NUCLEAR ENGINEERING
서울대학교 공과대학 원자핵공학과

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3DST

Modelling of mildly relativistic runaway electrons

Development of reduced-kinetic model and validation in KSTAR ohmic startup

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Main references

[1] H.-T. Kim et. al., Development of full electron magnetic plasma burn-through model and validation in MAST, *Nucl. Fusion*. 62, 126012 (2022)
[2] Y. Lee et. al., Kinetic modelling of start-up runaway electrons in KSTAR and ITER, *Nucl. Fusion*. 63, 106011 (2023)
[3] Y. Lee et. al., Binary Nature of Collisions Facilitates Runaway Electron Generation in Weakly Ionized Plasmas, *Phys. Rev. Lett*. 133, 175102 (2024)

30th IAEA Fusion Energy Conference (IAEA FEC 2025)
Oct 16th, 2025, Cheongdu

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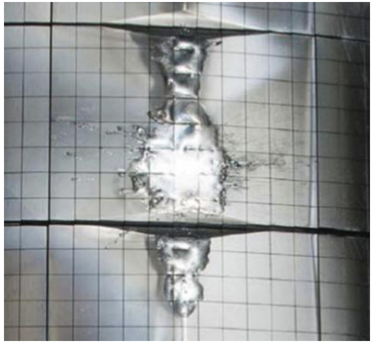
Lay physical and engineering foundation of designing a RE-free scenario in future fusion reactors

Introduction

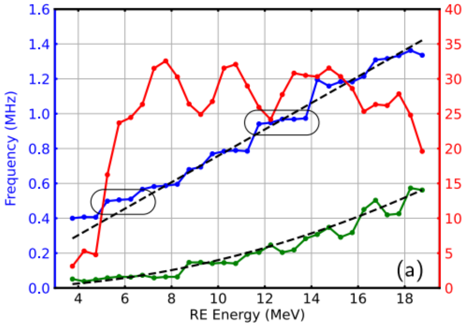
Runaway Electrons

- Runaway Electrons (REs)
  - Runaway electrons are the energetic electrons that will be continuously accelerated by the electrical field due to the decrease in the Coulomb collision frequency with increasing energy [Wilson1925].

- Hazards of REs
  - Damage to devices [Matthews et al., 2016]
  - Trigger instabilities [Liu et al., 2023]



[JET in-vessel image]



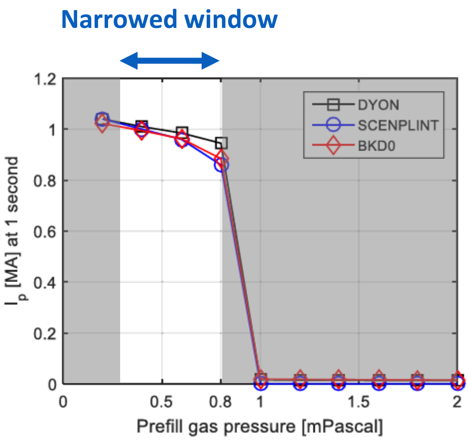
[CAW excited by REs]

- Disruption REs
  - Main interest of RE research community [Breizman et al., 2019].

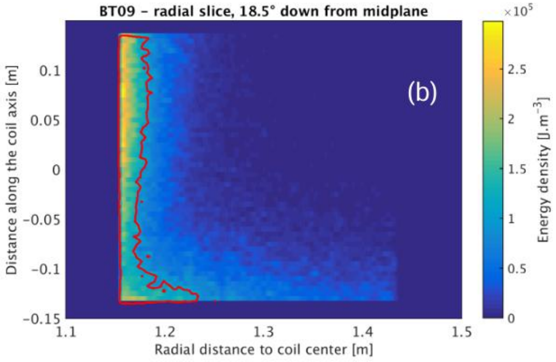
Startup runaway electrons – Obstacles of ITER startup

- Strict conditions for burn-through success
  - Plasma-driven failure at high prefill pressure (>= 0.8 mPa) Kim2020NF
  - Runaway-driven failure at low prefill pressure (<= 0.3 mPa) Gribove2018EPS Hoppe2022JPP
    - ➢ The conservative prediction suggested the failure at 0.6 mPa. Lee2024PRL

- Risk of catastrophic threat
  - Toroidal field coil quench
    - ➢ Reported in WEST



Kim2020NF

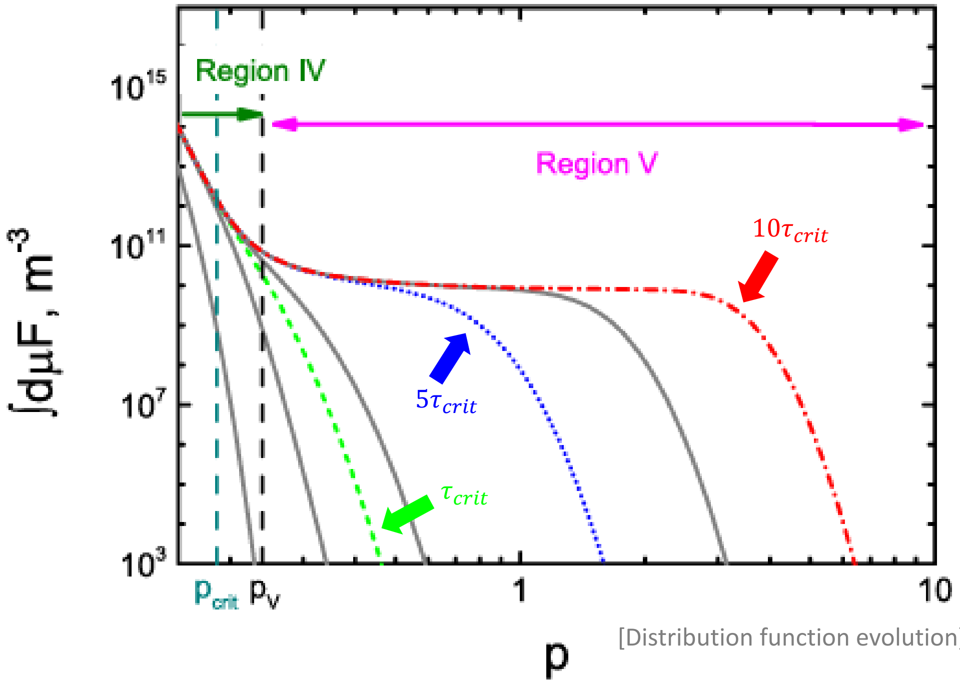


Ruex2021FEC

Safe plasma startup in ITER requires understanding of startup REs.

Improved understanding of startup runaway physics

- Runaway electrons are born at the region-based critical momentum p_V.
  - Not the force-free momentum p_{crit} often referred to as the critical momentum.



[Distribution function evolution]

Force-free critical momentum p_{crit}

$$F = F_{electric} - F_{fric} = 0$$

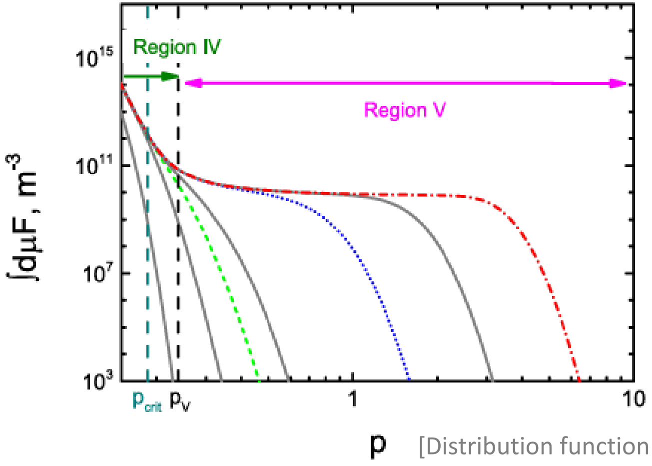
Region-based critical boundary p_V

Region IV	Region V
Dominant energy diffusion due to $F \approx 0$	Dominant acceleration due to $F > 0$

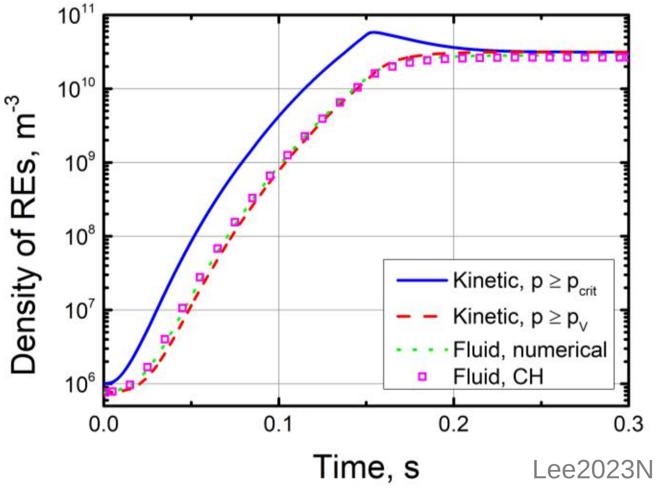
p_V

Improved understanding of startup runaway physics

- The initial startup runaway momentum is the region-based momentum p_V.
  - Not the force-free momentum p_{crit} often referred to as the critical momentum.



[Distribution function evolution]



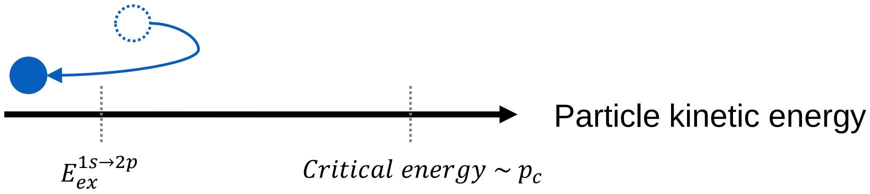
Lee2023NF

  - Main Conclusions
    - ➢ Fluid description of runaway density evolution is good.
    - ➢ Primary runaway particles are born with initial momentum p_V.

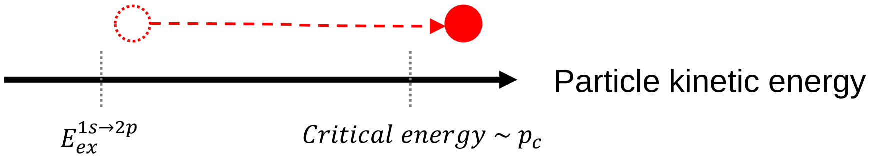
Improved understanding of startup runaway physics

- In early startup, runaway generation mechanism in non-diffusive.

Inelastic collision prohibits electron acceleration

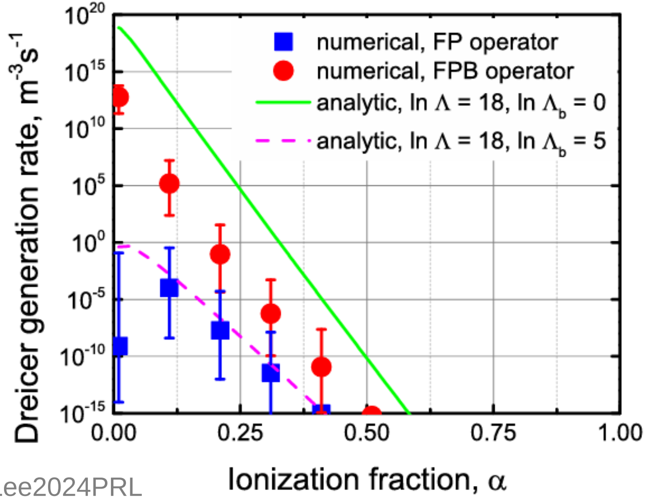


Collisionless acceleration allows electron energy gain above p_c

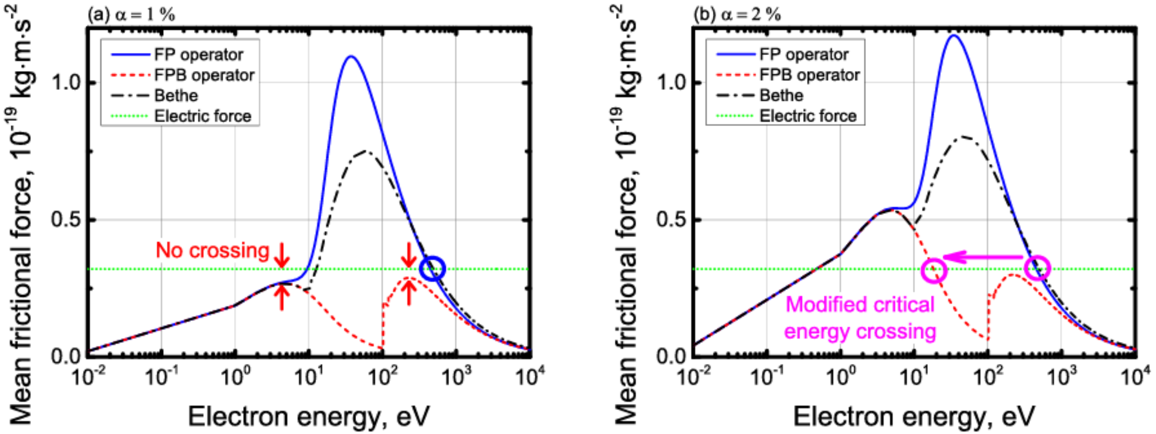


Improved understanding of startup runaway physics

- In early startup, runaway generation mechanism in non-diffusive.
  - The Fokker-Planck description severely underestimates the generation rate.
    - ➢ The effective critical momentum can be significantly reduced or even disappear.



Lee2024PRL



Lee2025arXiv

This implies $v_{RE} \ll c$ and thereby necessitates a mildly relativistic correction

Model development

Reduced kinetic model of mildly relativistic runaway electrons

Coupling with DYON

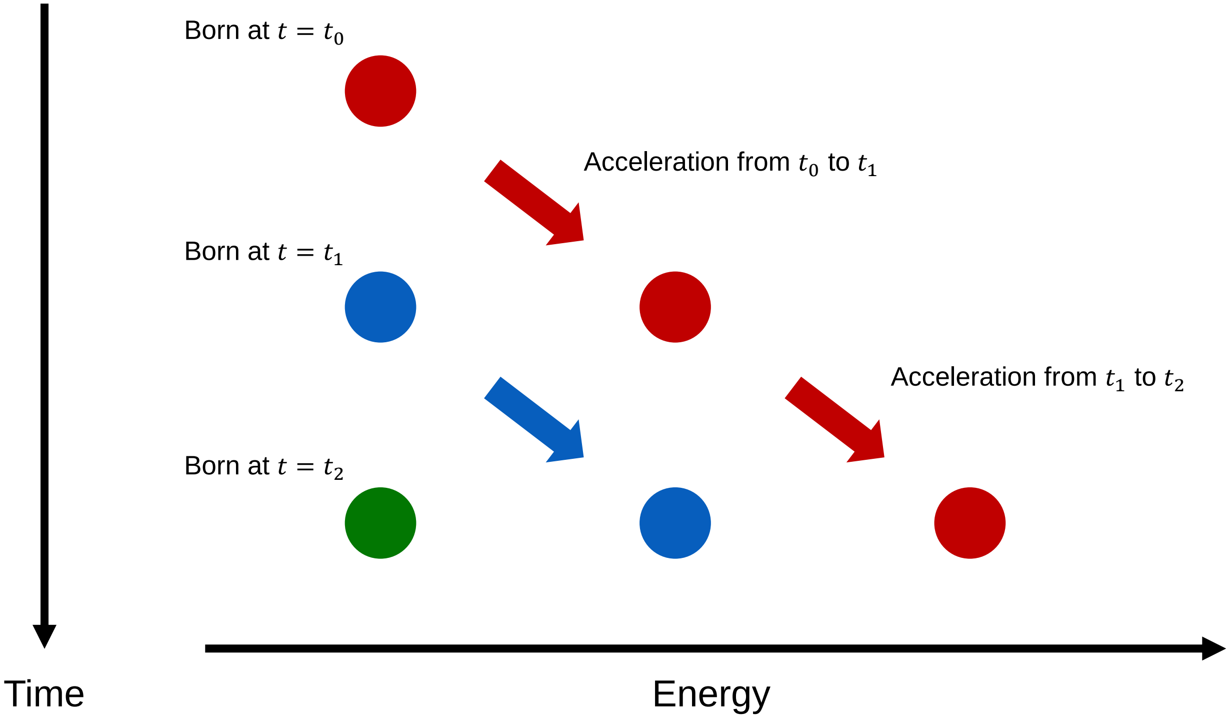
Multi fluid approximation of mildly relativistic runaway current

- Multi-fluid description of runaway electrons

$$t_0 = t_0$$

$$t_1 = t_0 + dt$$

$$t_2 = t_0 + 2dt$$



Multi fluid approximation of mildly relativistic runaway current

- The multi-fluid runaway model is consistent with the kinetic model.
  - The total runaway current density is "sum" of every runaway fluid currents

$$j_{RE,i+1} = ec \sum_{i' \leq i} dn_{RE,i'+\frac{1}{2}} \beta_{i'+\frac{1}{2}}(t_{i+1}),$$

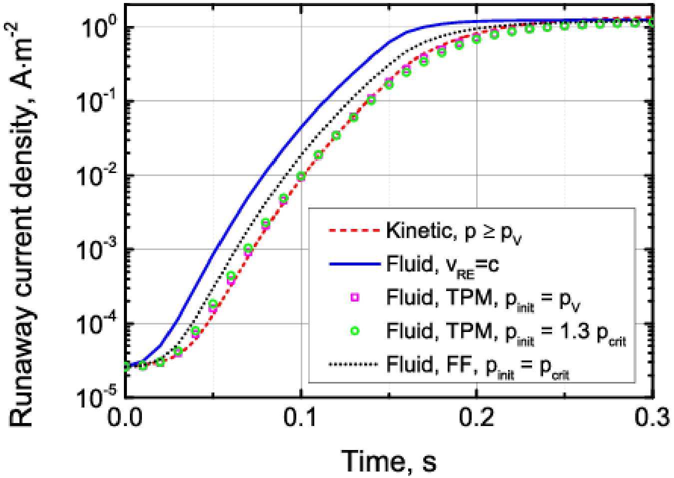
  - Fluid runaway velocity

$$\beta_{i'+\frac{1}{2}}(t_{i+1}) = \begin{cases} \beta_V \approx p_V & \text{if } i = i' \\ \beta_{i'+\frac{1}{2}}(t_i) + \boxed{(\frac{d\beta}{dt})_{i'+\frac{1}{2}}}(t_{i+1} - t_i) & \text{if } i > i' \end{cases}.$$

Seed velocity

Accelerated velocity

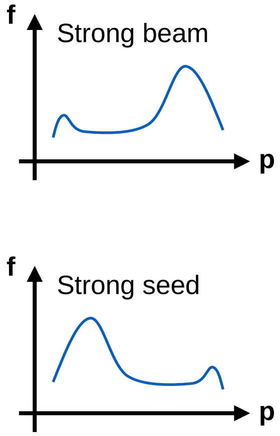
Test Particle Method (TPM)

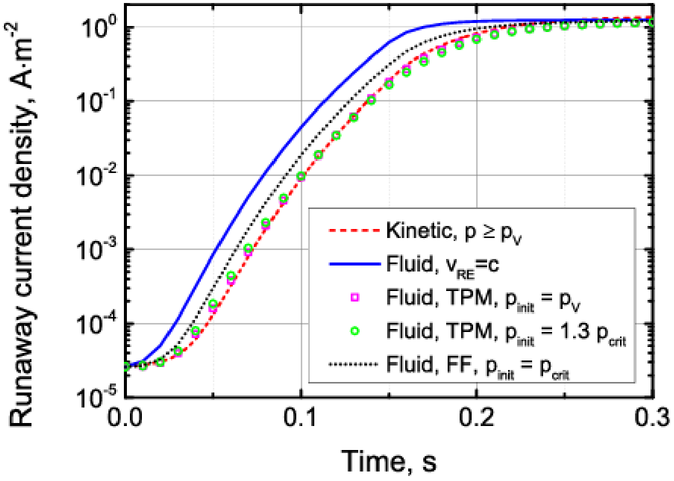


Successful verification !

Single fluid approximation of mildly relativistic runaway current

- Simple idea is to introduce the mean runaway velocity $\beta_{RE,i} \equiv \frac{j_{RE,i}}{ecn_{RE,i}}$
  - Runaway current density : $\frac{dj_{RE}}{dt} = ec\beta_V \frac{dn_{RE}^{seed}}{dt} + ec\frac{d\beta_{RE}}{dt} n_{RE}^{beam} + \ ...$
    - ➢ Single fluid model has comparable accuracy to multi-fluid free fall model.
  - Two critical asymptotes
    - ➢ When runaway seeding is weak
      - β_{RE} goes to runaway "beam" velocity.
    - ➢ When runaway seeding is strong
      - β_{RE} goes to runaway "seed" velocity.





Model development

Reduced kinetic model of mildly relativistic runaway electrons

Coupling with DYON

Transport features of runaway electrons during startup

- Runaway transport mechanism relies on magnetic configuration.

Closed field configuration

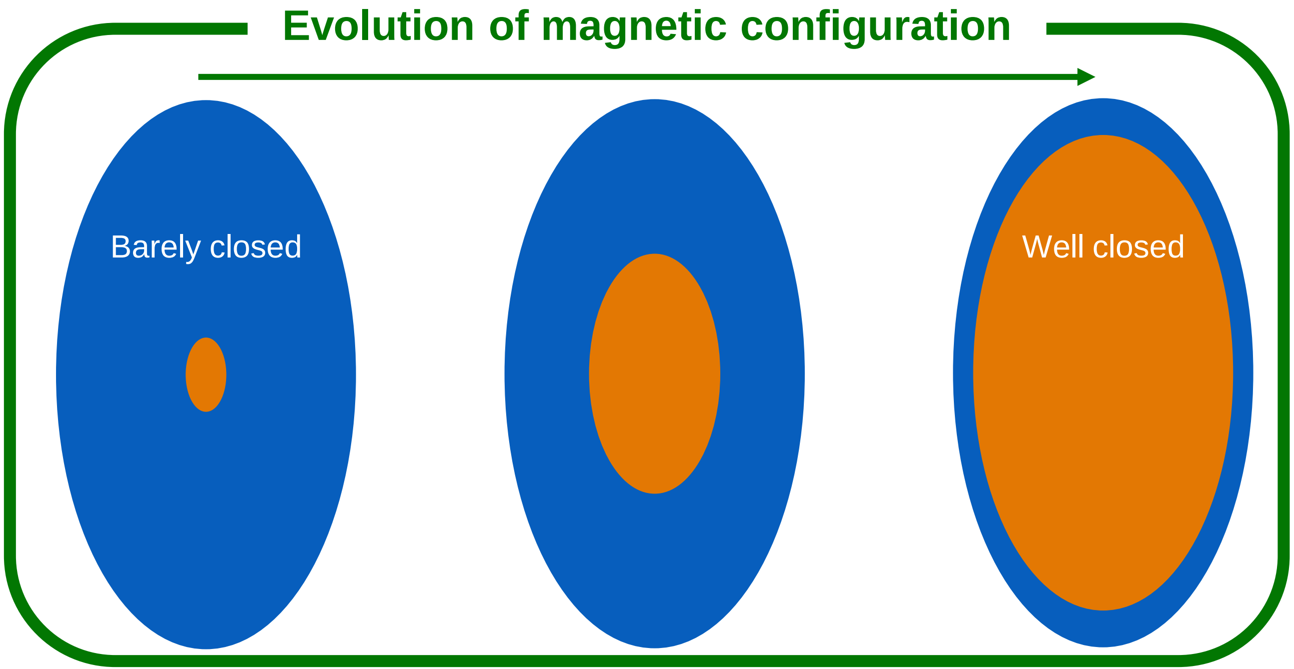
Radial stochastic transport

$$\tau_{RE} \propto \frac{a^2}{v_{RE}}$$

Open field configuration

Parallel streaming loss

$$\tau_{RE} \approx \frac{L}{v_{RE}}$$



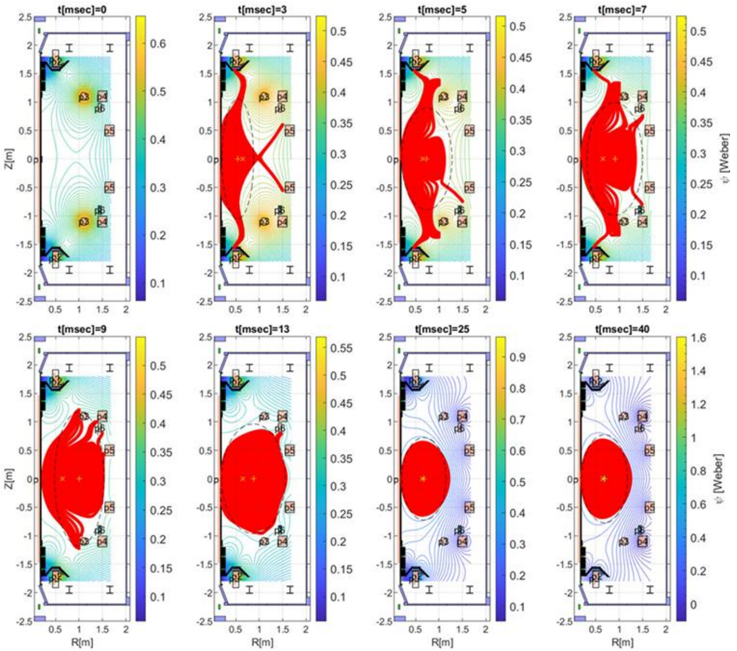
Need to be coupled with mildly relativistic runaway velocity $v_{RE} \neq c$!

Reliable startup design by multi-machine validated code, DYON

- Self-consistent coupling with DYON

- Key code features
  - Multi-machine validated code.
    - ➢ MAST-U, DIII-D, EAST, KSTAR, VEST
  - Unique approach for *model-based* description of magnetic configuration.
  - Minimize free parameters and reduce solution non-uniqueness.
    - ➢ Critical lesson from startup RE model validation in JET [deVries2025NF].

Regular oral talk on model validation
by H.-T. Kim et al
17th Oct, 11AM



Kim2022NF

Two macroscopic populations on dual magnetic configuration

- Describe species in closed (cl) and open (op) magnetic configurations
  - The particle-conserving evolution of runaway particle density

$$\frac{dn_{RE}^{cl}}{dt} = S_p^{cl} + (\gamma_{ava}^{cl,i} - \frac{1}{\tau_{RE,\perp}^{cl}})n_{RE}^{cl} - \boxed{n_{RE}^{cl}\frac{d}{dt}\log V_p^{cl},}$$

Particle-conserving correction

$$\frac{dn_{RE}^{op}}{dt} = S_p^{op} + (\gamma_{ava}^{op,i} - \frac{1}{\tau_{RE}^{op}})n_{RE}^{op} + \boxed{\frac{V_p^{cl}}{V_p^{op}}\frac{n_{RE}^{cl}}{\tau_{RE,\perp}^{cl}}} - \boxed{n_{RE}^{op}\frac{d}{dt}\log V_p^{op}.}$$

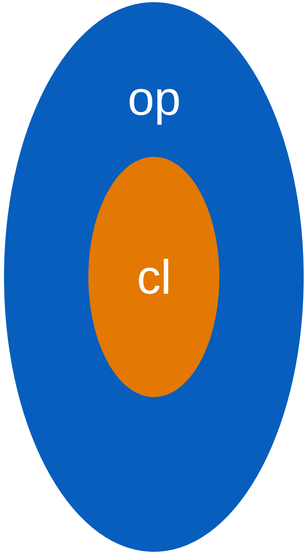
  - The momentum-conserving evolution of runaway current density

$$\frac{dj_{RE}^{cl}}{dt} = ecS_p^{cl}\beta_V^{cl} + (\gamma_{ava}^{cl} - \frac{1}{\tau_{RE,\perp}^{cl}})j_{RE}^{cl} + j_{RE}^{cl}\frac{d}{dt}\log\beta_{RE}^{cl} - \boxed{j_{RE}^{cl}\frac{d}{dt}\log V_p^{cl},}$$

Momentum-conserving correction

$$\frac{dj_{RE}^{op}}{dt} = ecS_p^{op}\beta_V^{op} + (\gamma_{ava}^{op} - \frac{1}{\tau_{RE}^{op}})j_{RE}^{op} + j_{RE}^{op}\frac{d}{dt}\log\beta_{RE}^{op} + \boxed{\frac{V_p^{cl}}{V_p^{op}}\frac{j_{RE}^{cl}}{\tau_{RE,\perp}^{cl}}} - \boxed{j_{RE}^{op}\frac{d}{dt}\log V_p^{op}.}$$

Transport from closed to open field region



S_p : Primary generation rate
γ_{ava} : Runaway avalanche growth rate
τ_{RE} : Runaway confinement time
V_p : Plasma volume

Self-consistent coupling with DYON

- Self-consistent *runaway current* evolution

Amended circuit equations

$$\frac{dI_p}{dt} = \frac{1}{L_p}\Big(V_{loop} - R_p(I_p - I_{RE}^{op} - I_{RE}^{cl}) - \frac{dL_p}{dt}I_p\Big),$$

$$\frac{dI_{RE}^{cl}}{dt} = ecA^{cl}S_p^{cl}\beta_V^{cl} + I_{RE}^{cl}\frac{d}{dt}\log\beta_{RE}^{cl} + (\gamma_{ava}^{cl,j} - \frac{1}{\tau_{RE,\perp}^{cl}})I_{RE}^{cl},$$

$$\frac{dI_{RE}^{op}}{dt} = ecA^{op}S_p^{op}\beta_V^{op} + (\gamma_{ava}^{op} - \frac{1}{\tau_{RE}^{op}})I_{RE}^{op} + I_{RE}^{op}\frac{d}{dt}\log\beta_{RE}^{op} + \frac{R^{cl}}{R^{op}}\frac{I_{RE}^{cl}}{\tau_{RE,\perp}^{cl}}.$$

Dominant balancing

$$n_{RE}^{op} \approx S_p^{op}\tau_{RE,\parallel}^{op},$$

$$I_{RE}^{op} \approx ecA^{op}S_p^{op}\beta_V^{op}\tau_{RE,\parallel}^{op},$$

- Self-consistent *runaway confinement* on dual magnetic configurations

$$\tau_{RE,\parallel}^{op} \approx \frac{< L_{op} >}{v_{RE}^{op}}$$

DYON model

Runaway model

$$\tau_{RE,\perp}^{cl} \approx c\frac{a_{cl}^2\tilde{b}_r^2}{2\pi R_0 v_{RE}^{cl}B_\phi^2}$$

$$\tau_{RE}^{cl} \approx \tau_{RE,\perp}^{cl},$$

$$(\tau_{RE}^{op})^{-1} \approx (\tau_{RE,\perp}^{op})^{-1} + (\tau_{RE,\parallel}^{op})^{-1}$$

Model validation

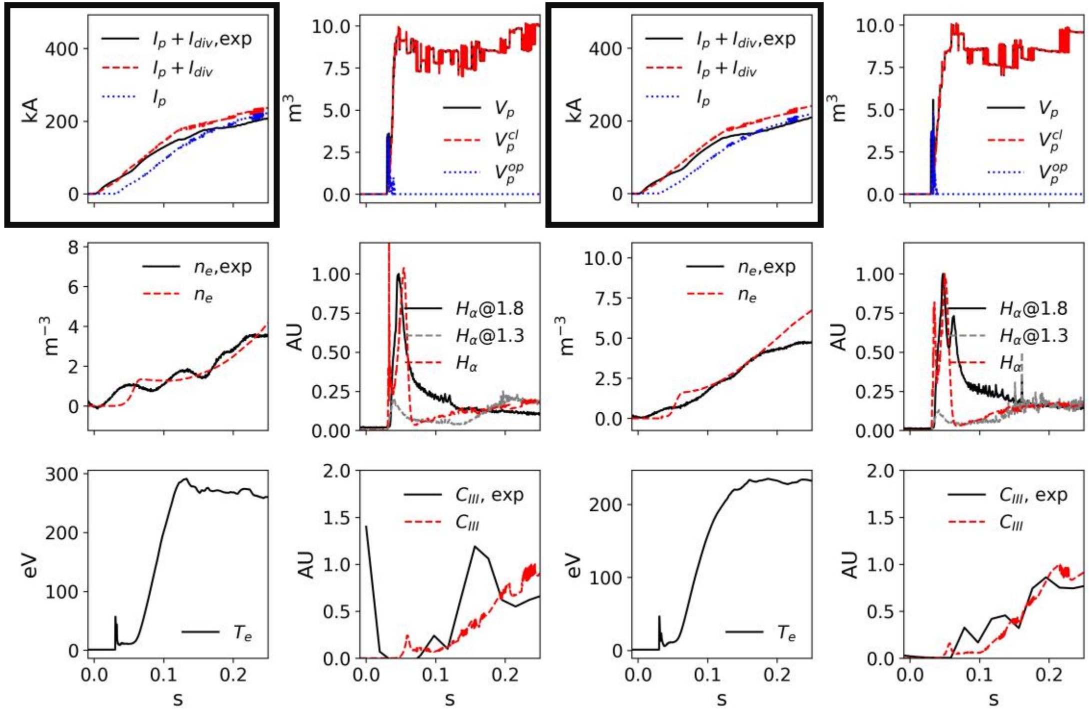
Validation in KSTAR ohmic startup

Validation of DYON-RE in KSTAR Ohmic startup

- Reliable prediction of plasma parameters by coupled DYON-RE

26031 (RE rich)

27340 (RE scarce)



1. **Measured rogoski coil current agrees with synthetic signal ($I_p + I_{div}$)**
2. Measured line-averaged electron density agrees with synthetic averaged electron density (n_e)
3. Measured line missions agree with synthetic line emission intensity (H_α, C_{III})
   * Indirect Te validation

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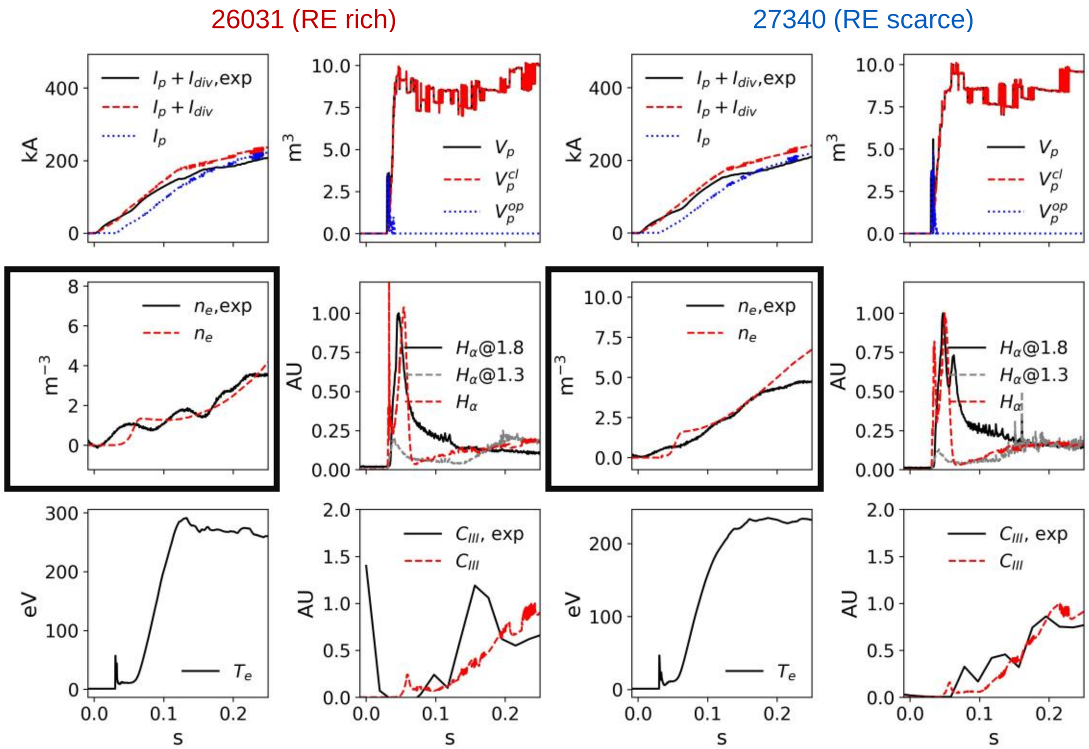

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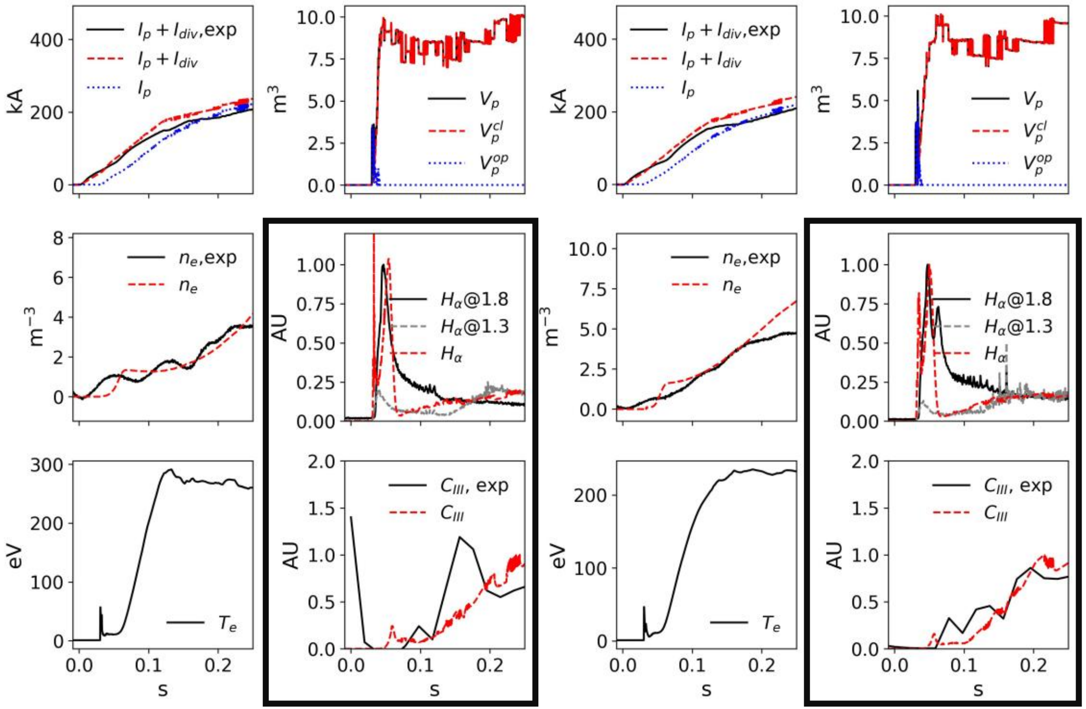

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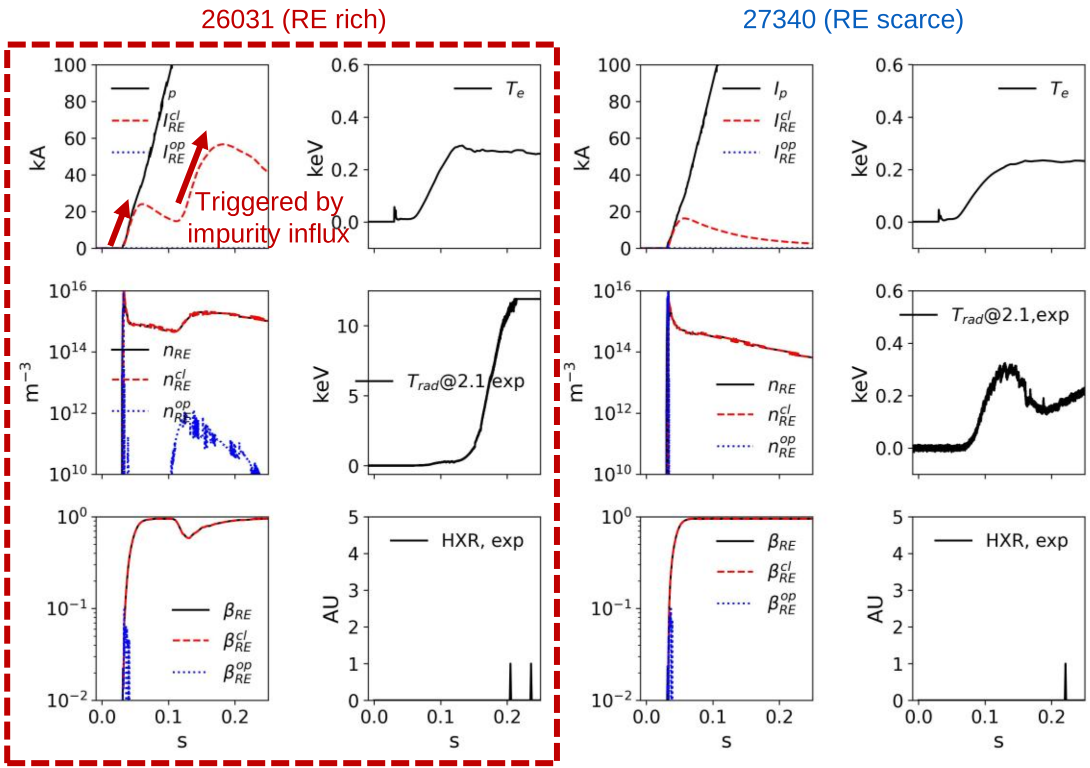
Validation of DYON-RE in KSTAR Ohmic startup

- Qualitative validation of runaway signatures



In RE rich discharge,

- Two-stage runaway generations are observed. 2nd stage trigger is impurity influx.
- Strong runaway seeding (~ t=0.1 s) triggers anomalous increase in nonthermal ECE radiation (> 12 keV [exp] $\gg 0.25$ keV [DYON]).
- During strong runaway production, mildly relativistic correction renders $\beta < 1$.
- Note that highly relativistic runaway electrons do not satisfy the resonance condition so can't explain the anomalous increase.

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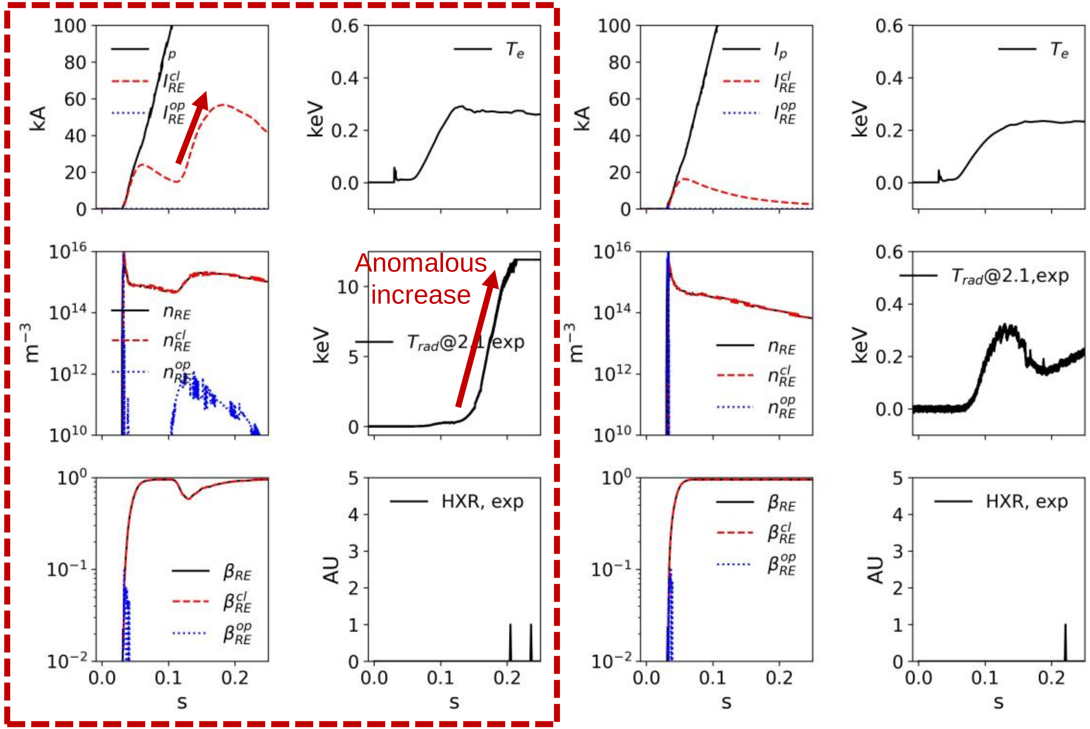

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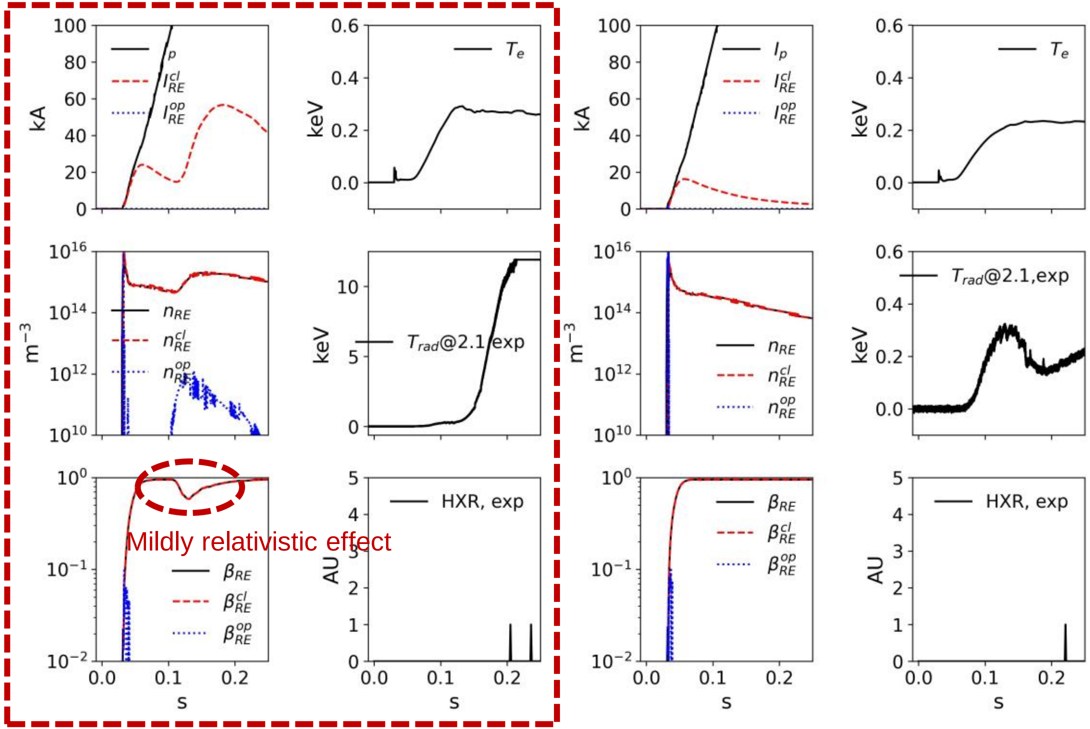

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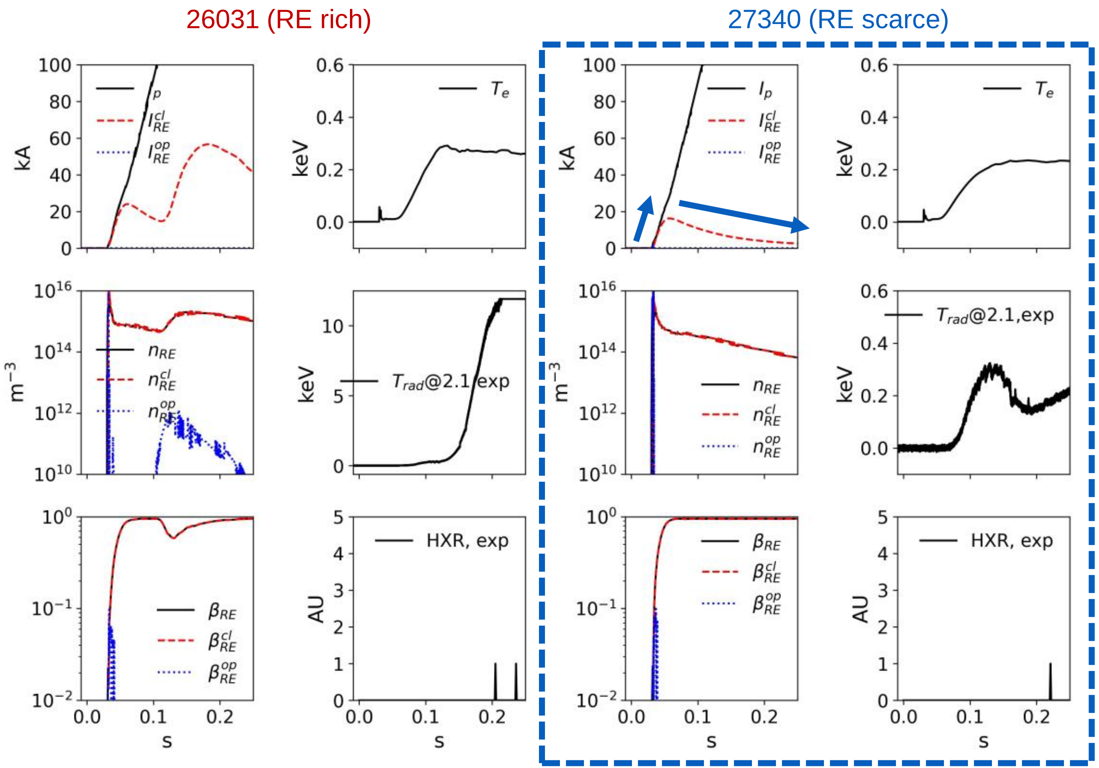
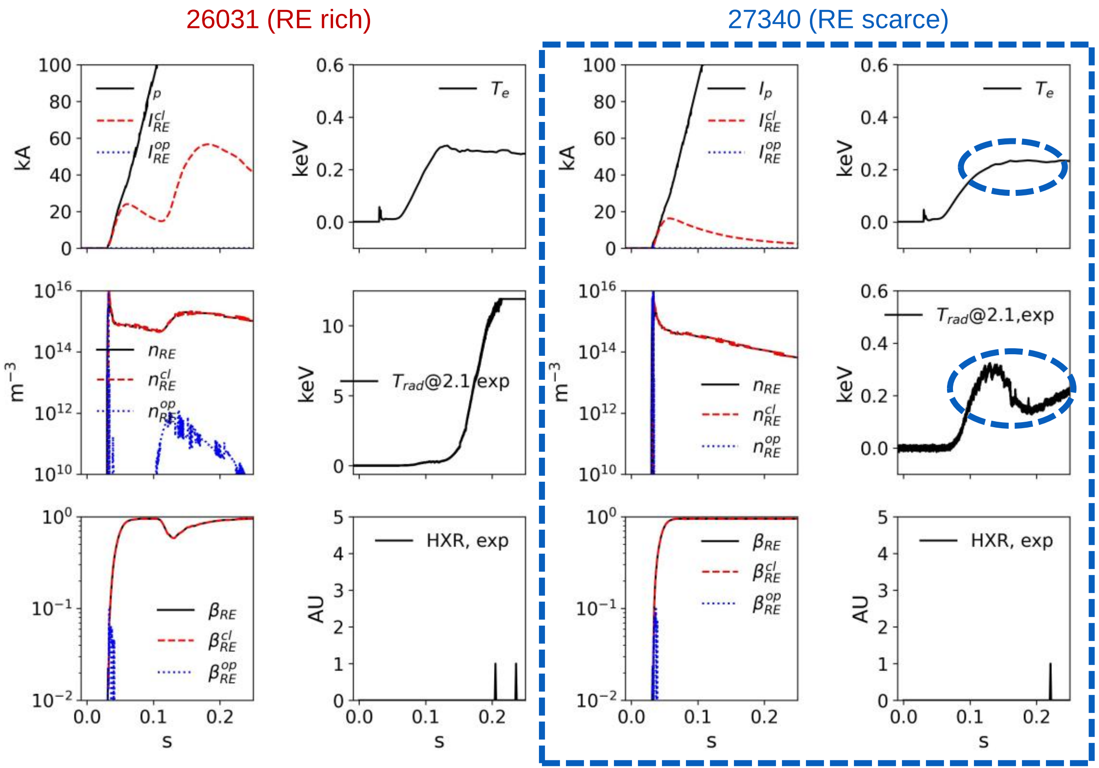


In RE scarce discharge,

- Strong startup runaway seed forms (~ 20 kA) and decays.
- Electron temperature (~ 0.23 keV) has a comparable order to measured ECE intensity (0.2 ~ 0.3 keV).
- DYON prediction suggested kinetic instability is triggered by runaway beam but stabilized due to their deconfinement.

Validation of DYON-RE in KSTAR Ohmic startup

- Qualitative validation of runaway signatures



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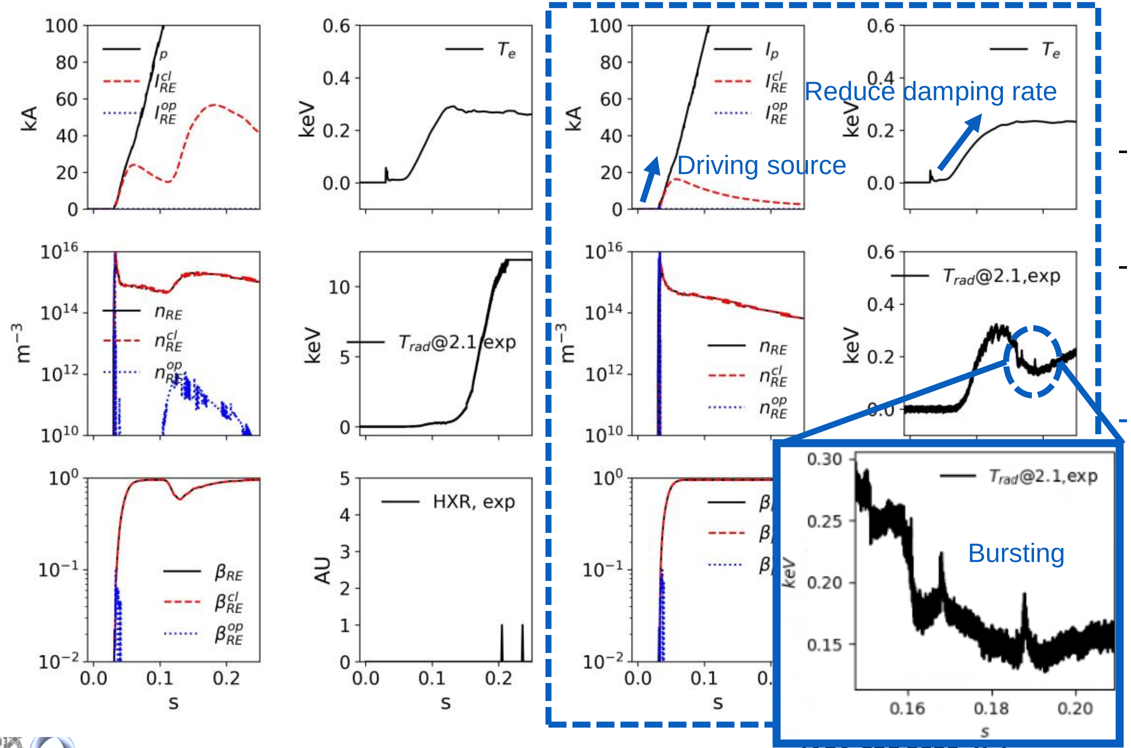

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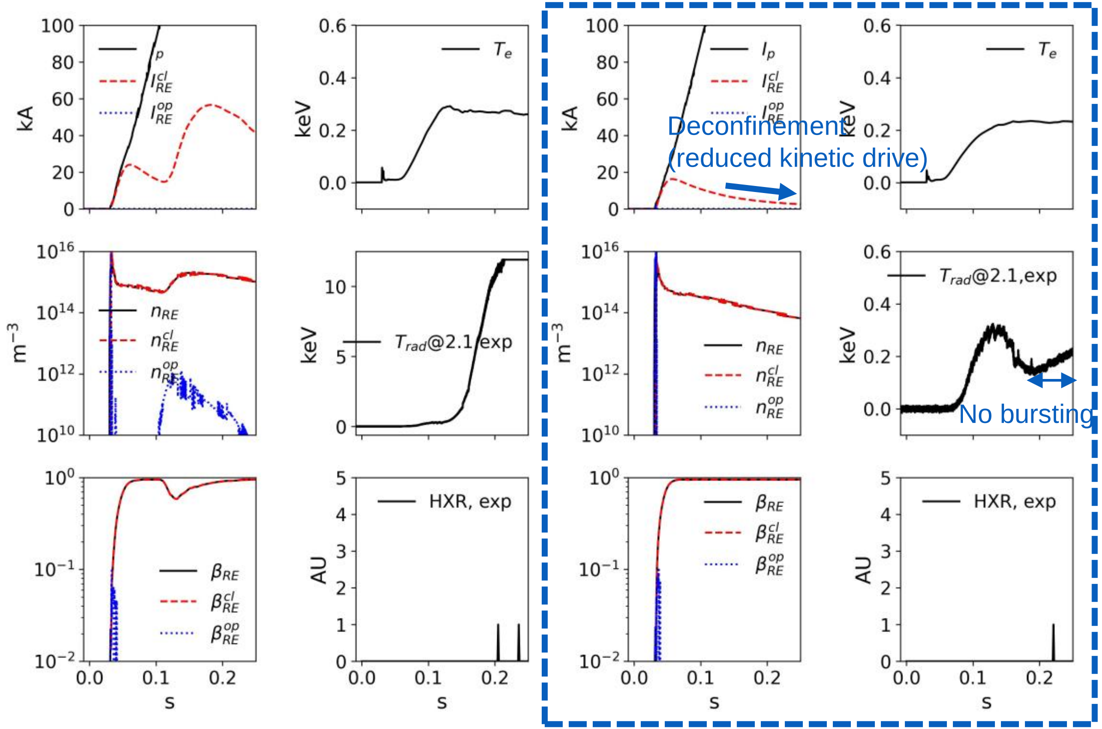

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Conclusions

- Lay physical and engineering foundation of designing a RE-free scenario in future fusion reactors
  - Model development of reduced startup runaway model
    - **Single fluid model** with non-light-speed velocity $v_{RE} \neq c$
      - No overestimation in **runaway current density**
      - No underestimation in **runaway confinement time**.
    - **Self-consistent coupling** with reliable startup code DYON.
  - Model validation in KSTAR Ohmic startup
    - In RE rich shot,
      - Timing of strong runaway seed formation coincides with that of anomalous increase in non-thermal ECE intensity.
    - In RE scarce shot,
      - Measured ECE intensity is comparable to DYON's electron temperature.
      - Bursting characteristics in ECE intensity is consistent with formation and loss of runaway beam.