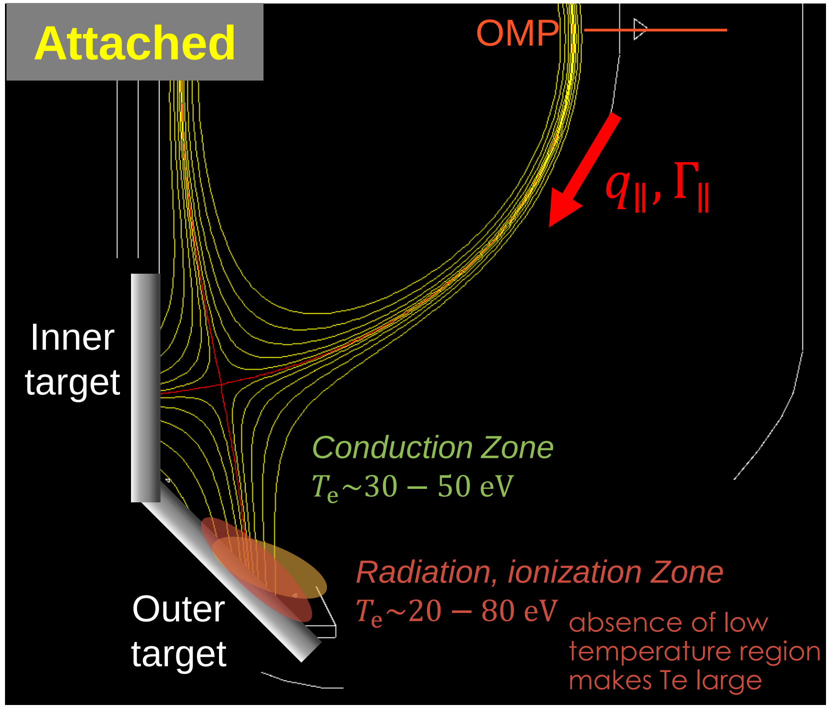
   → Long enough dt (EIRENE) gives fully relaxed ionization profile for each EIRENE call, for given plasma background, ignoring neutral propagation time

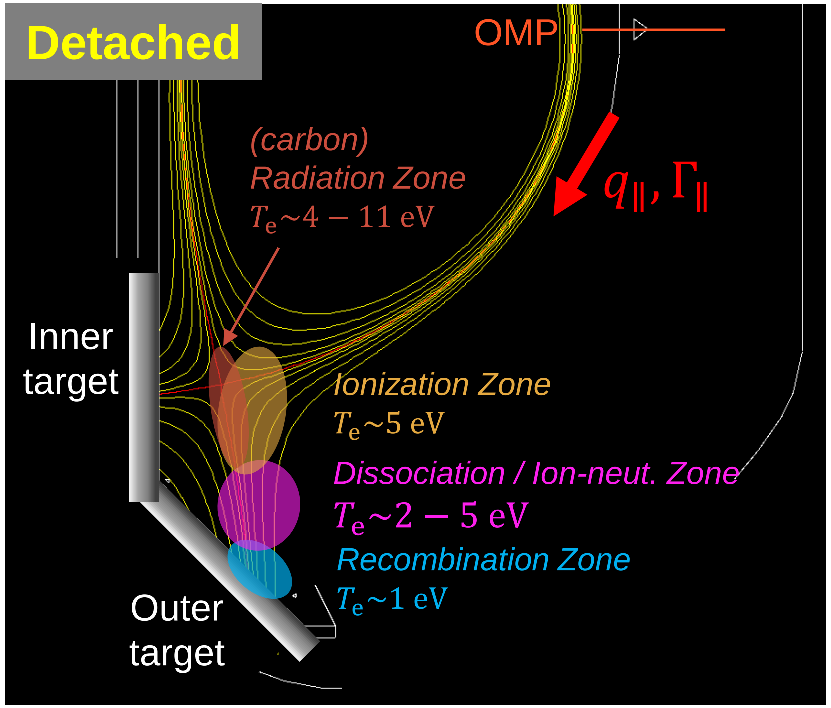
   → Still okay for ***QSS time-dependent simulation*** (***only B2.5*** plasma side) if the phenomenon of interest is governed by plasma dynamics rather than neutral dynamics (i.e., assuming neutral dynamics >> plasma dynamics)

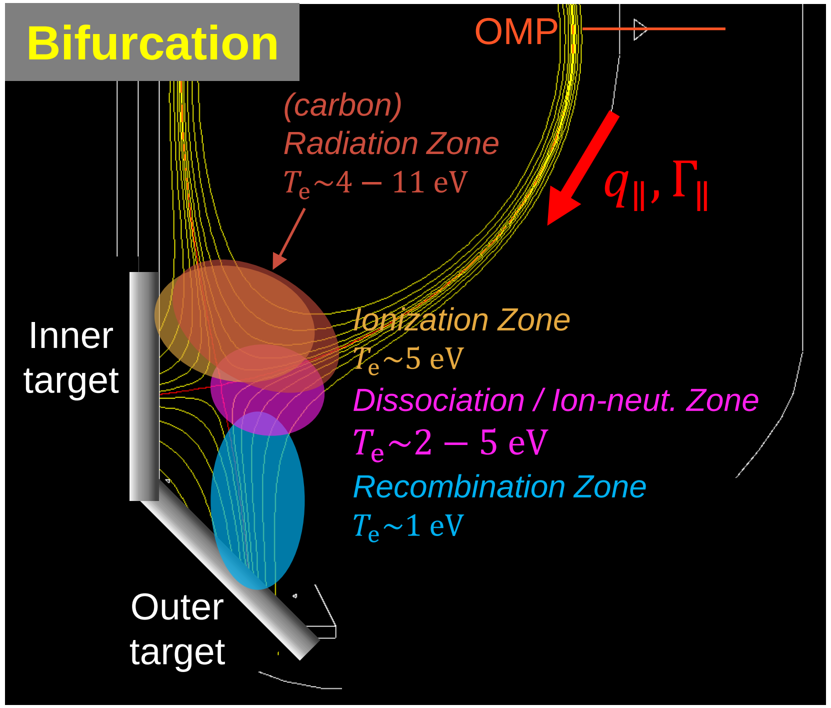
2) Time-dependent EIRENE (***full time-dependent SOLPS-ITER simulation***)
   - dt (B2.5) = dt (EIRENE) = 1e-6 to 1e-4 s (practical range)
   - Using the "census data" that records long-lived neutral information (position, velocity and weight) in a time-dependent stratum
   - Small dt requires more census data → limits practical range of dt

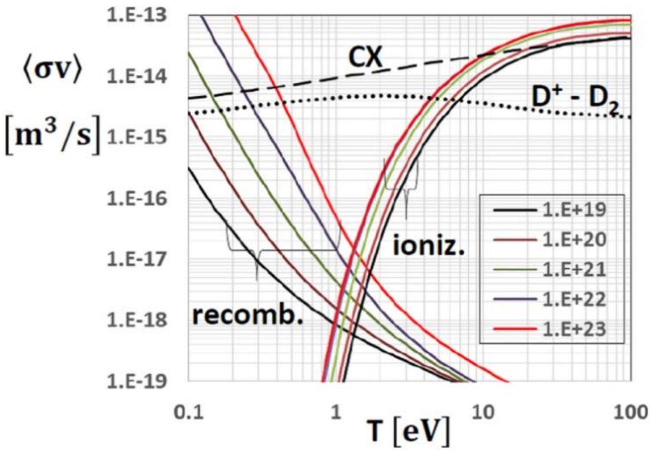
Schematic of volumetric processes coupled with Te

→ *Inspired by M. Fenstermacher PPCF 1999*

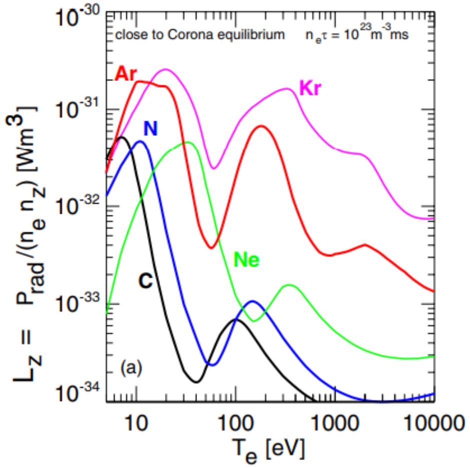








P. Stangeby PPCF 2018



A. Kallenbach PPCF 2013

Sources from the neutrals can be underestimated with default dt (EIRENE)

- KSTAR L-mode gas puff scan with different EIRENE scheme and time step

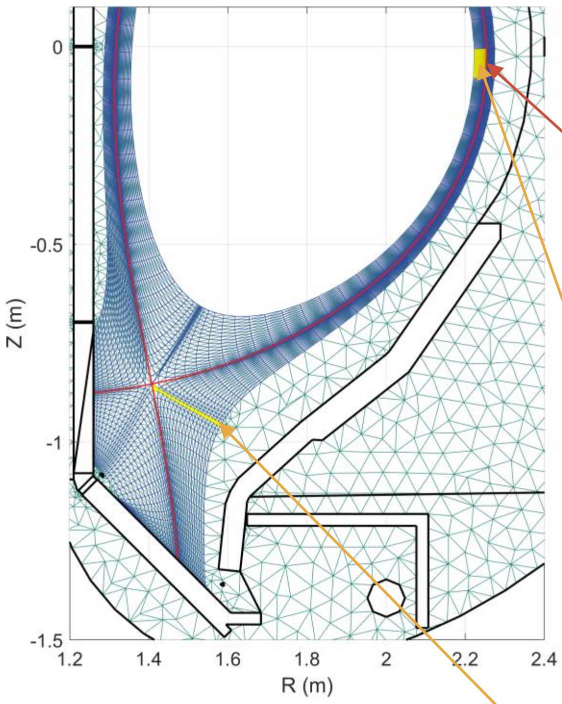
/data1/f3p/SOLPS_runs/KSTAR/KSTAR_bifurcation/r
_steady_state_1e20_QSS_eirene_step_dt_1e9_longe
_cpu

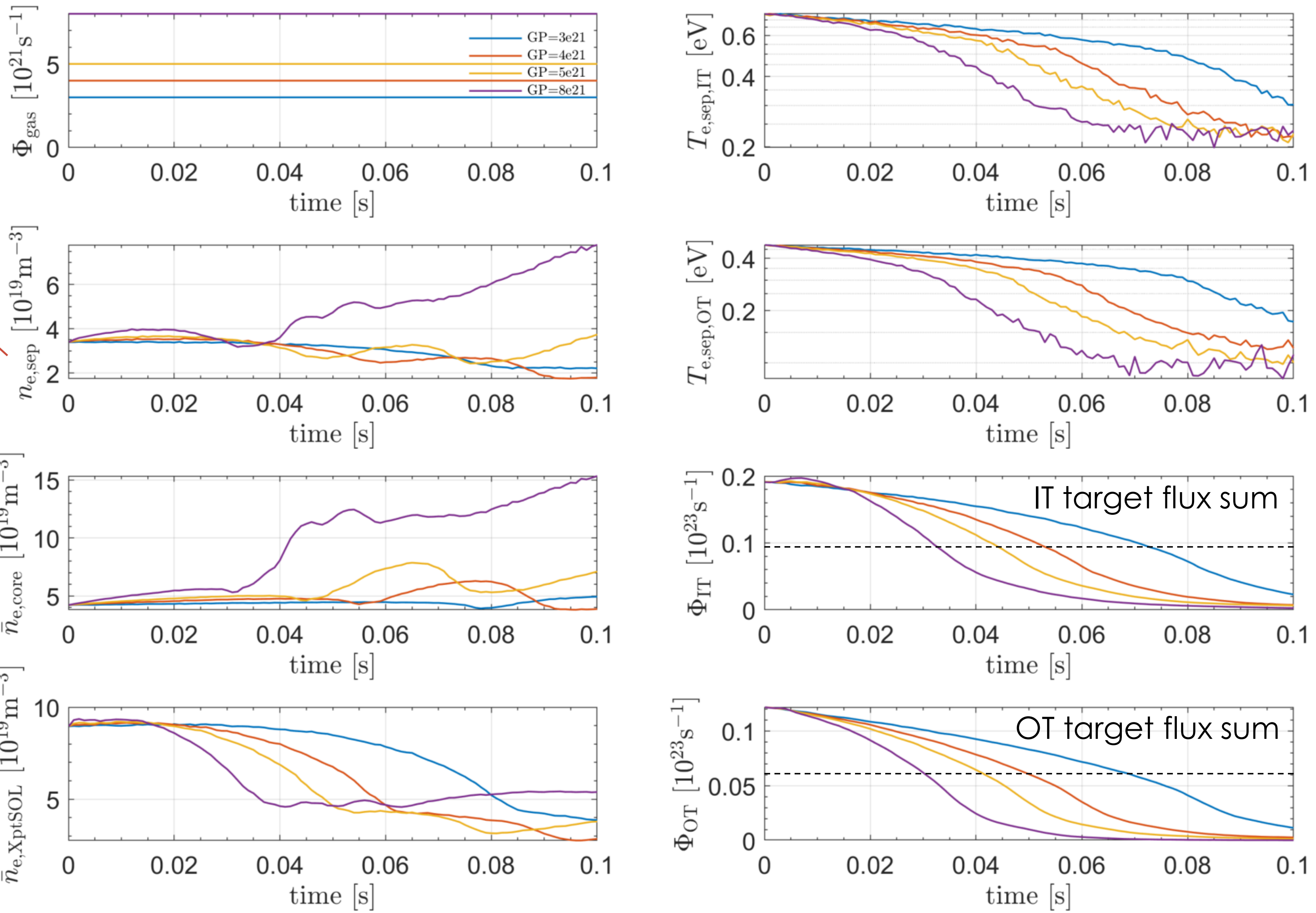
dt (EIRENE) [s]	1e-3 (default)	1.0	1.33e9 (ITER-like)	1.33e9 (ITER-like)	1e-4 = dt (B2.5)
EIRENE scheme	QSS	QSS	QSS	QSS	**Time-dependent**
NTCPU [s]	50	50	50	**90**	**100**
D_2 puff rate = 1e20 atom/s	Particle balance not achieved	$n_{e,sep} = 1.1 \times 10^{19}\ \mathrm{m}^{-3}$	$n_{e,sep} = 1.1 \times 10^{19}\ \mathrm{m}^{-3}$	$n_{e,sep} = 5.1 \times 10^{18}\ \mathrm{m}^{-3}$	3e18 with NPRNL = 200000
D_2 puff rate = 1e22 atom/s	$n_{e,sep} = 1.1 \times 10^{19}\ \mathrm{m}^{-3}$	$n_{e,sep} = 2.0 \times 10^{20}\ \mathrm{m}^{-3}$	$n_{e,sep} = 2.0 \times 10^{20}\ \mathrm{m}^{-3}$	$n_{e,sep} = 2.0 \times 10^{20}\ \mathrm{m}^{-3}$	Bb8 (density 급증중)

Update result

- Default EIRENE time step is not sufficient for KSTAR L-mode due to cut-off of the long-lived neutrals due to long mean free path of neutrals by 1) KSTAR geometry and 2) low density, low temperature in given discharge condition
- Lack of the ionization source from cut-off can be compensated by increasing puffing rate
- ITER-like dt (EIRENE) gives the same result as dt (EIRENE) = 1.0 case, limited by CPU time (50 s here)
- Time-dependent run gives the same steady-state solution as QSS scheme ?

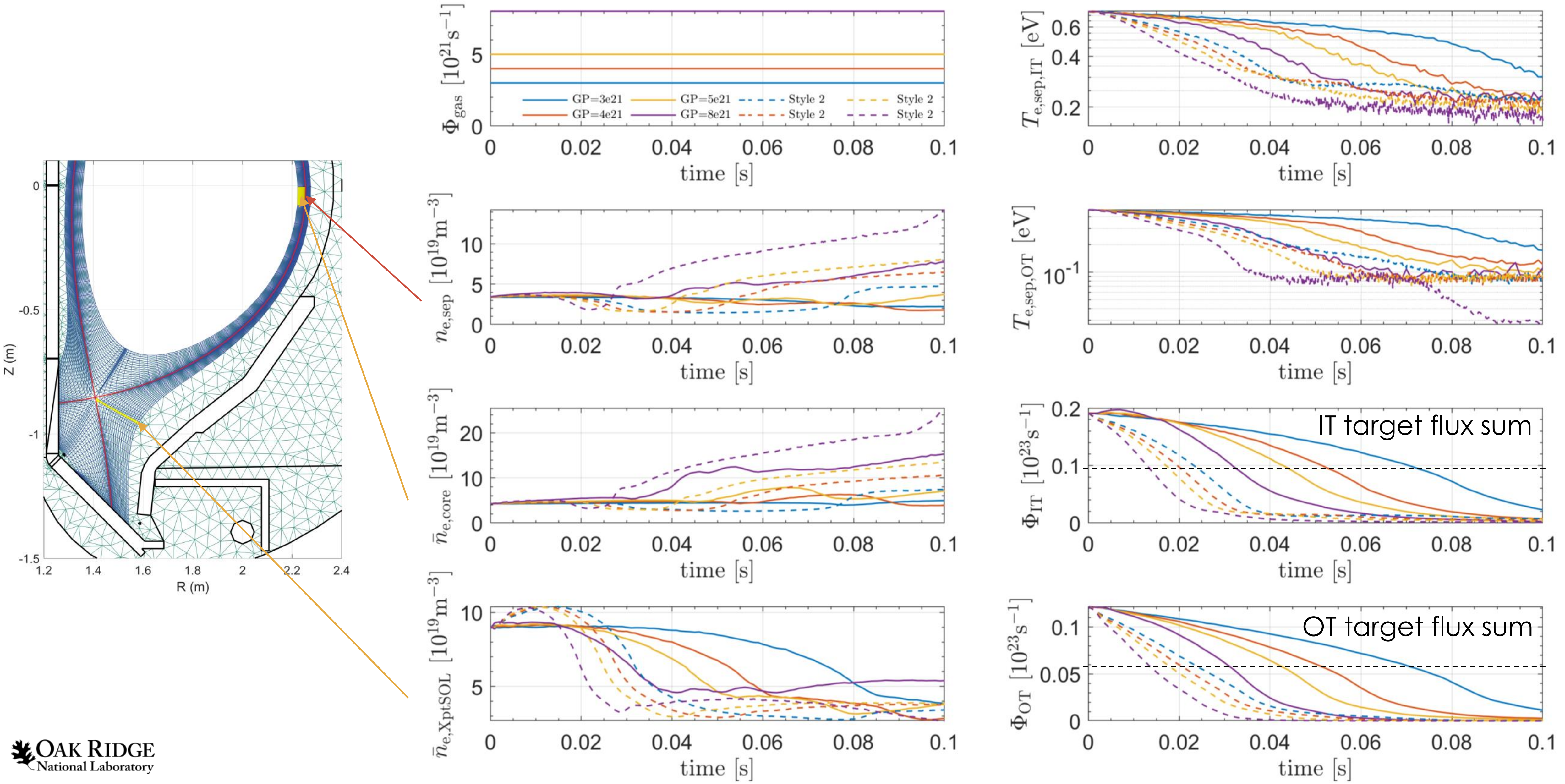
Time-scale of bifurcation depends on the throughput



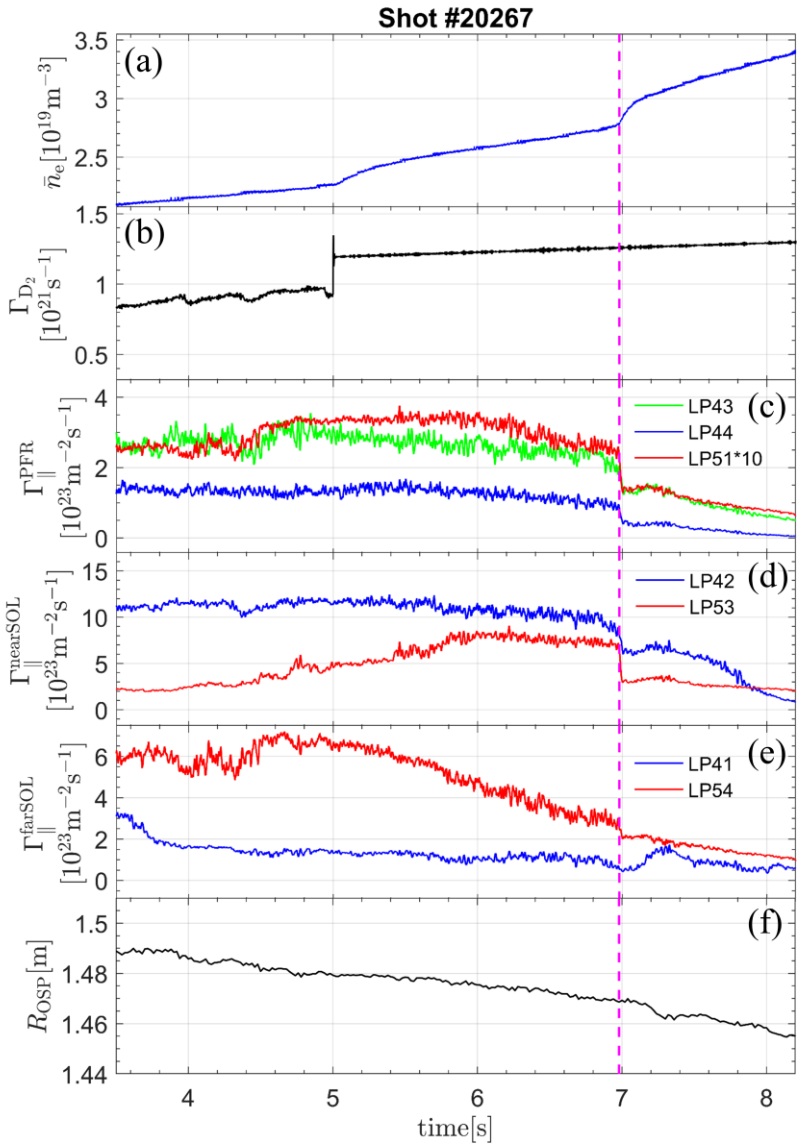


OAK RIDGE National Laboratory

Time-scale of bifurcation depends on the throughput

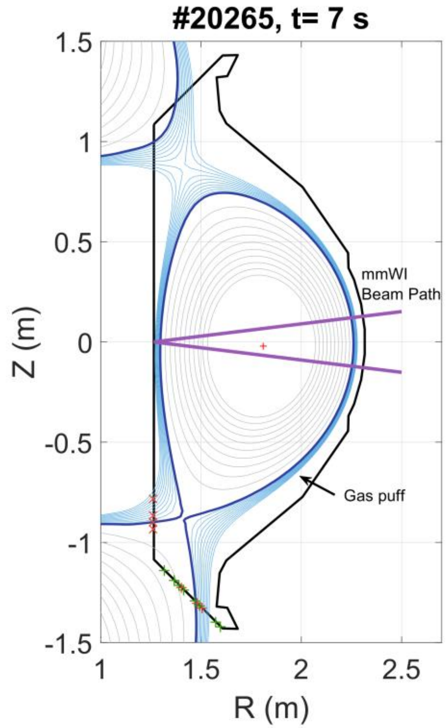


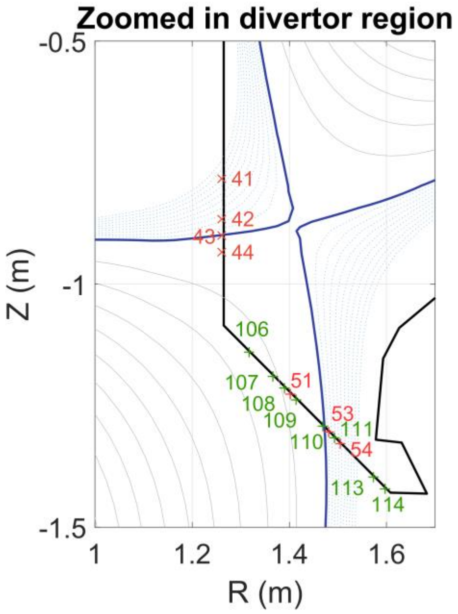
Target flux bifurcation in KSTAR L-mode experiment



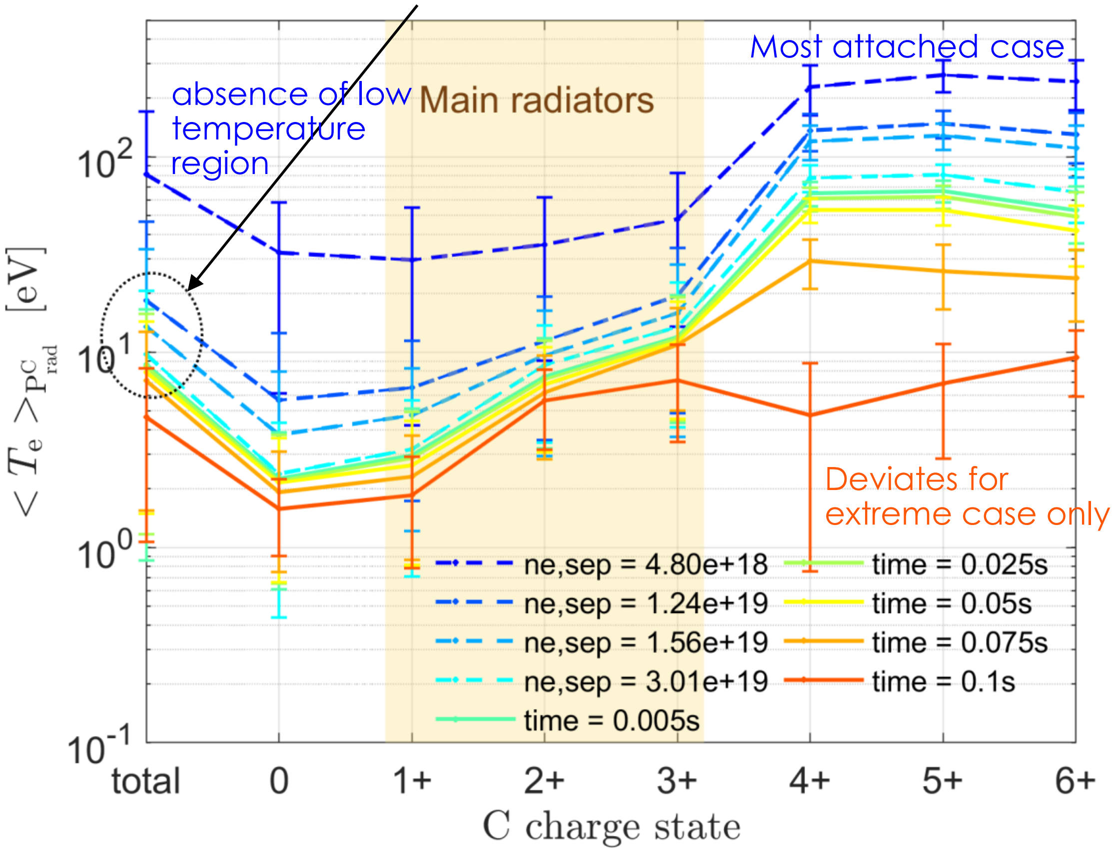
Discharge condition

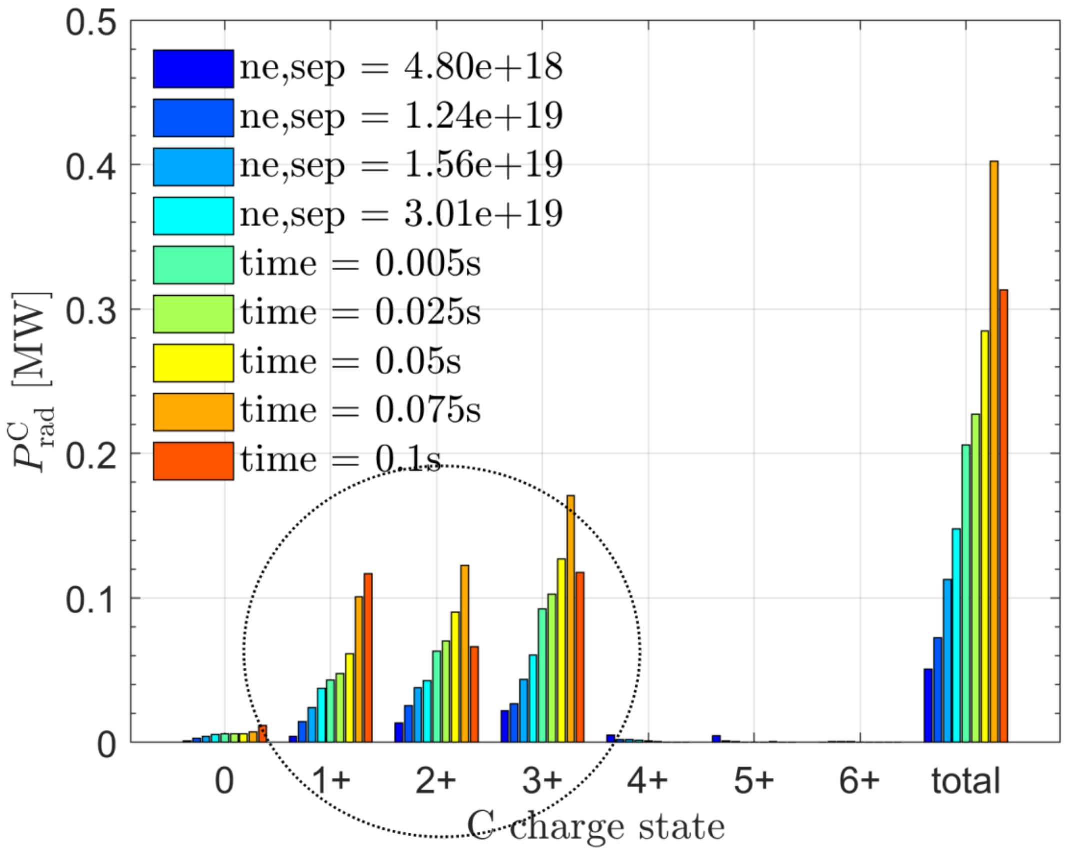
- $I_\mathrm{p} = 0.6\ \mathrm{MA}, B_\mathrm{T} = 2.5\ \mathrm{T}$ (forward field, ion B×∇B direction downwards into the lower divertor)
- External heating power = 0.93 MW (mostly from neutral beam)
- $\bar{n}_\mathrm{e} = 2.0 - 3.5 \times 10^{19}\ \mathrm{m}^{-3}$ ramped with fixed gas puff (1e21/s) without feedback control of fuel throughput





Majority of C radiation comes from: Te = 4-11eV (over whole region)





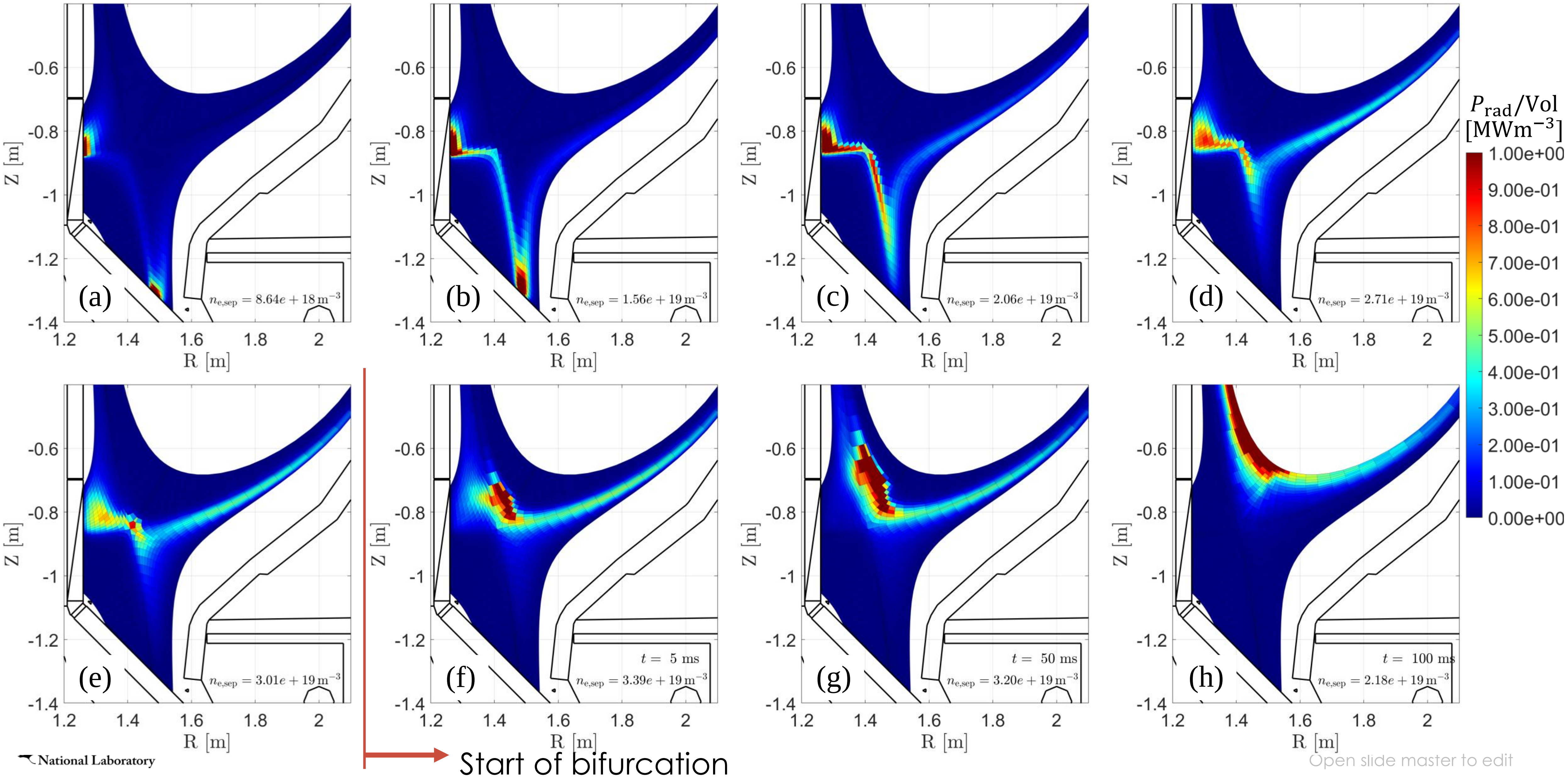
$$< T_e >_{P^C_{rad}} \equiv \frac{\sum T_e P^C_{rad} \Delta V}{\sum P^C_{rad} \Delta V}, \quad \delta < T_e >_{P^C_{rad}} \equiv \sqrt{\frac{\sum \left(T_e - < T_e >_{P^C_{rad}}\right)^2 P^C_{rad} \Delta V}{\frac{M-1}{M} \sum P^C_{rad} \Delta V}}$$

M: number of non-zero weights

- $< T_e >_{P^C_{rad}}$ is well coupled with T_e except for the extreme cases
  → Lack of low T_e region for low recycling cases makes curve deviation
- Main radiators: C^{1+}, C^{2+}, C^{3+} ($< T_e >_{P^C_{rad}} = 1-3, 5-8, 10-11$ eV, respectively for $f^C_{rad} > 10$ %)

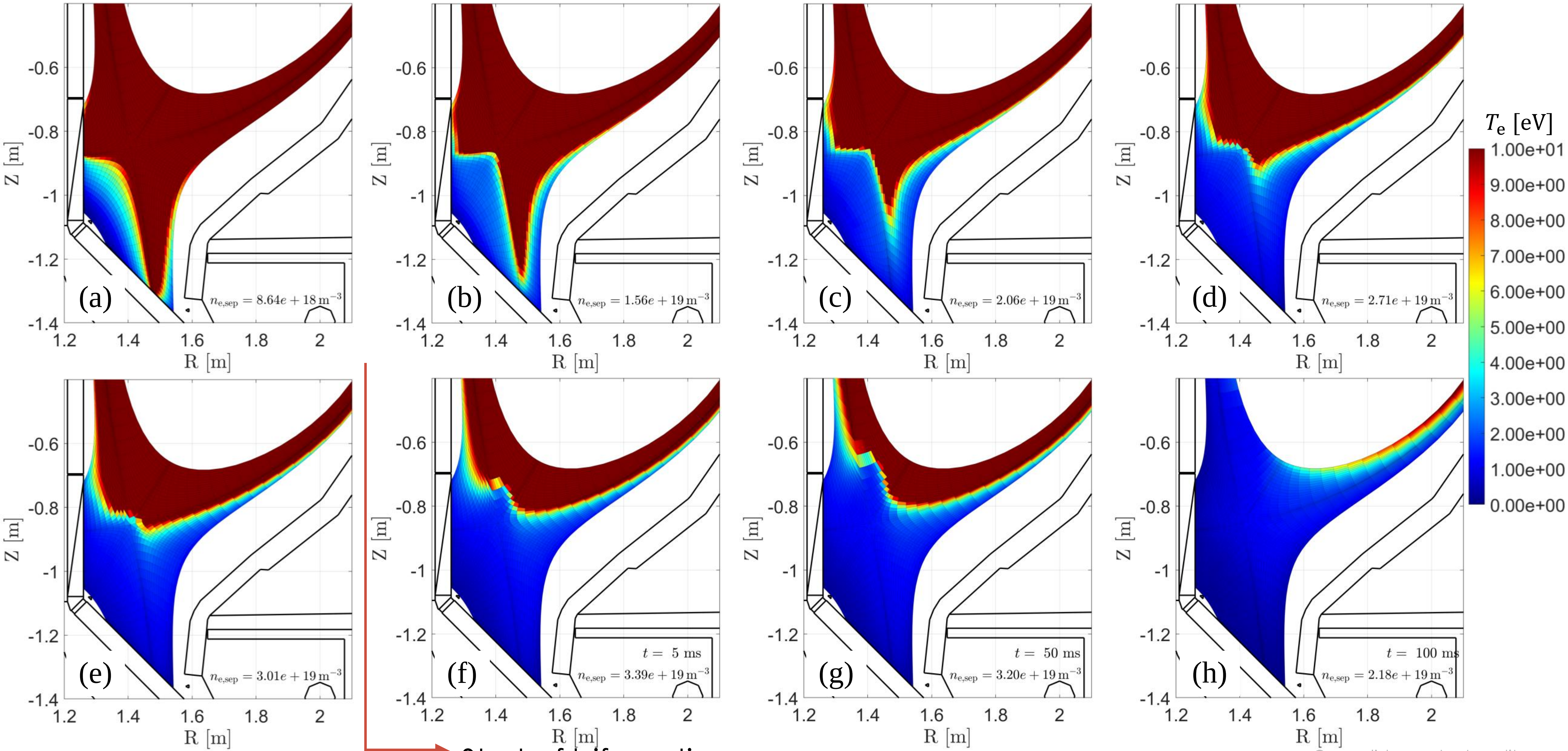
(a)-(e): steady-state solutions
(f)-(h): time-dependent solutions

$P_{\mathrm{rad}}/\mathrm{Vol}$: radiation spot penetrates core



(a)-(e): steady-state solutions
(f)-(h): time-dependent solutions

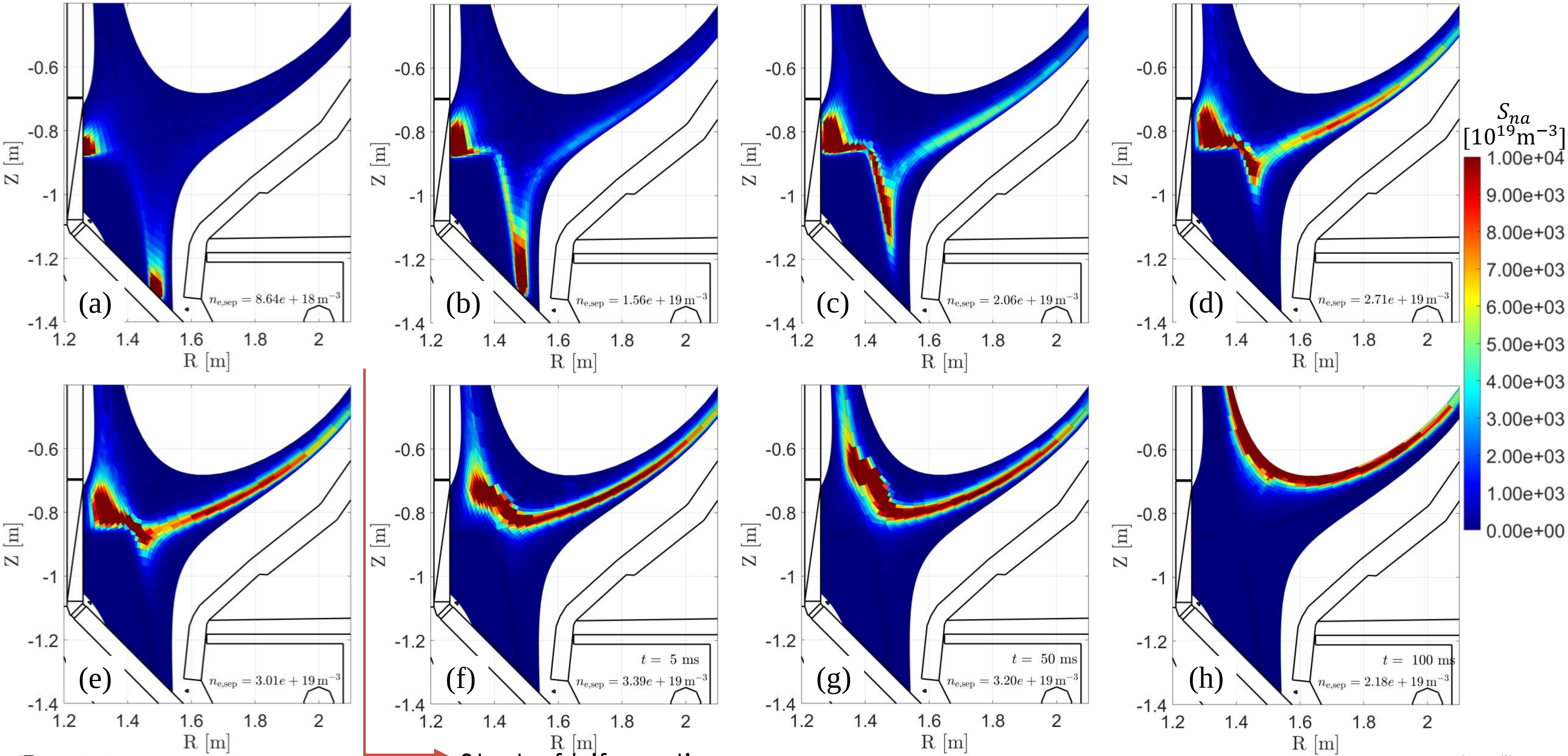
T_{e}: 5eV front penetrates core



Start of bifurcation

(a)-(e): steady-state solutions
(f)-(h): time-dependent solutions

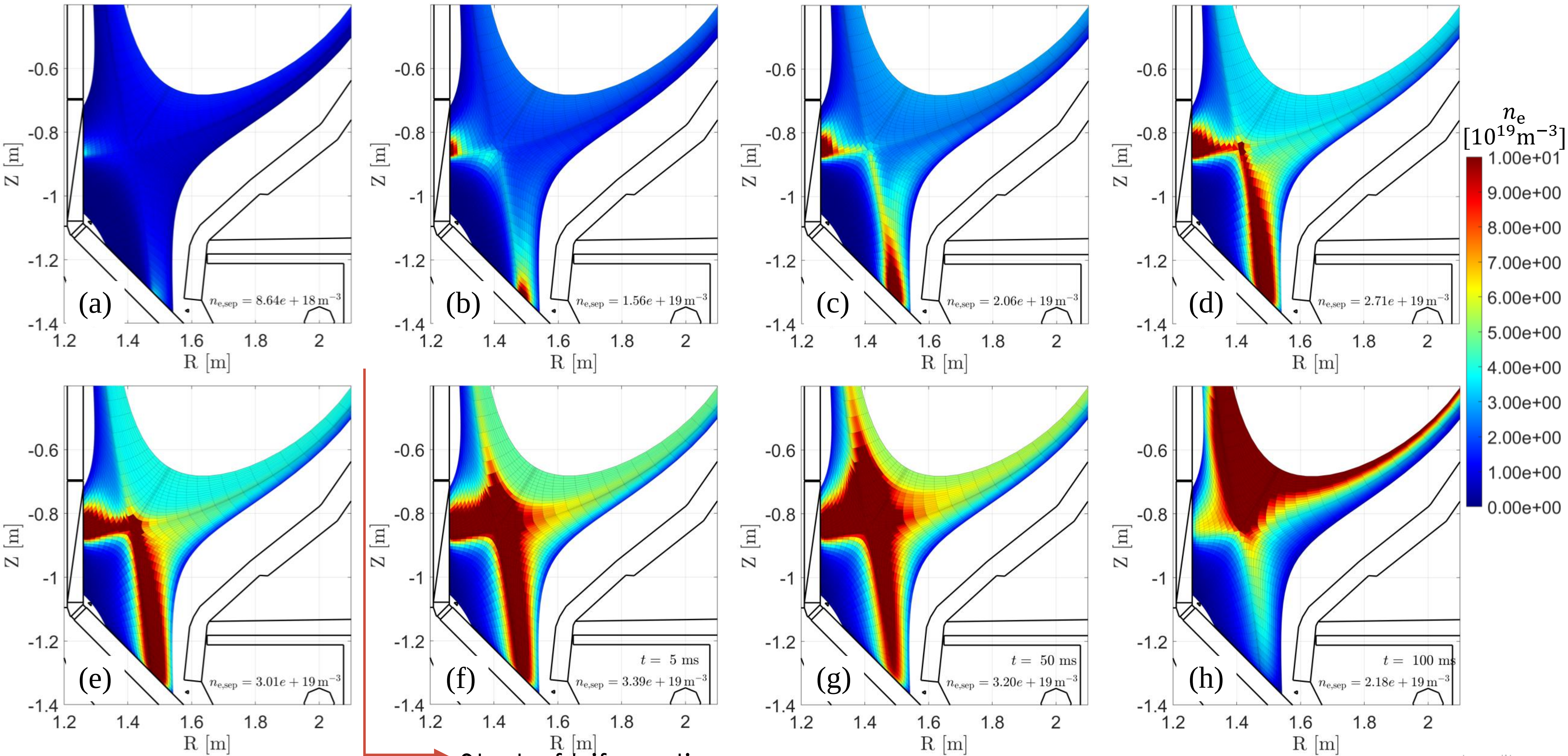
S_{na}: ionization front penetrates core



Start of bifurcation

(a)-(e): steady-state solutions
(f)-(h): time-dependent solutions

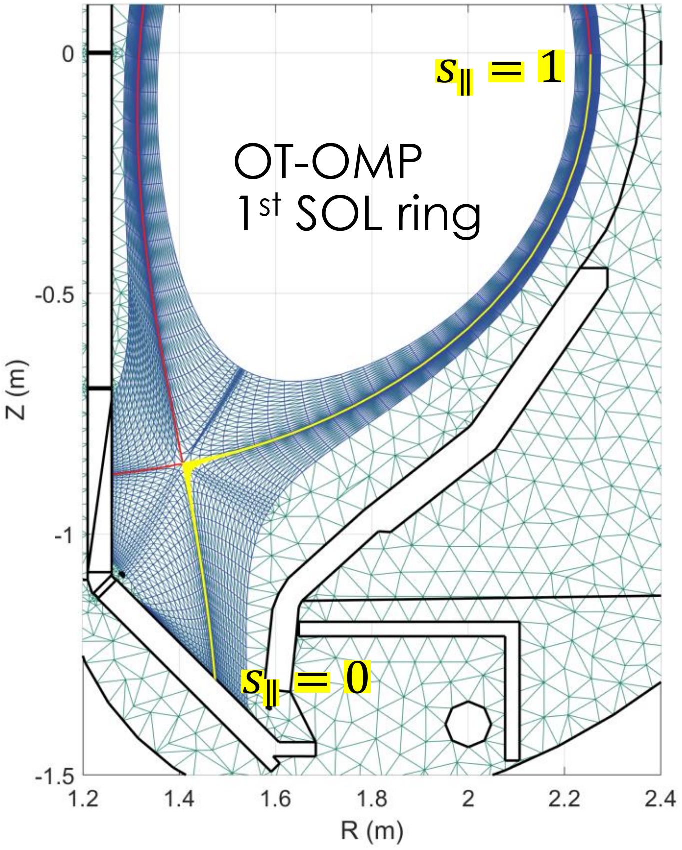
n_{e}: hd zone moves target → Xpt → core (Xpt)

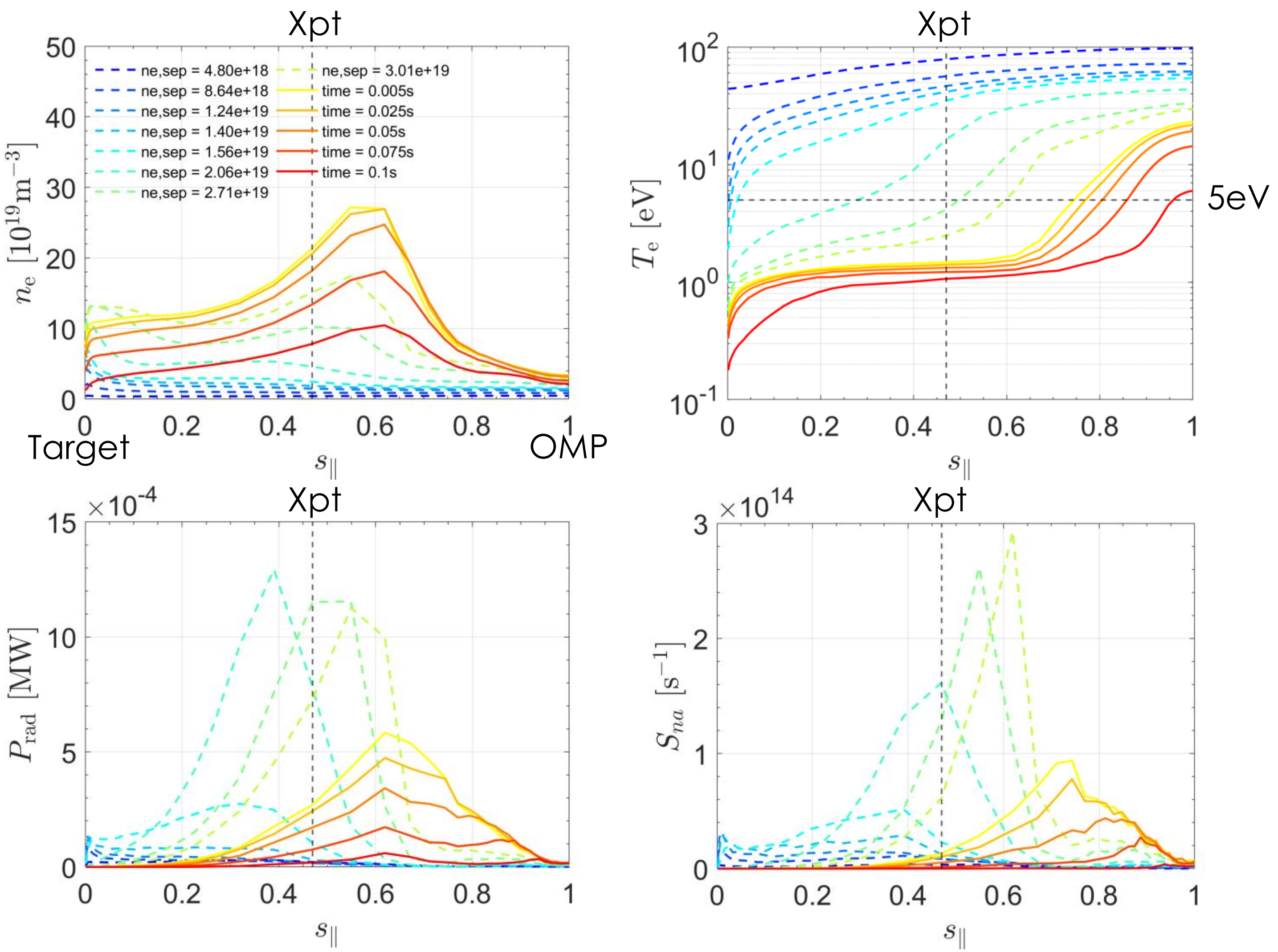


Start of bifurcation

Parallel distribution (OT~OMP) of $n_\mathrm{e}, T_\mathrm{e}, P_\mathrm{rad}, s_n$ (1st SOL ring)

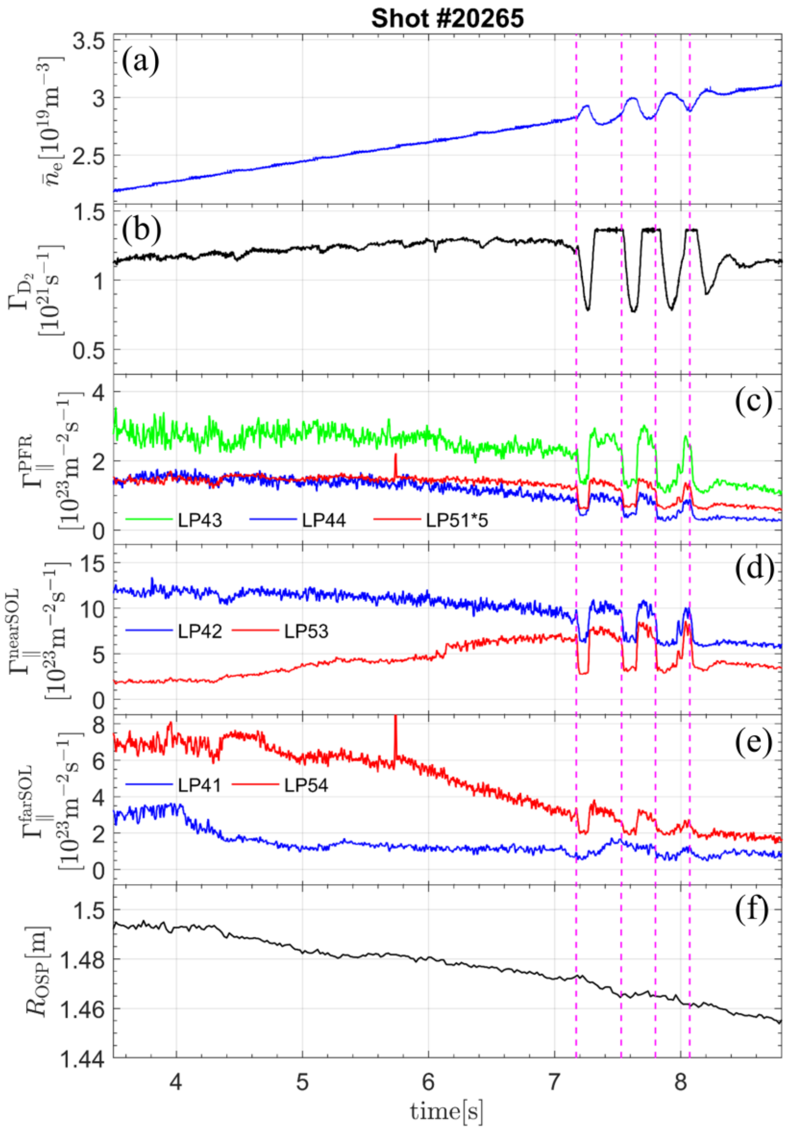
$s_\parallel$: normalized parallel coordinate
OT ($s_\parallel = 0$) - OMP ($s_\parallel = 1$)





- High density zone forms at [target → Xpt], then peak decreases
- $T_\mathrm{e}(s_\parallel)$ is always monotonic and 5eV front moves upstream across Xpt
- Ionization front, radiation front moves upstream across Xpt, then peak value gradually decreases at further upstream

Target flux bifurcation in KSTAR L-mode experiment

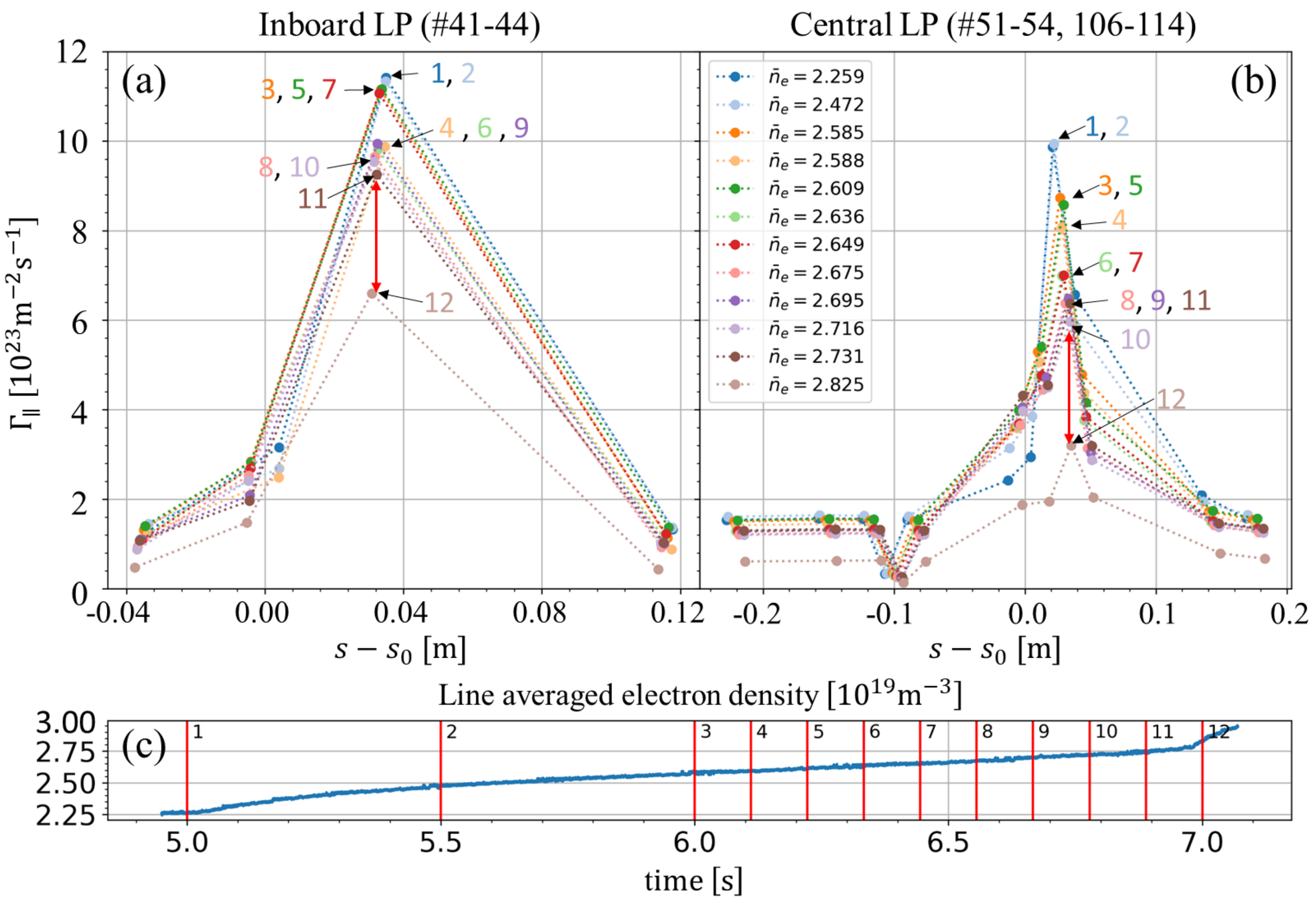


Discharge condition

- $I_p = 0.6$ MA, $B_T = 2.5$ T (forward field, ion B×∇B direction downwards into the lower divertor)
- External heating power = 0.93 MW (mostly from neutral beam)
- $\bar{n}_e = 2.0 - 3.0 \times 10^{19}\ \mathrm{m^{-3}}$ ramped with feedback control of fuel throughput

- Transition happens in 10-30 ms
  → intermediate state in the middle of the target flux cliff is unstable
- Time scale is similar or longer than the parallel SOL transport timescale

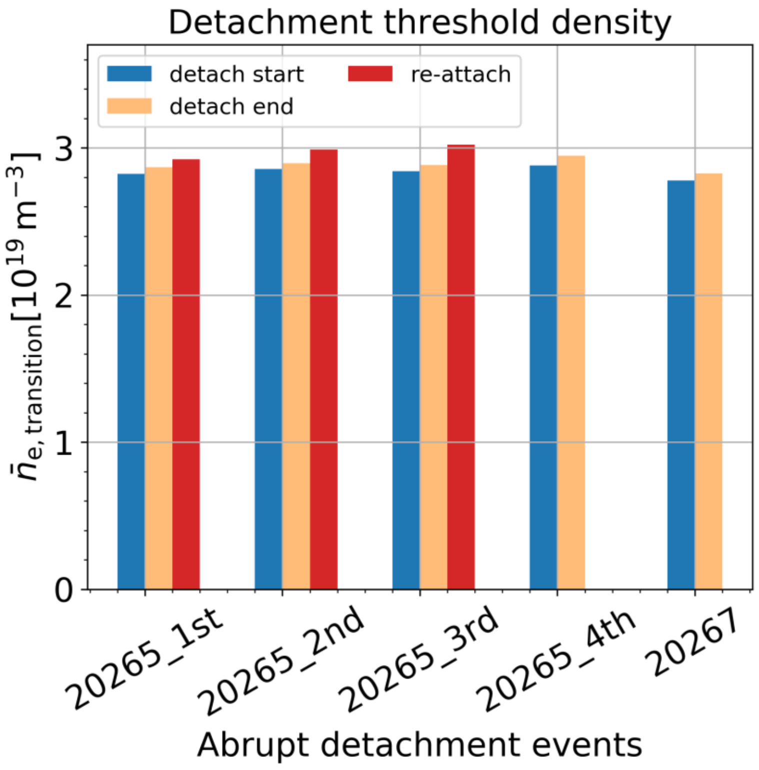
Characteristic of the target flux bifurcation



Target flux rollover

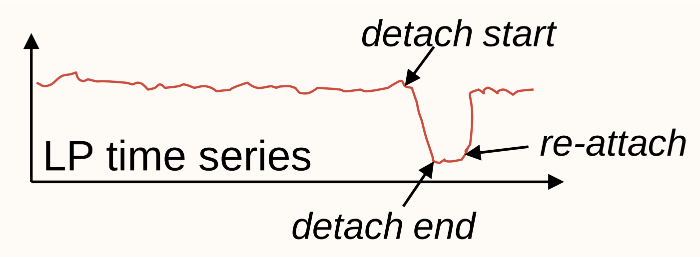
→ stable rollover + abrupt & unstable transition

Characteristic of the target flux bifurcation



1) Existence of the ‘critical density’:
Bifurcation-like transition to the detached regime happens when $\bar{n}_{\mathrm{e}}$ reaches at ‘critical density’ $\bar{n}_{\mathrm{crit.}}$

2) Hysteresis of ‘critical density’:
[Re-attachment $\bar{n}_{\mathrm{crit.}}$] > [detachment $\bar{n}_{\mathrm{crit.}}$]
→ Representation of divertor condition with delays, implies that there can be a better classifier such as divertor (downstream) physical quantities rather than upstream quantity, $\bar{n}_{\mathrm{e}}$



3) Bifurcation time-scale $\tau_{bifurcation}$: 10-40 ms

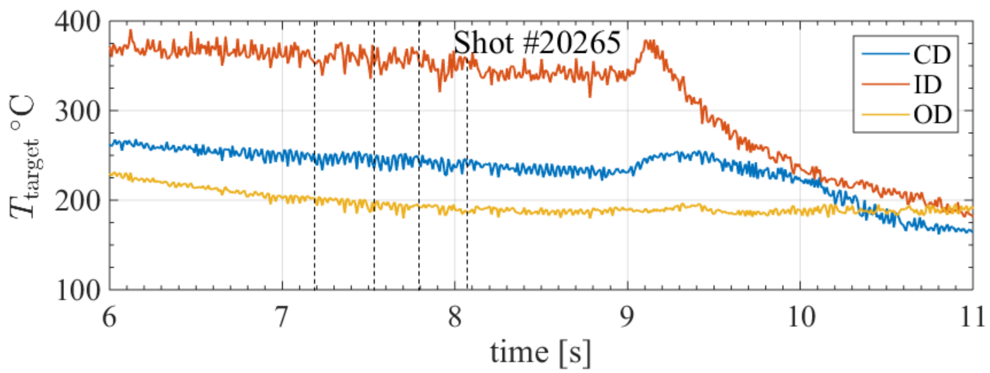
$$\tau_{\parallel} \leq \tau_{bifurcation} < \tau_{\perp}$$

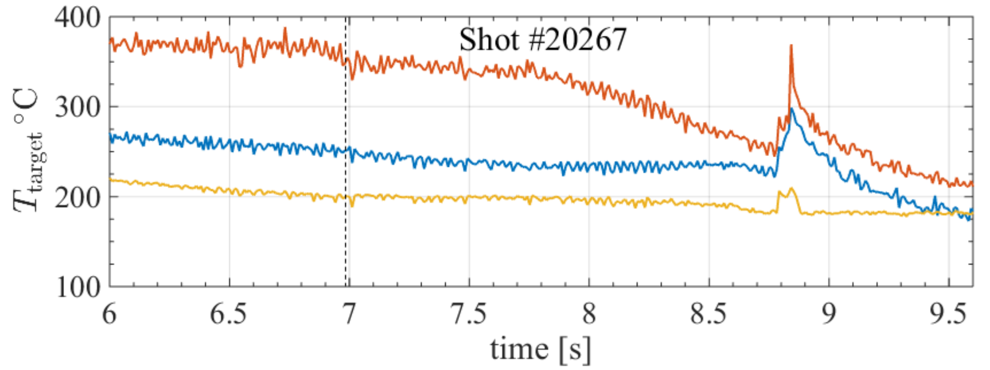
	1st detach	2nd detach	3rd detach	4th detach	#20267 detach
$t_{\mathrm{detach\,start}}$ [sec]	7.170	7.528	7.798	8.070	6.970
$t_{\mathrm{detach\,end}}$ [sec]	7.200	7.548	7.814	8.109	7.000
Δt [sec]	0.030	0.020	0.016	0.039	0.030

Bifurcation is not related with carbon sputtering

- In JET (with carbon divertor), self-sustained oscillation of the detached <-> attached states were observed A. Loarte PRL 1999

- KSTAR maximum target temperature





➢ At least $Y_{\rm chem}$ does not change!

➢ Attached state
- strong $q_{\parallel t}, \Gamma_{\parallel t}$
- strong sputtering
- strong C rad ($Y_{\rm chem}$↑)

[*self-sustained oscillation*]

➢ Detached state
- weak $q_{\parallel t}, \Gamma_{\parallel t}$
- weak sputtering
- weak C rad ($Y_{\rm chem}$↓)