Assimilation of deuterium into relativistic runaway electron beams and the implications for benign terminations in present devices, ITER, and future devices

by

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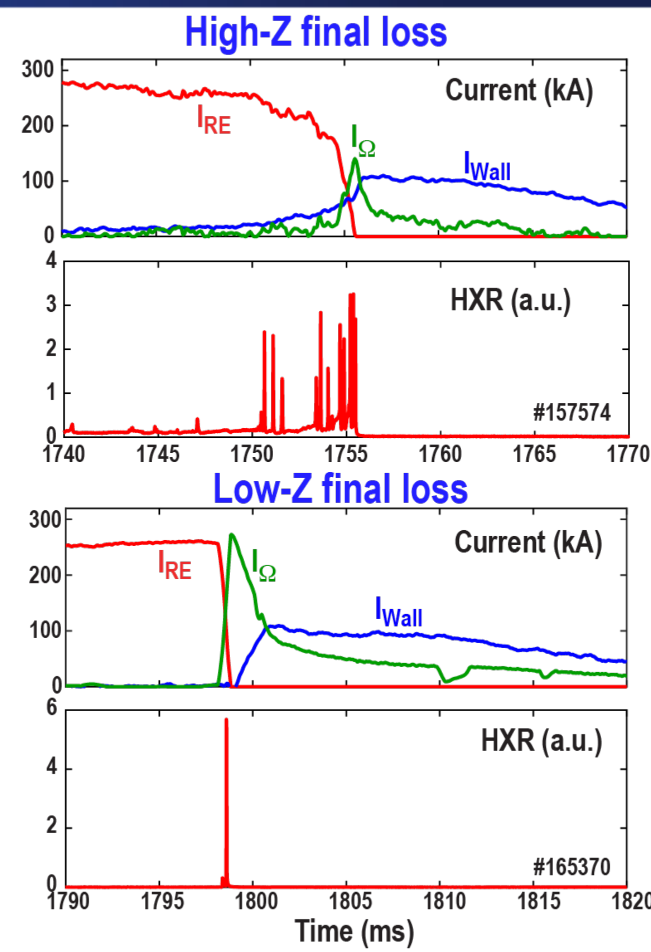
Outline

- **Motivation** – why are we interested in deuterium assimilation into runaway electron (RE) plateaus?
- **Overview** – quick overview of present data on RE plateaus
- **1D diffusion model** – trying to model deuterium assimilation in present devices
- **Predictions for ITER**
- **Predictions for some other future devices (SPARC and STEP)**
- **Future work**

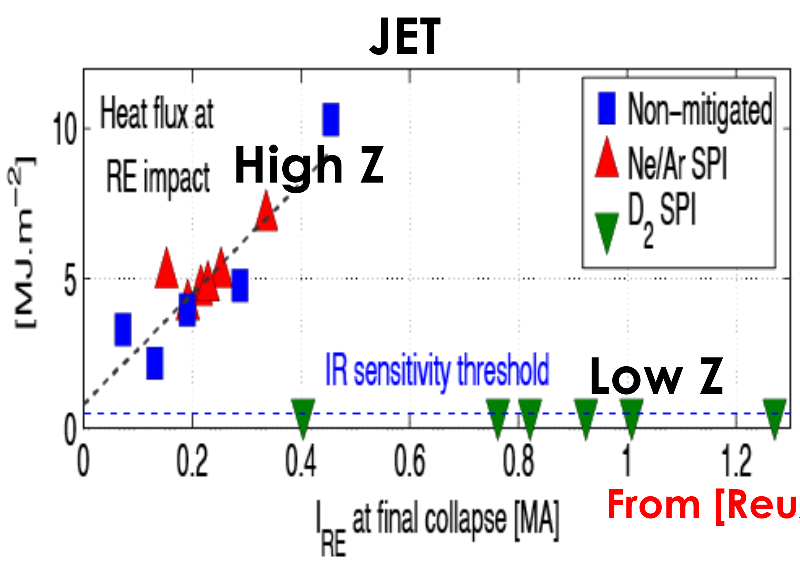
Motivation (1/2): Low-Z RE plateaus formed by massive D_2 injection tend to have low conversion of magnetic to kinetic energy

- Massive D_2 injection ”purges” high-Z impurities out of RE plateau.
- Resulting low-Z RE plateau has very fast, high-growth rate final loss MHD instability.
- Often, all REs lost to wall in single large instability.
- RE current all converted to thermal plasma (Ohmic) current.
  - Very little conversion of magnetic to kinetic energy.
- For high-Z final loss, many small instabilities cause longer loss process.
  - Significant conversion of magnetic energy into kinetic energy.

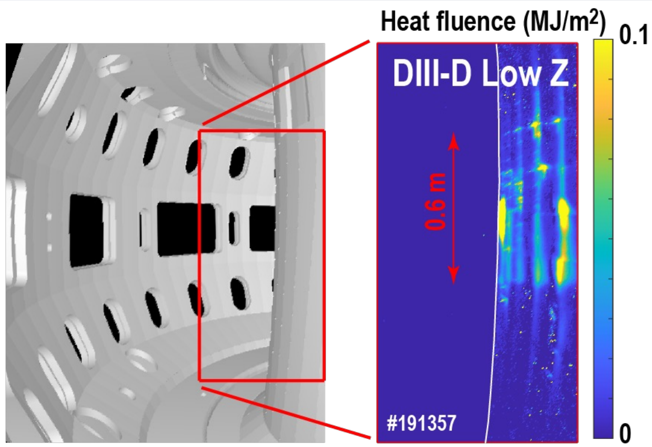


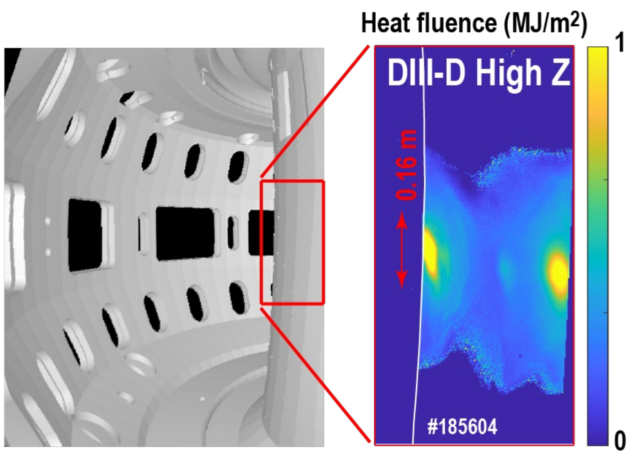
Motivation (2/2): Low-Z RE plateaus formed by massive D_2 injection appear to have large wetted area when hitting wall

- **Low Z RE plateau has very fast, high-growth rate final loss MHD instability.**
- **RE wetted area very large, giving low heat fluence.**
- **Observed in many machines (JET, DIII-D, TCV, ASDEX).**



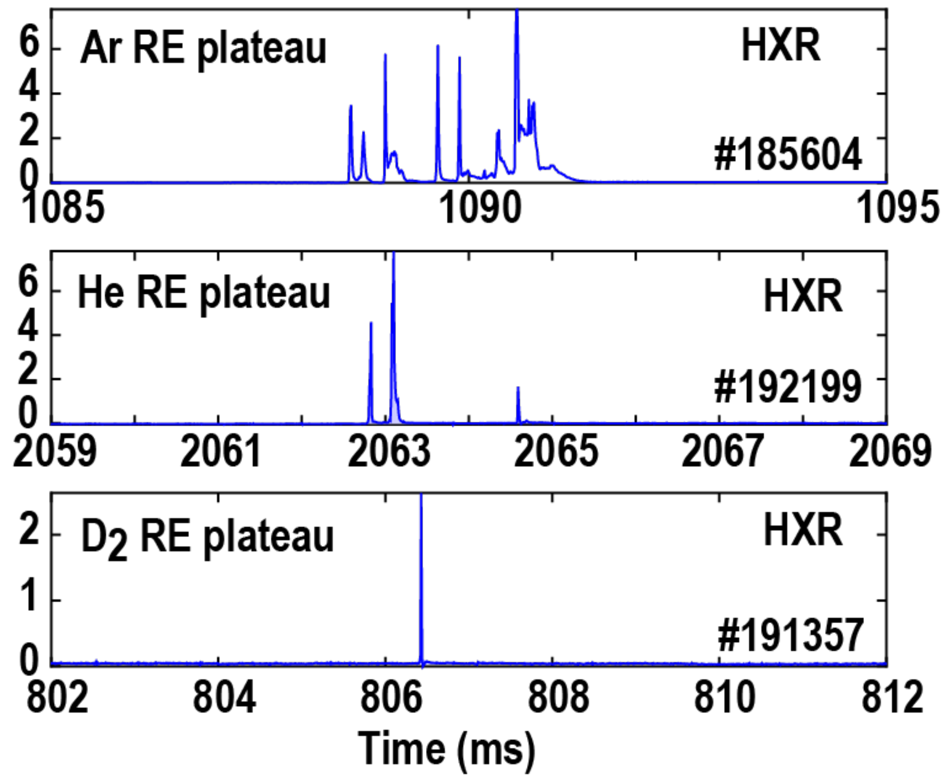
From [Reux, 2021]





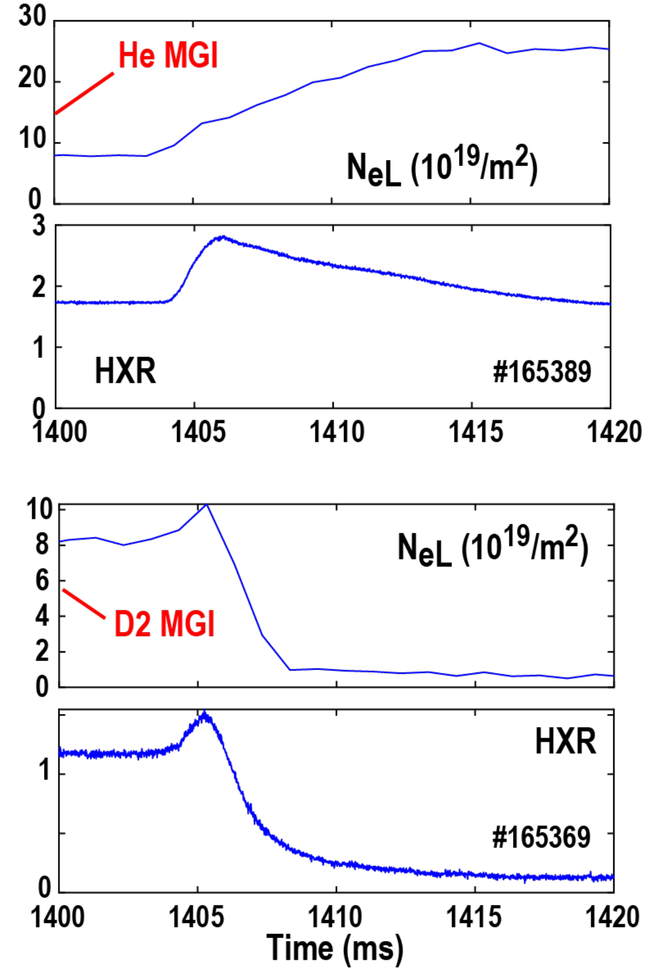
Even helium gas does not give single loss event - something special about D_2?

- **Large helium injection does not usually give single loss event.**
- **Usually only observed after massive H_2 or D_2 injection.**



Special effect of D_2 thought to be linked to volume recombination

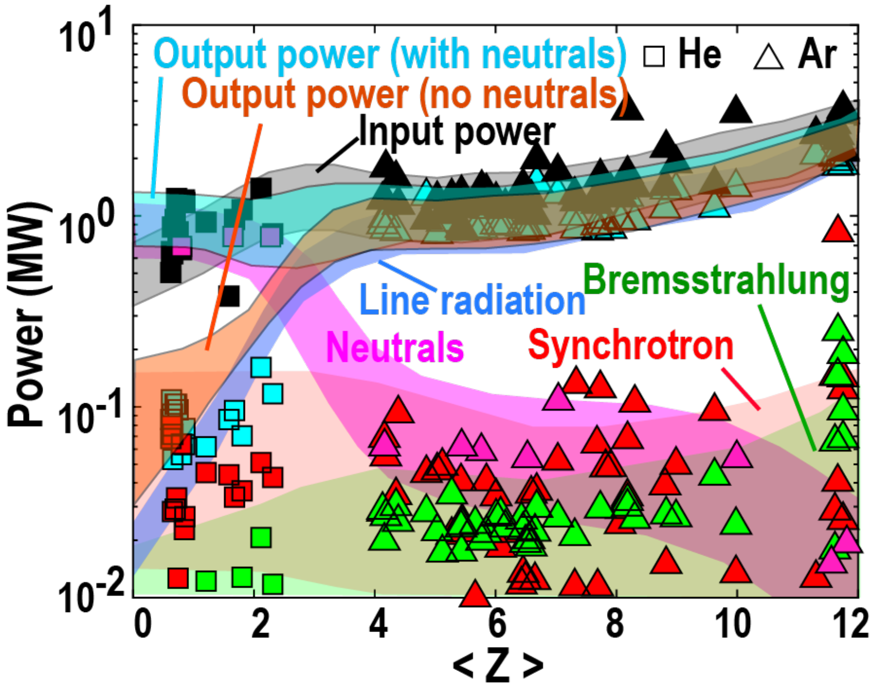
- **He MGI causes rise in thermal electron density and slight drop in HXR level.**
  - **- Partial expulsion of high-Z (Ar) impurities out of core**
- **D_2 MGI causes large drop in thermal electron density and large drop in HXR level.**
  - **- Large expulsion of high-Z impurities out of core**



Neutrals play major role in cooling RE plateaus at low Z (applies to both He and D_2)

- **At high Z, input power mostly balanced by line radiation.**
- **At low Z, neutral cooling begins to dominate.**
  - **- Cannot model low-Z RE plateaus without considering neutrals!**

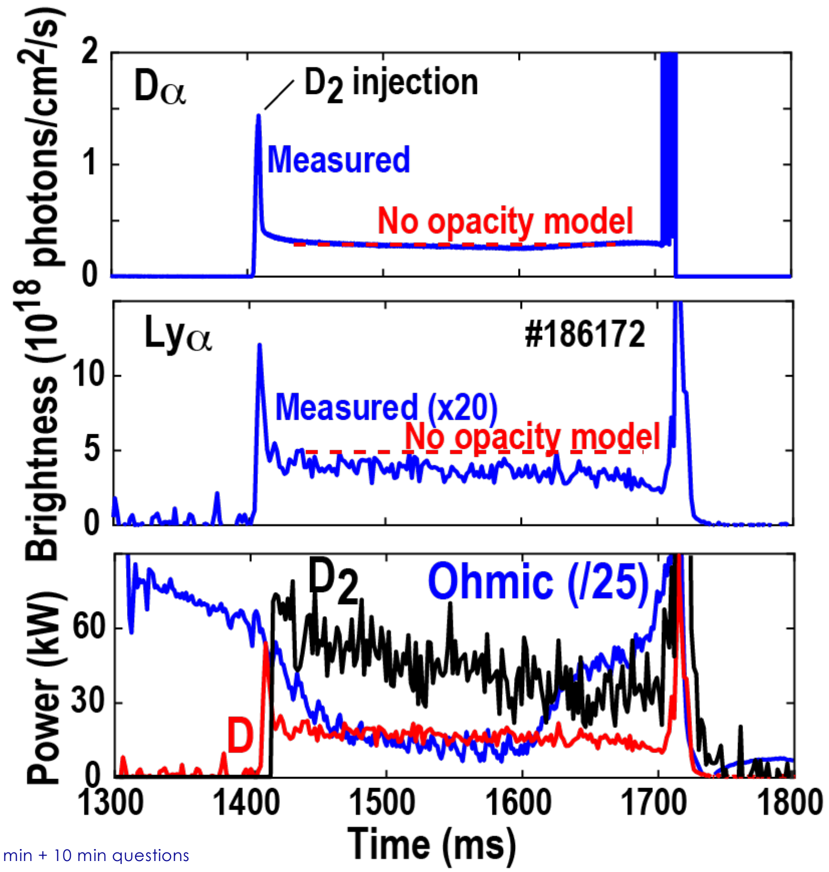
DIII-D RE plateau power balance



For D_2 purged RE plateaus, line radiation is dominantly from D_2 lines – large molecule density!

- **Line radiation power is dominated by D_2 lines (Werner and Lyman bands).**
- **D present also but Ly-α strongly trapped (~20x).**
- **Molecules are present at significant levels in RE plateau and need to be included for accurate modeling.**

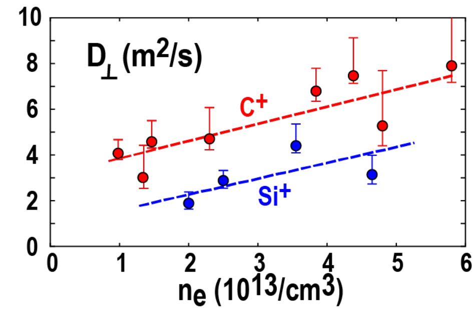
DIII-D D_2 purged RE plateau radiated power



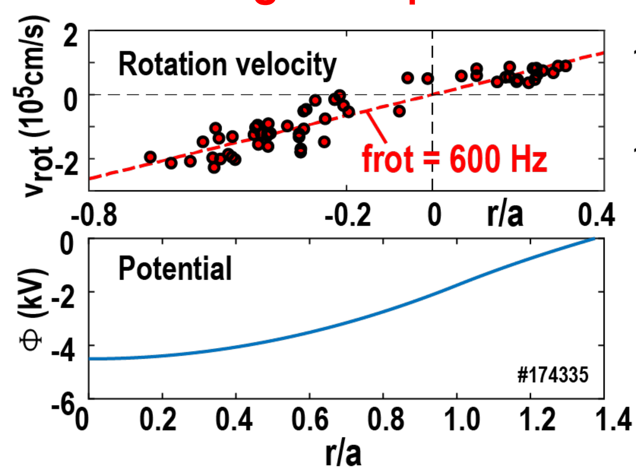
RE plateau cross-field ion transport of order few m^2/s

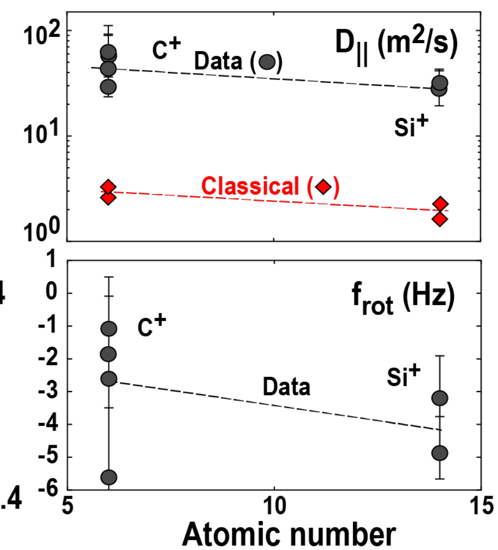
- Ion diffusion coefficients are larger than classical in both perp and para directions for high Z plateaus. $D_{i,perp}$ ~ 2 – 5 m^2/s.
- Toroidal ion rotation very slow ~ 2 – 5 Hz, poloidal rotation faster ~ 0.5 kHz.
- Measured for high Z only! Need to assume similar for low Z.

DIII-D high-Z RE plateaus



DIII-D high-Z RE plateaus

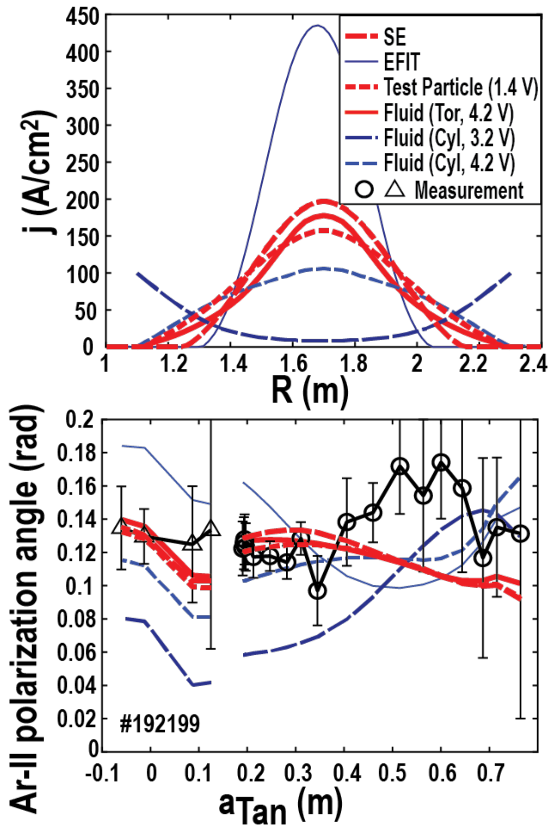




Current profile appears to be centrally peaked

- **Polarization angle of Ar-II line emission used to constrain current profile for low Z (He purged) RE plateaus.**
- **Consistent with slightly peaked current profile models (red curves).**
- **Has only been measured for medium Z (He-purged) RE plateau, not D_2 purged.**

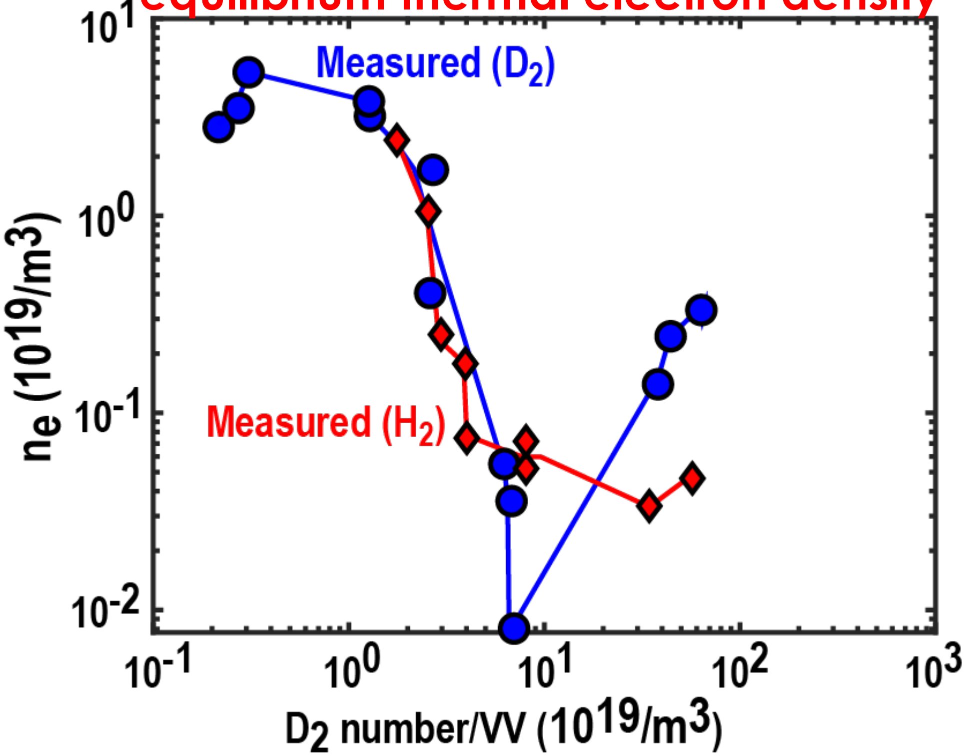
DIII-D low Z (He purge) RE plateaus



H_2 appears to behave fairly similar to D_2 on DIII-D

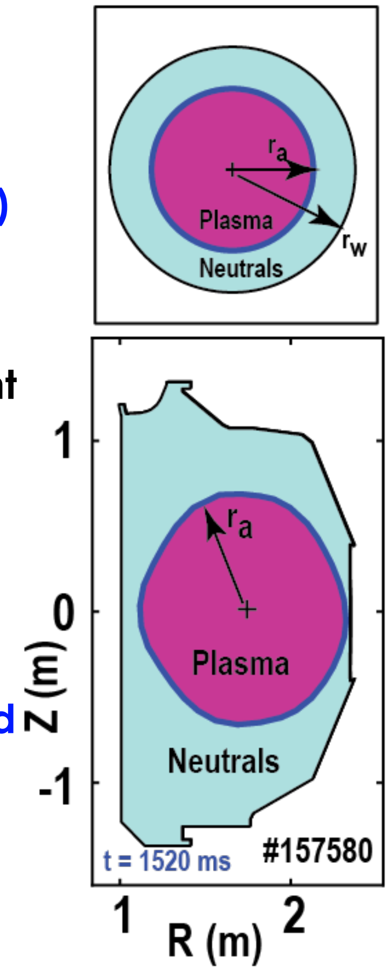
- **Do not have extensive data on H_2 vs D_2 yet on DIII-D or JET.**
  - **- Most existing data from TCV (see U. Sheikh presentation this conference)**
- **Available data does not show significant differences.**
  - **- Equilibrium n_e similar**
  - **- Recombination timescale similar.**

DIII-D D_2 or H_2 purged RE plateau equilibrium thermal electron density



1D impurity diffusion model

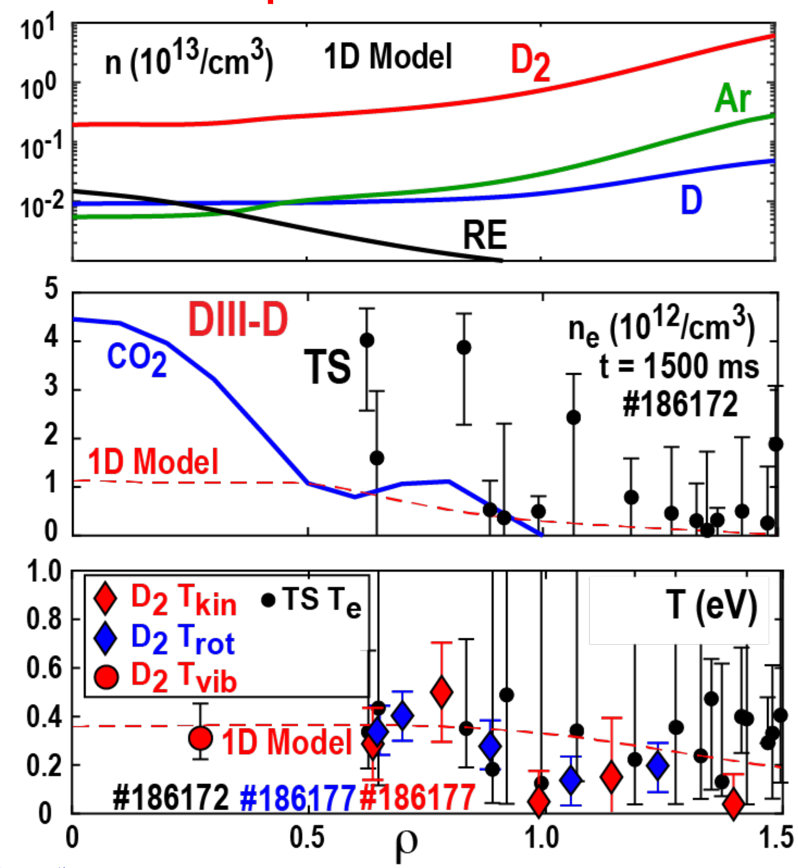
- Approximate actual 3D geometry with 1D cylindrical geometry.
  - REEs confined to some radius r_a, neutrals up to some radius r_w.
  - Estimate r_a from magnetic reconstructions.
  - Typically chose r_w to be halfway between r_a and r_{vv} (vacuum vessel radius)
- Ions diffuse radially at some prescribed diffusion coefficient D_i ~ 2 m^2/s.
- RE diffusion coefficient typically chosen small D_{RE} ~ 0.2 m^2/s.
- Neutrals diffuse radially with classical neutral diffusion with some enhancement factor D0 to account for convection cells.
  - Simulations suggest D0 ~ 3 [Frolov,2005] at low pressure. Matching data suggests D0 should be somewhat larger, D0 ~ 5 – 9.
- RE energy distribution modeled with test particle model.
- Loop voltage not modeled by full Ampere/Faraday + control system.
  - Input desired I_p and model tries to adjust loop voltage to match with limited slew rate (typically ~0.2 V/ms).
- D molecules D_2 included as well as molecular ions included up to D_3^+.



1D model able to capture measured T_e ~ 0.4 eV in low Z D_2 purged RE plateau

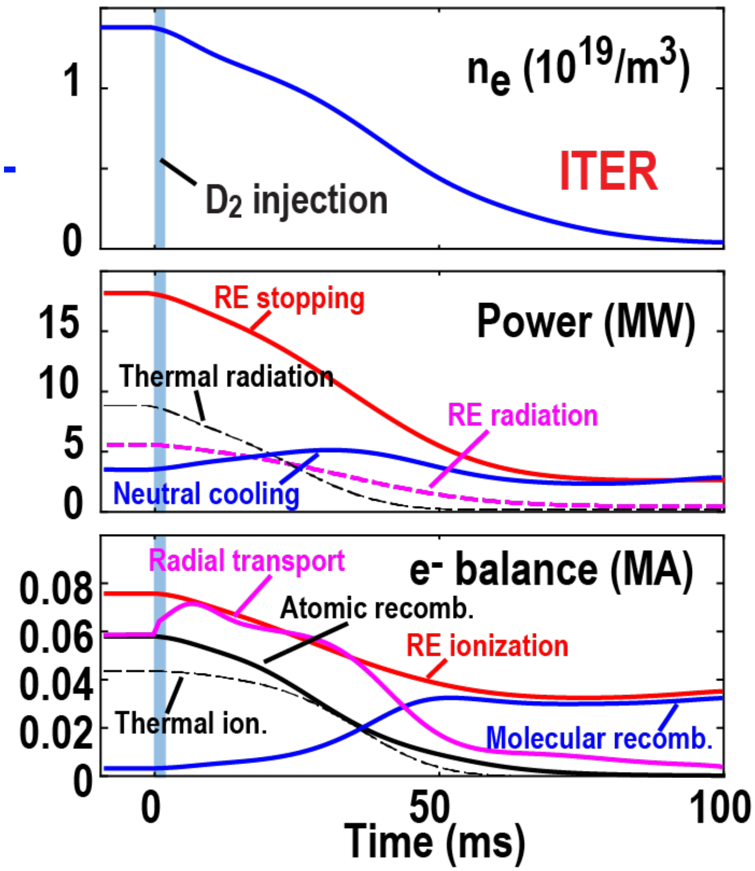
- Cold plasma in low Z RE plateau appears to be in thermal equilibrium with $T_e \sim T_i \sim T_{vib} \sim T_{rot} \sim T_{kin} \sim 0.4$ eV.
  - In agreement with 1D diffusion model.
- Electron density not always good match.
  - Can be varied by changing r_w .
- Dominant neutral species is D_2.
  - Comparable to cold electron density n_e
- High Z impurity (Ar) mostly in neutral form and mostly outside plasma.

DIII-D low Z (D_2 purged) RE plateaus



Power and particle balance change character dramatically when moving from high Z to low Z

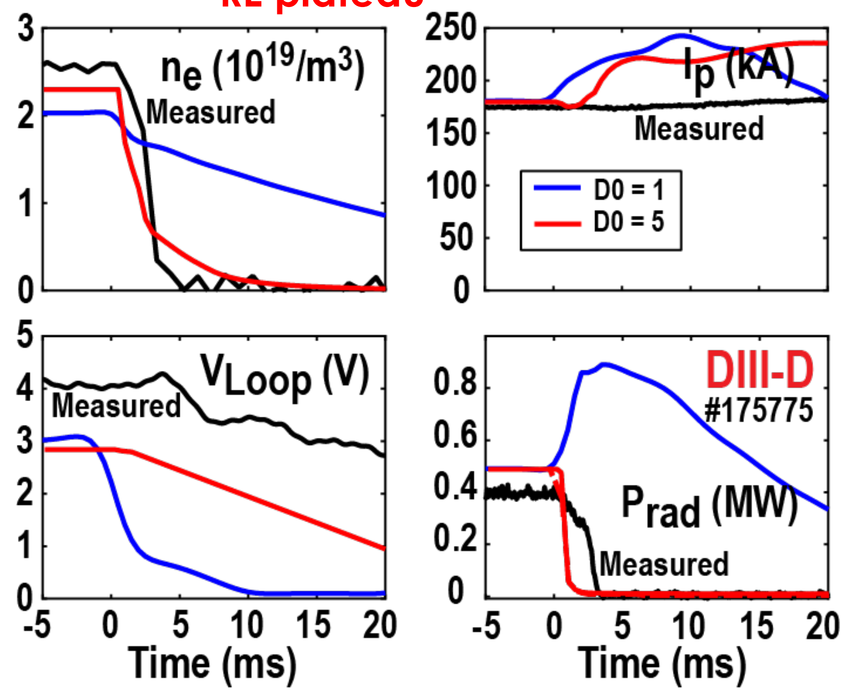
- 1D model of D_2 purge in ITER shown here.
  - Dominant processes predicted are similar in DIII-D or JET, but timescales different.
- Dominant power loss initially line radiation from thermal electron impact.
  - Shifts to neutral cooling after D_2 injection.
- Dominant free electron balance is RE impact ionization balanced with radial transport initially.
  - Shifts to RE impact ionization balanced by molecular recombination after D_2 injection.



Tuning neutral convection correction D0 in DIII-D – matching measured n_e decay rate gives factor D0 ~ 5

- **Decay rate of thermal electron density provides strong constraint on D0.**
- **In DIII-D, D0 ~ 5 gives reasonable match to measured ne decay rate.**
  - **- Use D0 = 5 as default value for this free parameter.**

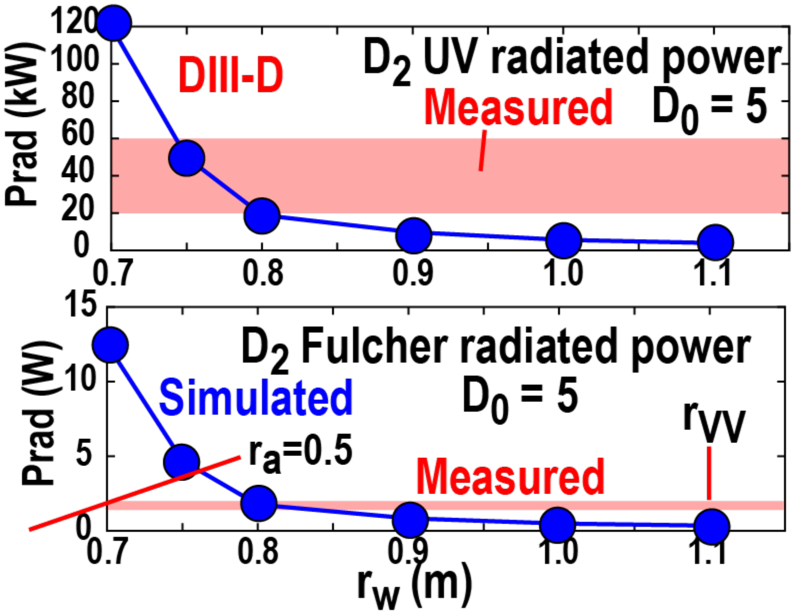
DIII-D low Z (D_2 purged) RE plateau



Tuning effective wall radius r_w: matching D_2 radiated power suggests using r_w halfway between r_p and r_{VV}

- r_w is free parameter which sets volume neutrals can occupy.
- In DIII-D, matching D_2 radiated power in purged RE plateaus gives r_w ~ 0.8 m.
  - This is halfway between r_a and r_{VV}.
  - Use halfway point as default.

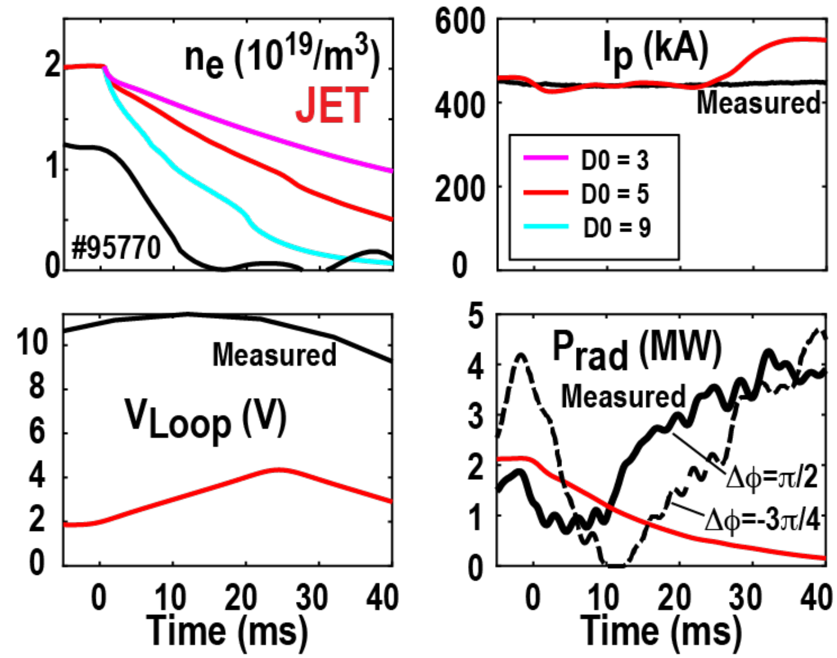
DIII-D low Z (D_2 purged) RE plateaus



Tuning D0 in JET – to match measured ne decay rate need to turn up neutral diffusion by factor D0 ~ 9.

- Default D0 = 5 appears to be too low to match observed n_e decay rate in JET.
  - D0 ~ 9 works better.
- Poor agreement with measured loop voltage in JET.
  - Usually within 2x in DIII-D.
  - Can be off by 5x in JET.
  - Still not resolved, maybe needs higher RE radial diffusion?
- Also, poor agreement with measured radiated power.
  - This has been resolved – instrumental artefact; effect of neutrals on JET bolometers (N. Schoonheere work).

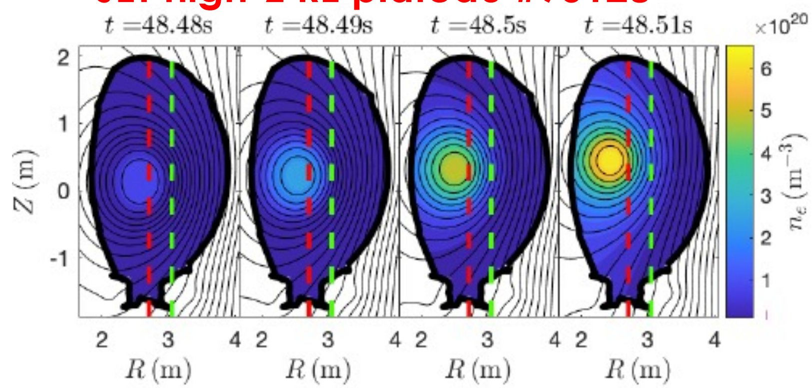
JET low Z (D_2 purged) RE plateaus



Matching high loop measured loop voltage in JET challenging for 1D model, even when decreasing r_w

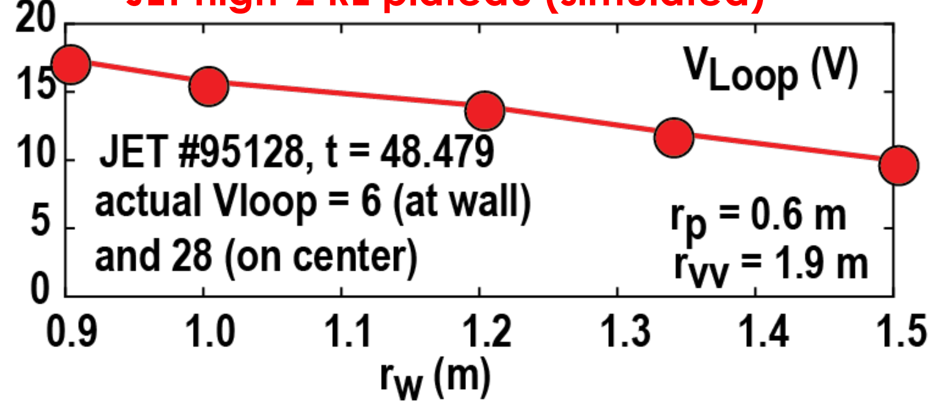
- Big difference with DIII-D cases – no position control.
  - DIII-D RE plateaus held steady on center with dI/dt = 0 until ready to study final loss.
  - JET RE plateaus scraping off against CP and have dI/dt < 0.
- For high-Z JET RE plateau, did scan of r_w.
- r_p = 0.6 m here and r_{vv} = 1.9 m, so nominal starting point is 1.2 m.
- Even going down to r_p = 0.9 m not giving central loop voltage of 28 V.
- Need to turn up RE radial transport?

JET high-Z RE plateau #95128



(courtesy of M. Beidler)

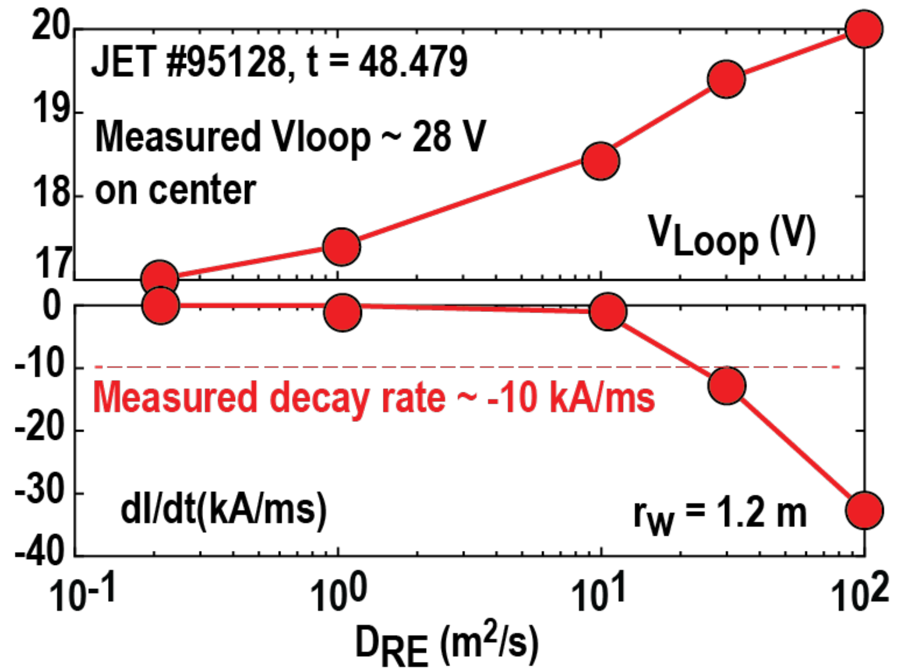
JET high-Z RE plateau (simulated)



JET current decay during RE plateau scrape-off suggests radial transport could be large in JET?

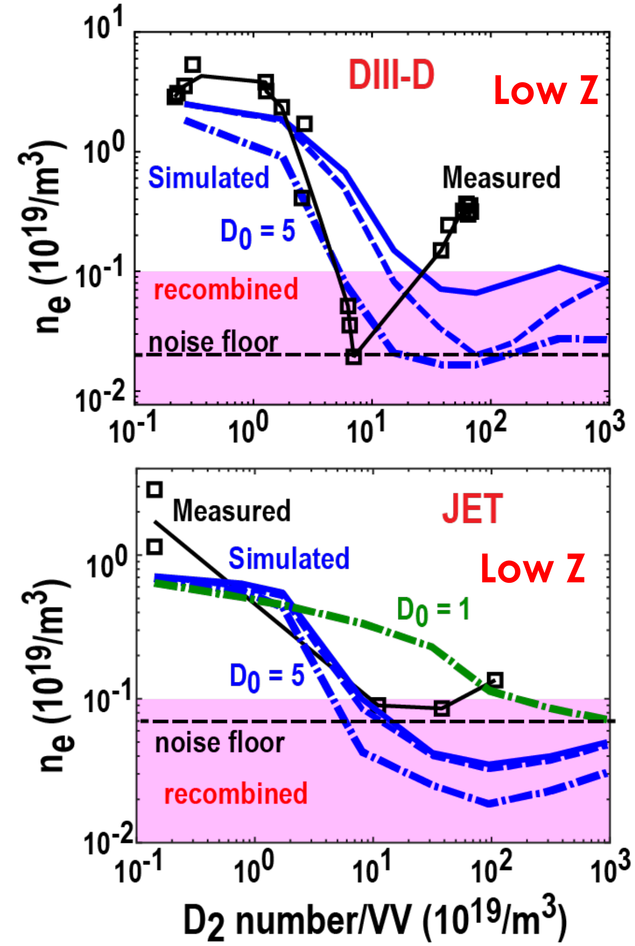
- **Matching high Vloop and large current decay in JET high-Z RE plateau challenging.**
- **By turning up D_{RE} to high values > 10 m^2/s, get get higher V_{loop}.**
- **Also, starting to get decaying I_p, just as observed in the experiment.**
- **Suggests that higher D_{RE} (not default low D_{RE} = 0.2 m^2/s) is more correct JET ?**

JET high-Z RE plateau (simulated)



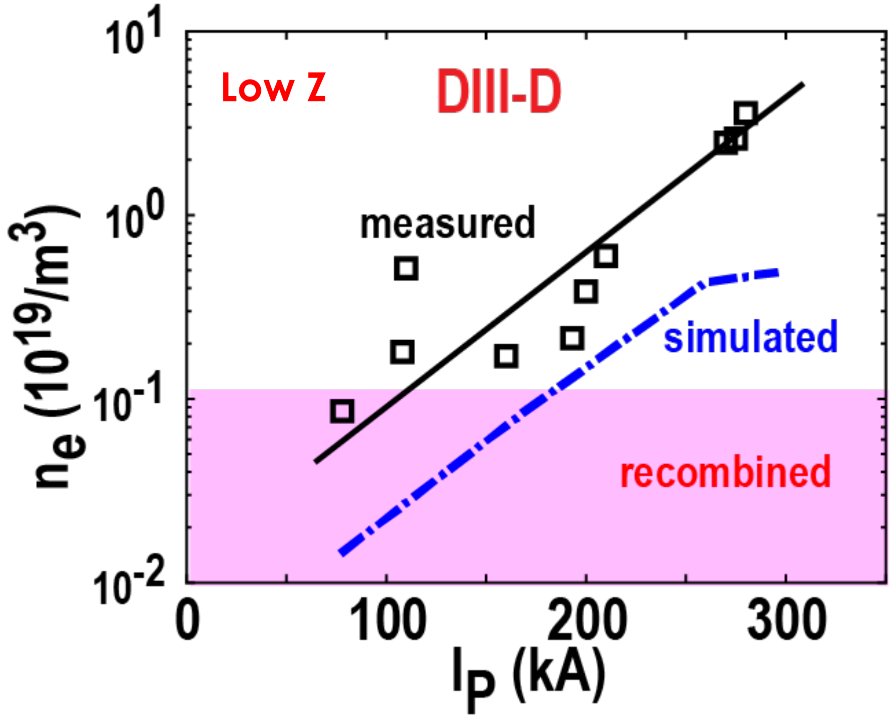
Partial recombination effect captured reasonably well by 1D model

- From now on, just keep "default" 1D model free parameters to keep things simple:
  - $r_w = (r_p + r_{VV})/2$
  - $D_{RE} = 0.2\ m^2/s$
  - $D_0 = 5$
- Can match equilibrium thermal n_e within 2x or so.
- Different blue curves are 1D model using different RE kinetic model approximations
  - Indicate uncertainty ~2x based on RE energy distribution.
- Define "recombined" as $n_e < 10^{18}/m^3$.
  - close to JET noise floor.
- Model not capturing observed "un-recombination" ("density limit") which happens at very high D_2 number.
  - Possibly due to D_0 dropping at higher D_2 density?



Observed recombination trend with I_p captured – harder to recombine as I_p is turned up

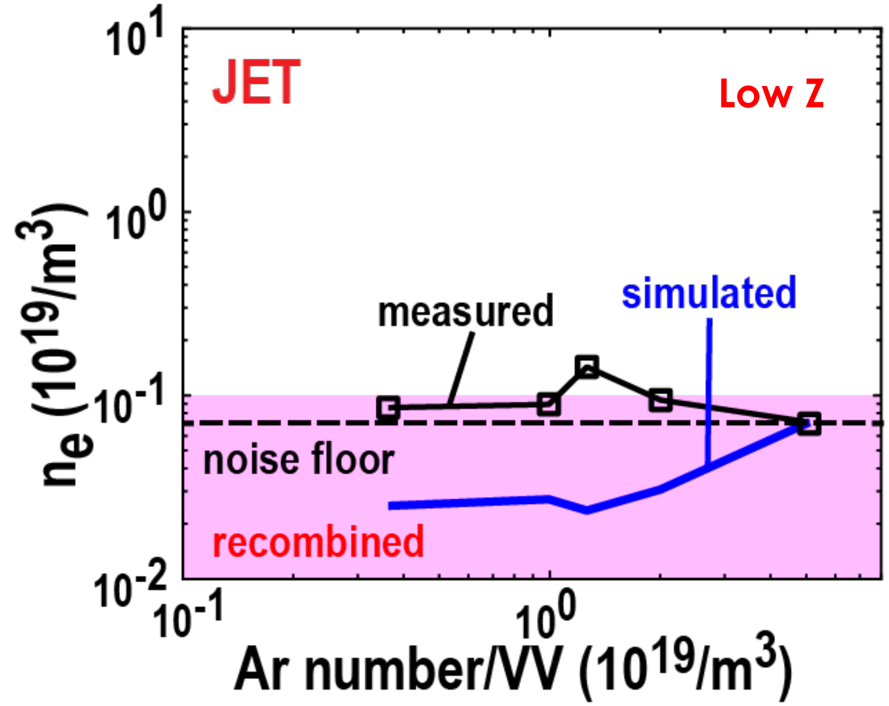
- Partial recombination is balance between RE + neutral ionization vs molecular ion recombination.
- Turning up Ip = turning up RE ionization source term, causing increase in n_e.
- This trend is seen experimentally, and trend is also captured in 1D model.



High Z impurity content not critical (as long as small compared with D_2 number)

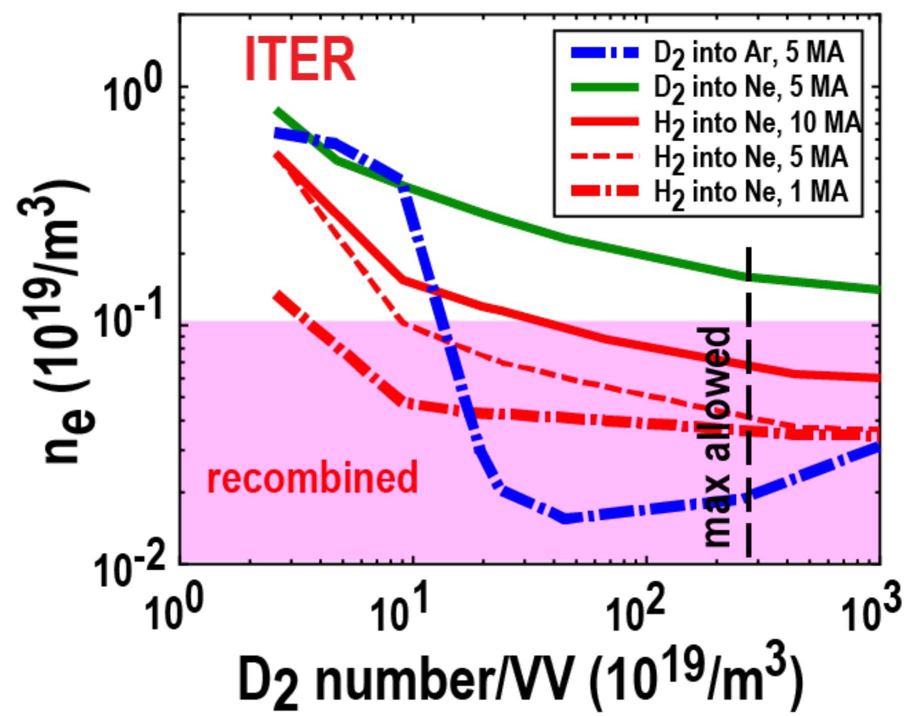
- **In experiments, injected D_2 number is typically much larger than Ar number.**

- **JET experiments changed Ar number in vacuum vessel.**
  - **- See little effect on equilibrium n_e.**
  - **- Lack of trend roughly captured by 1D model.**



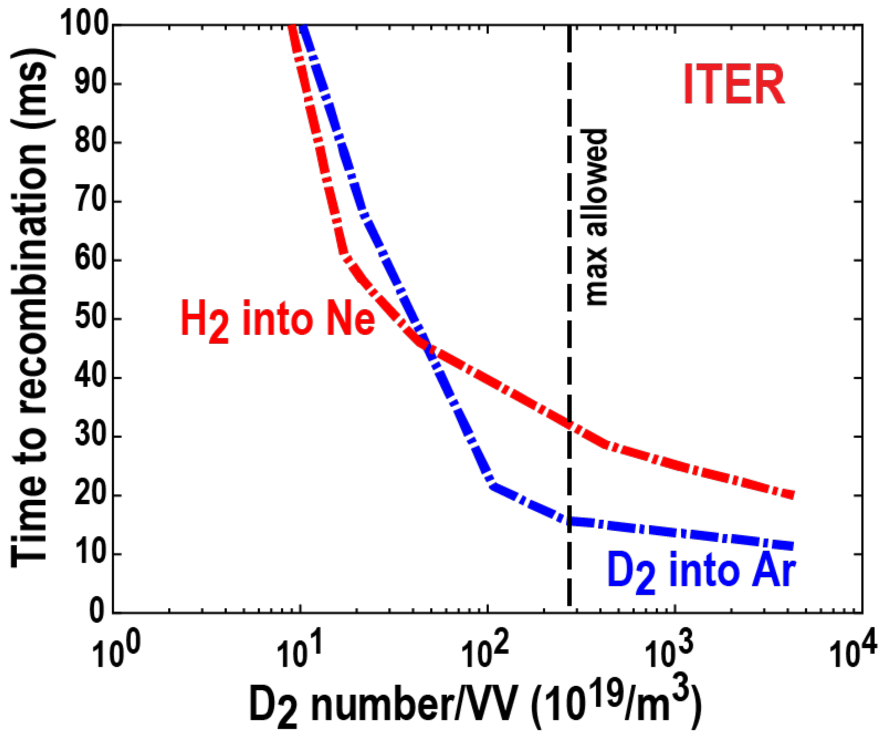
ITER simulations: should be able to reach recombined state in ITER

- For ITER, expect some neon already in plasma for TQ and CQ mitigation ("1st injection").
- Then fire in H_2 as "2nd injection".
- 1D model predicts Ne plasma harder to recombine than Ar plasma.
  - Due to lower molecular recombination via NeD^+ vs ArD^+.
- 1D model predicts that H_2 better at causing recombination than D_2.
  - Recycles off wall faster – gives better neutral cooling.
- Higher RE currents harder to recombine, as expected.



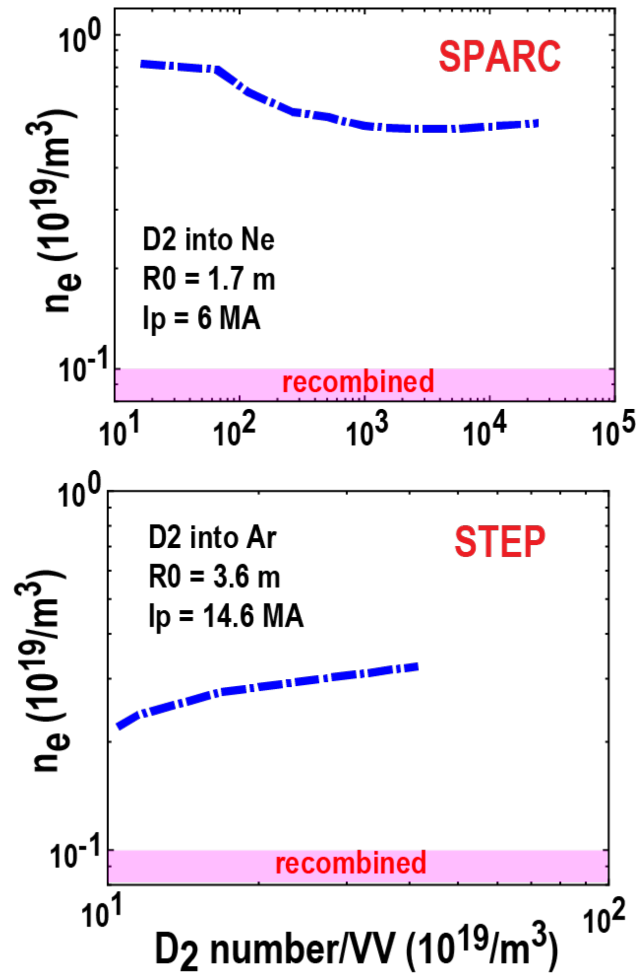
Recombination timescales in ITER are expected to be fast enough to beat VDE time

- **VDE timescale in ITER expected to be of order 100 ms.**
- **Want recombination timescale faster than this.**
- **Once recombination occurs, expect VDE to slow significantly, because dI/dt will slow.**
- **Time to recombination tends to be well under 100 ms for ITER and decreases as more H_2 is added.**



Other future devices – SPARC and STEP

- **RE plateau recombination was investigated for two other future devices:**
  - SPARC (medium-size tokamak, large aspect ratio, high current, D_2 into Ne)
  - STEP (large-size tokamak, low aspect ratio, high current, D_2 into Ar)
- **Neither achieve recombination within desired range of injected D_2 number.**
- **Recombination hard to achieve with high current density.**
- **Hard to achieve recombination with D_2 into Ne (least desirable combination), easiest with H_2 into Ar.**



Summary

- D_2 injection into RE plateaus is promising because it appears to reduce RE-wall heat fluence = “benign termination”.
  – Tied to volume recombination -> low impurity level -> big MHD
- 1D diffusion model has been developed for purpose of understanding RE plateau volume recombination.
  - Includes main essential ingredients: neutral cooling and molecular recombination.
- Present simulations indicate that yes volume recombination should be achievable in ITER.
- Simulations suggest achieving volume recombination in higher current density devices (SPARC and STEP) will be more challenging.
- This work is just first step, many areas for improvement
  - Need improvements to existing model IonBalance (better neutral transport, better RE transport) to try to capture ”density limit” for ITER.
  - Parallel lines of development:
    CQL3D: Fokker-Planck model, being adapted for this problem (A. Pigarov)
    DREAM: Fokker-Planck model, hope to adapt for this problem (N. Schoonheere)
    SOLPS: ionization/recombination balance model (M. Hoppe)