1-D Modeling of Massive Particle Injection in Tokamaks

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Introduction

- **Problem and Motivation**:
  - Fast radiative cooling of the plasma during preemptive plasma shutdowns & disruptions will be necessary to avoid divertor heat loads and halo current forces.
  - But rapid cooling generates huge toroidal electric fields potentially → large **RUNAWAY CURRENTS**
- **Possible Solution: Massive D_2 Particle Injection (MPI)**
  - Quench 90% of the current in 10 ms for DIII-D, and 50 ms for ITER before plasma contacts wall
  - Avoids Fleischmann-Rosenbluth avalanche runaway electron currents during disruption mitigation

$$J_R \approx \begin{cases} J_{\mathrm{seed}} \exp\left[\left(\dfrac{ep}{mc}\right)\displaystyle\int_0^t (E - E_{\mathrm{crit}})\,dt\right] & E > E_{\mathrm{crit}} \\ 0 & E < E_{\mathrm{crit}} \end{cases}$$

$$\boxed{E_{\mathrm{crit}} \cong 0.1 n_{e14} (\mathrm{V}/m)}$$

$$p = \frac{1}{\ln\Lambda}\sqrt{\frac{\pi}{3(Z+5)}}$$

seed current

FCQ provides a comprehensive tool to model plasma current and toroidal electric field evolution during MPI

- **FCQ is developed over an axisymmetric1-D domain where an assumption of large-aspect ratio circular flux surface is made.**

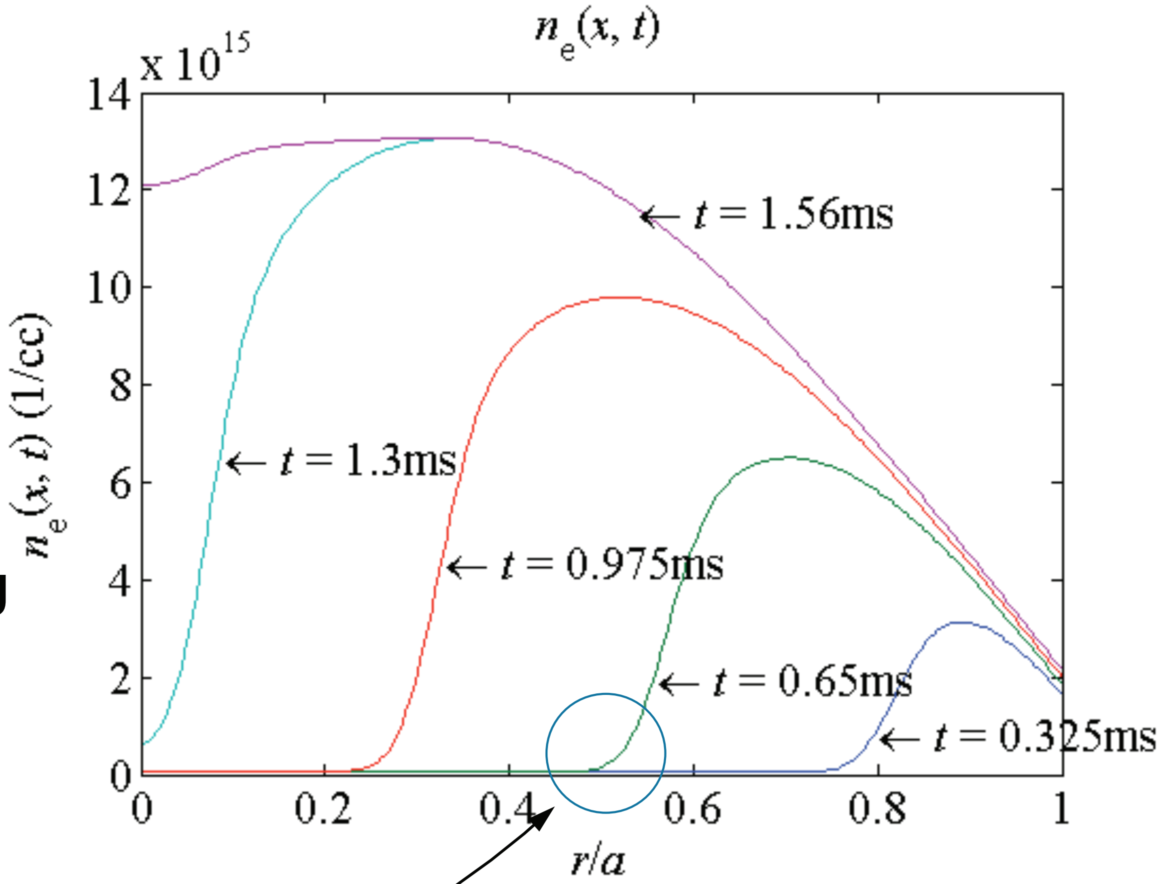
$$\begin{cases} \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\psi\right) = \mu_0\sigma(r,t)\frac{d\psi}{dt} + \mu_0 \boxed{J_{\text{seed}}\, e^{\frac{ep}{mc}\left(\psi-\int_0^t E_{\text{crit}}\,dt\right)}} - \mu_0 J_z(r,0) \quad \psi = \int_0^t E_z dt \\ n\frac{dE}{dt} = \frac{1}{r}\frac{\partial}{\partial r}\left(rn\chi\frac{\partial T}{\partial r}\right) + \sigma\left(\frac{d\psi}{dt}\right)^2 - P_{\text{brem}} - P_{\text{line}} - \left(3T + U_{\text{i}}\right)\frac{dn}{dt} \end{cases}$$

$$E = \frac{3}{2}(1+f_{\text{i}})T + f_{\text{i}}U_{\text{i}}, \quad U_{\text{i}} = 13.6\ eV, \quad f_{\text{i}} = \frac{n_{\text{e}}}{n}$$

- **Pfirsch-Schluter heat diffusion**
- **Use a modeled jet profile to simulate ablation under dilution cooling while penetration takes place**
- **Kadomtsev magnetic reconnection model to address *m*=1 kink instability**

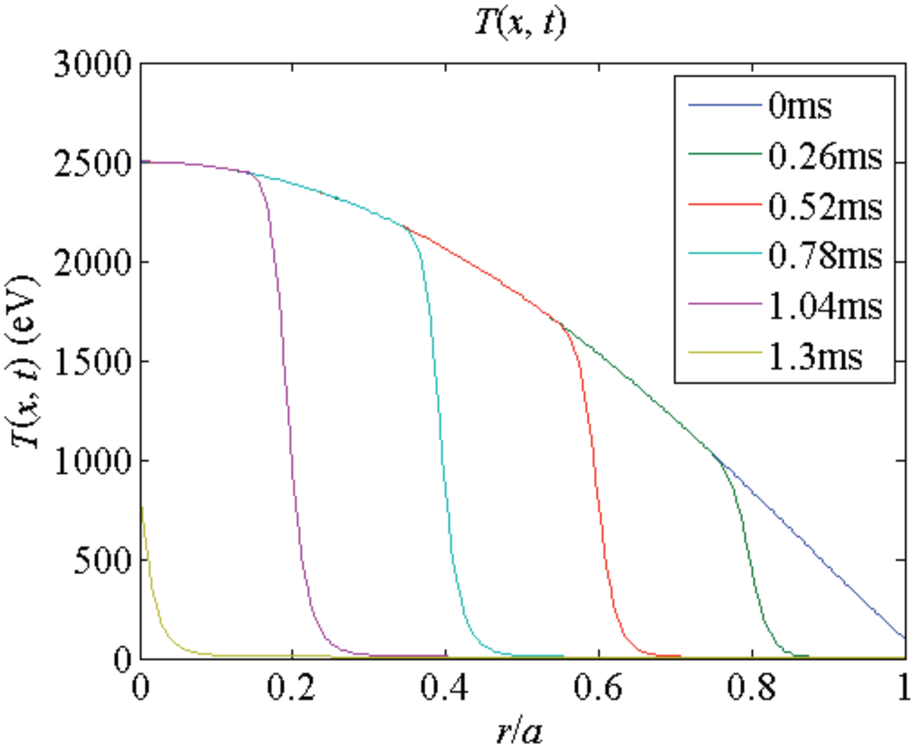
An analytical jet profile in [Parks, 1999] is modified to simulate wave front diffusion

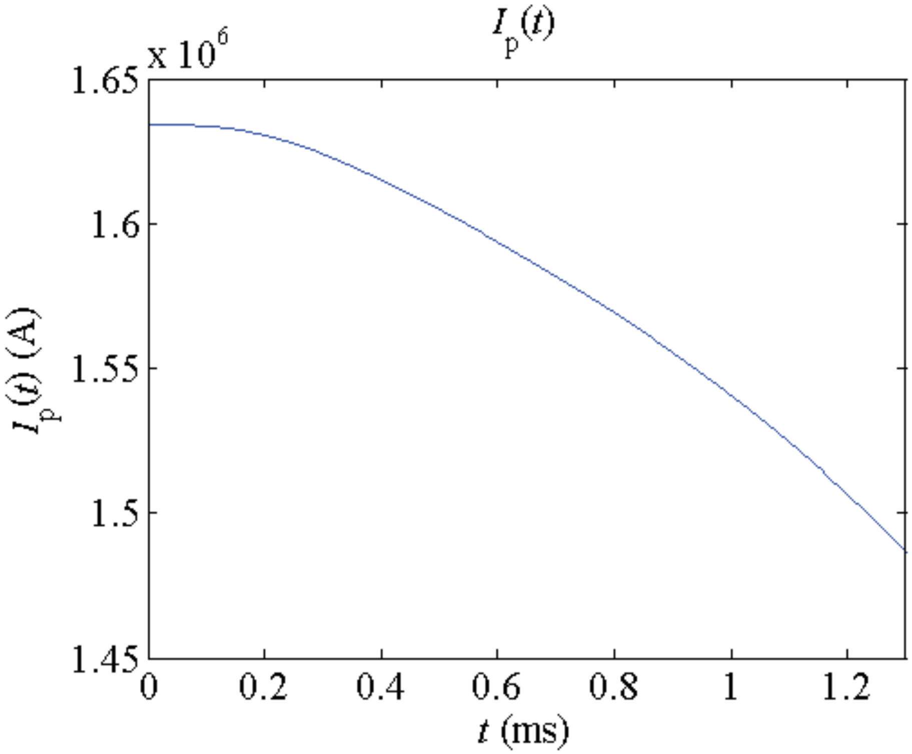
- **DIII-D simulation uses 100x-200x densification profiles. v_{jet} = 500m/s represents the ideal experimental capability to date.**
- **Wave front diffusion is simulated by convolving the “steep-front” jet density deposition profile in [Parks 1999] with a Gaussian filter.**



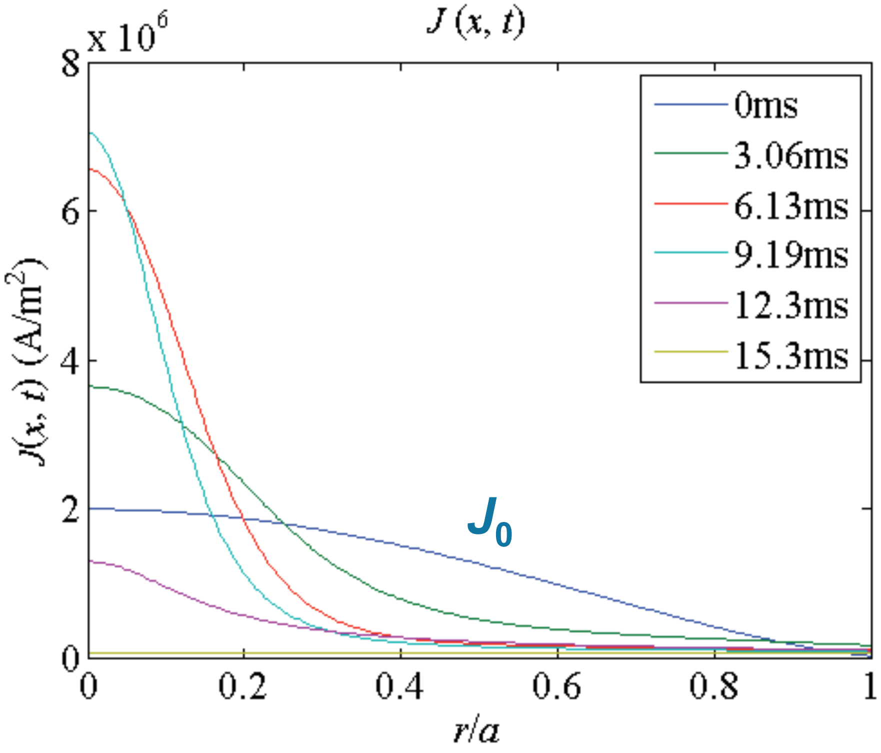
200x jet penetration profile for DIII-D

Dilution cooling during jet penetration: temperature drops but current profile is essentially unaltered

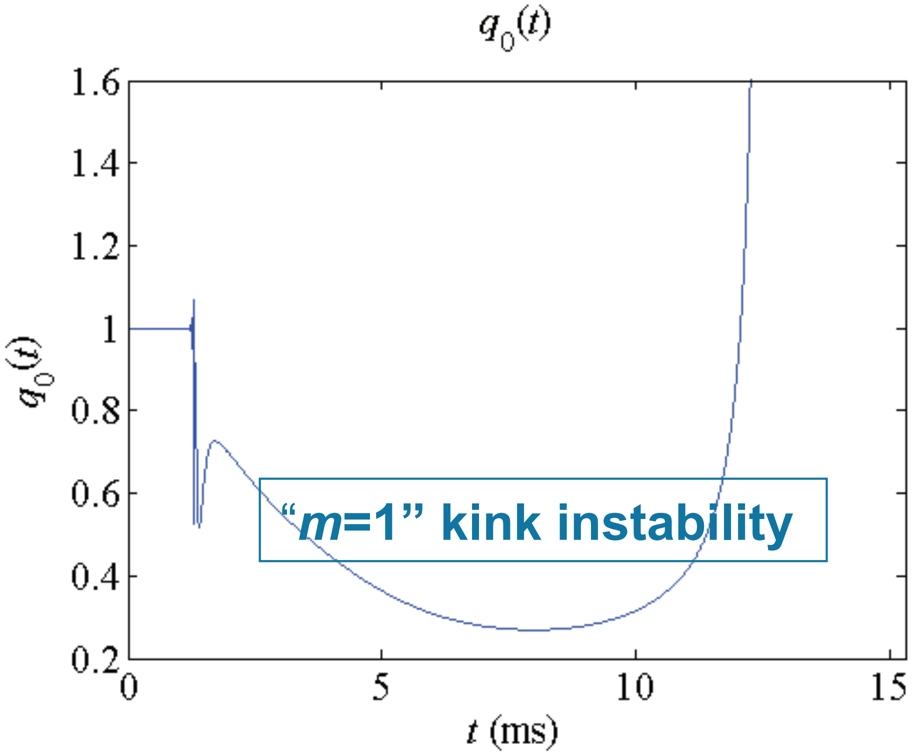




Current continues to decay after dilution cooling – unstable on–axis current peaking is observed

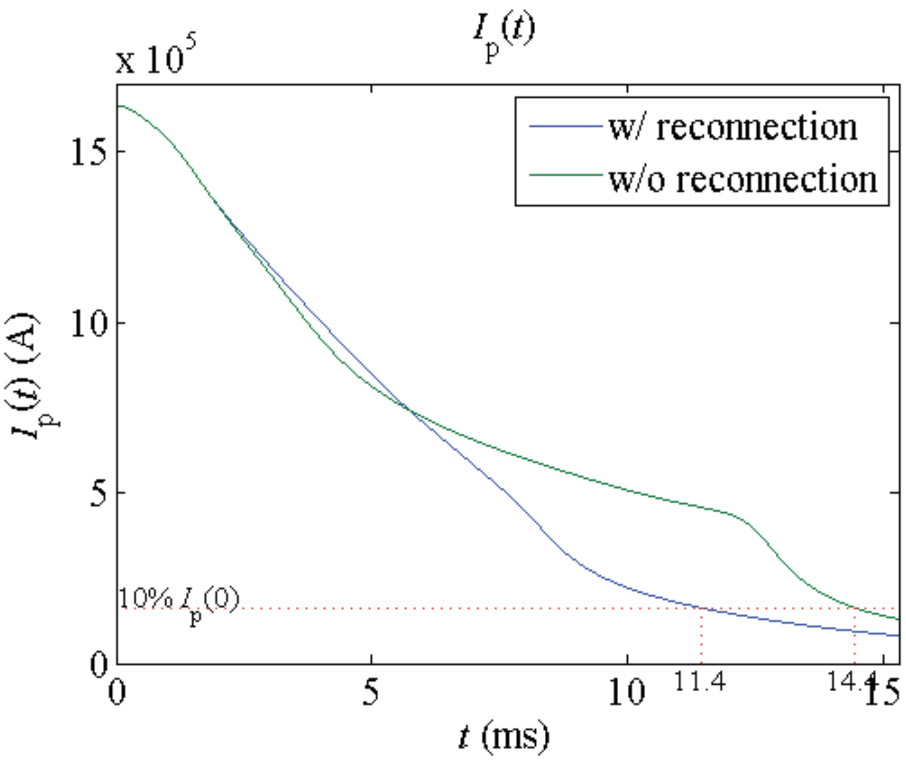


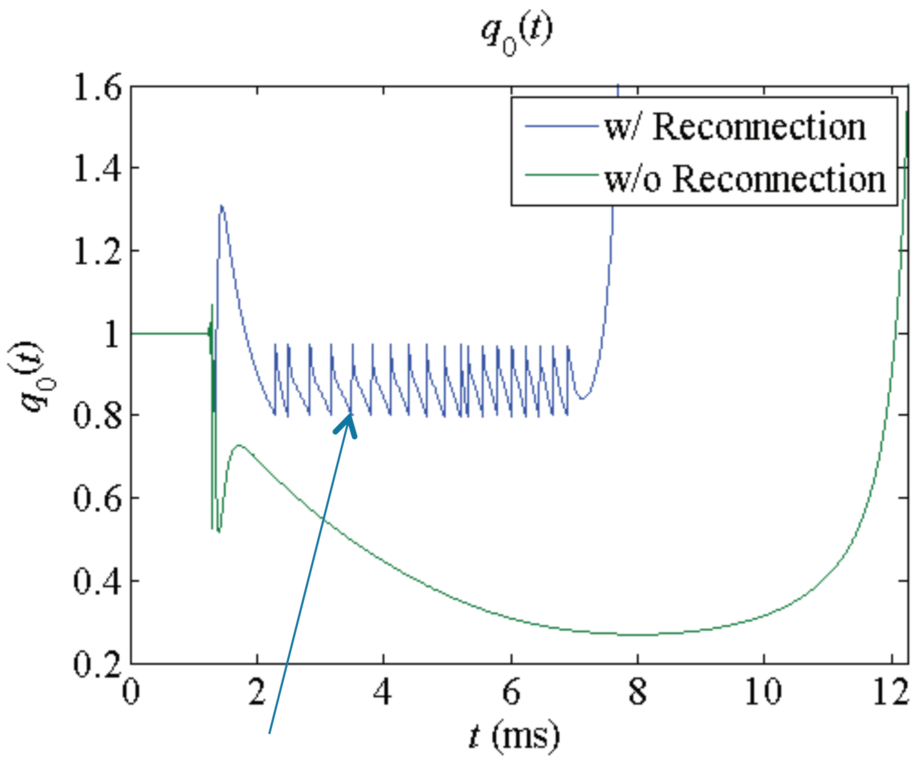
J_0



“*m*=1” kink instability

Kadomtsev reconnection promotes faster current decay

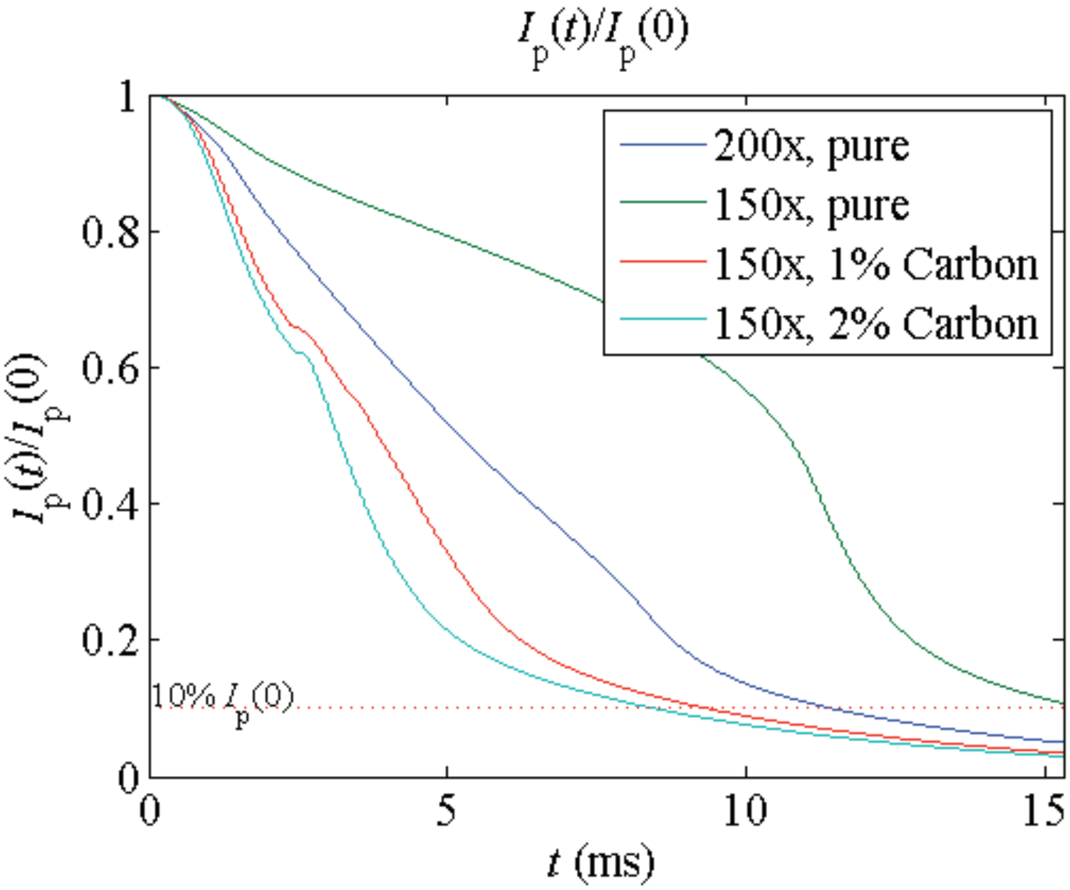




“Saw teeth” structure due to Kadomtsev reconnection

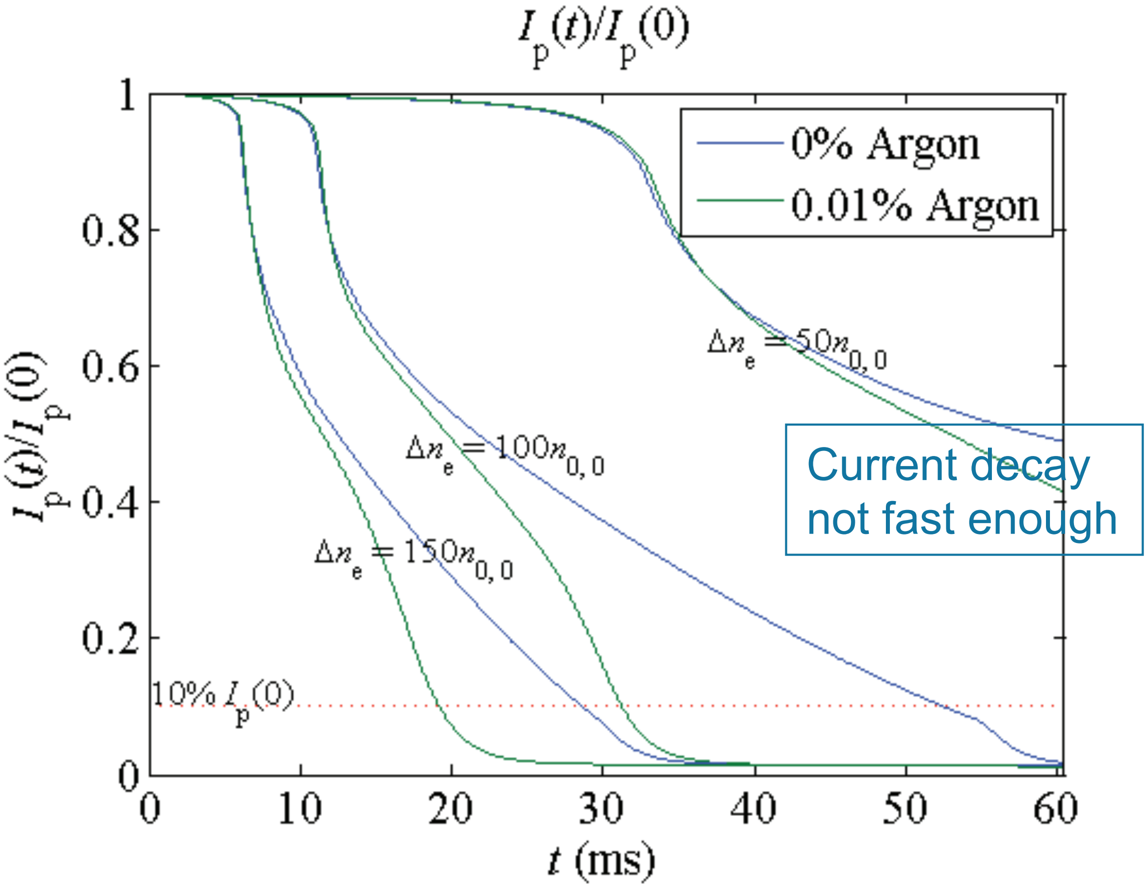
In situ carbon impurity in DIII-D dramatically accelerates current decay

- **Carbon has strong line radiation at 5-20eV, which helps to efficiently remove the remained energy stored in plasma current.**



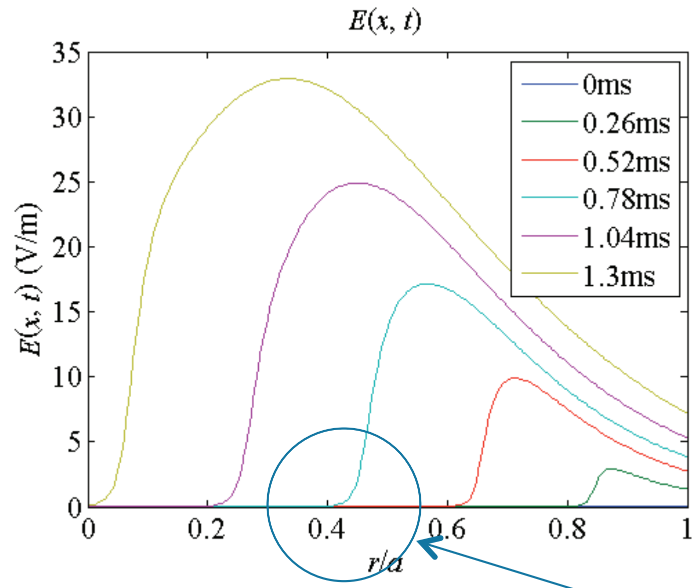
ITER requires at least 100x densification and may need Ar impurity radiation

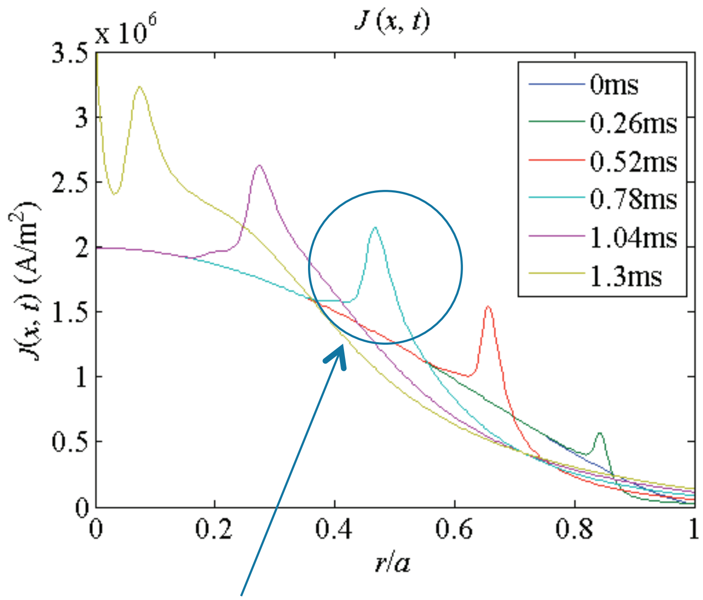
- **Assume *5% in situ* Be and 0-0.01% Ar deposited within 30% radius in the center**

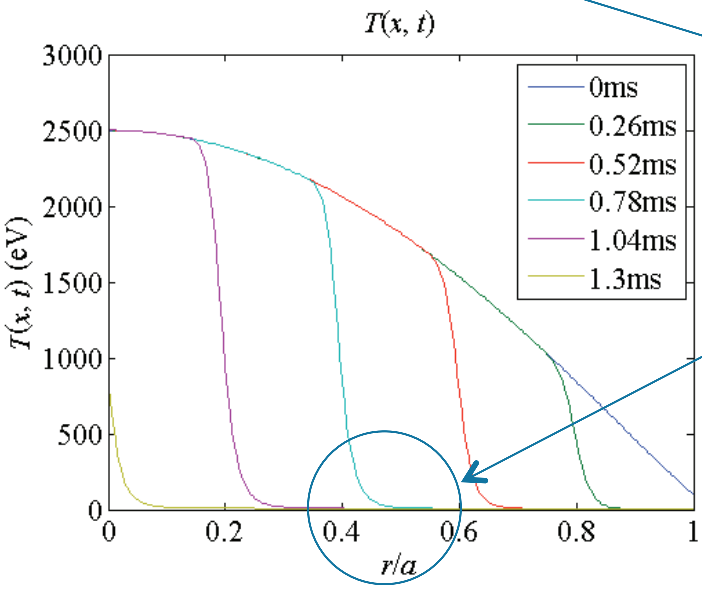


Current decay not fast enough

Moving “Shark-fin” structure on *J* profile during jet penetration can make a Dreicer runaway electron seed







- **High E field behind the wave front diffuses into the hot, low-density plasma to generate Dreicer runaway: low “critical” field exists**

$$E_{\mathrm{D}} \approx 2.6 \times 10^{-11} \frac{n_{\mathrm{e}}}{T_{\mathrm{e}}} \ln \Lambda_{\mathrm{t}} \ \ (\mathrm{V/m})$$

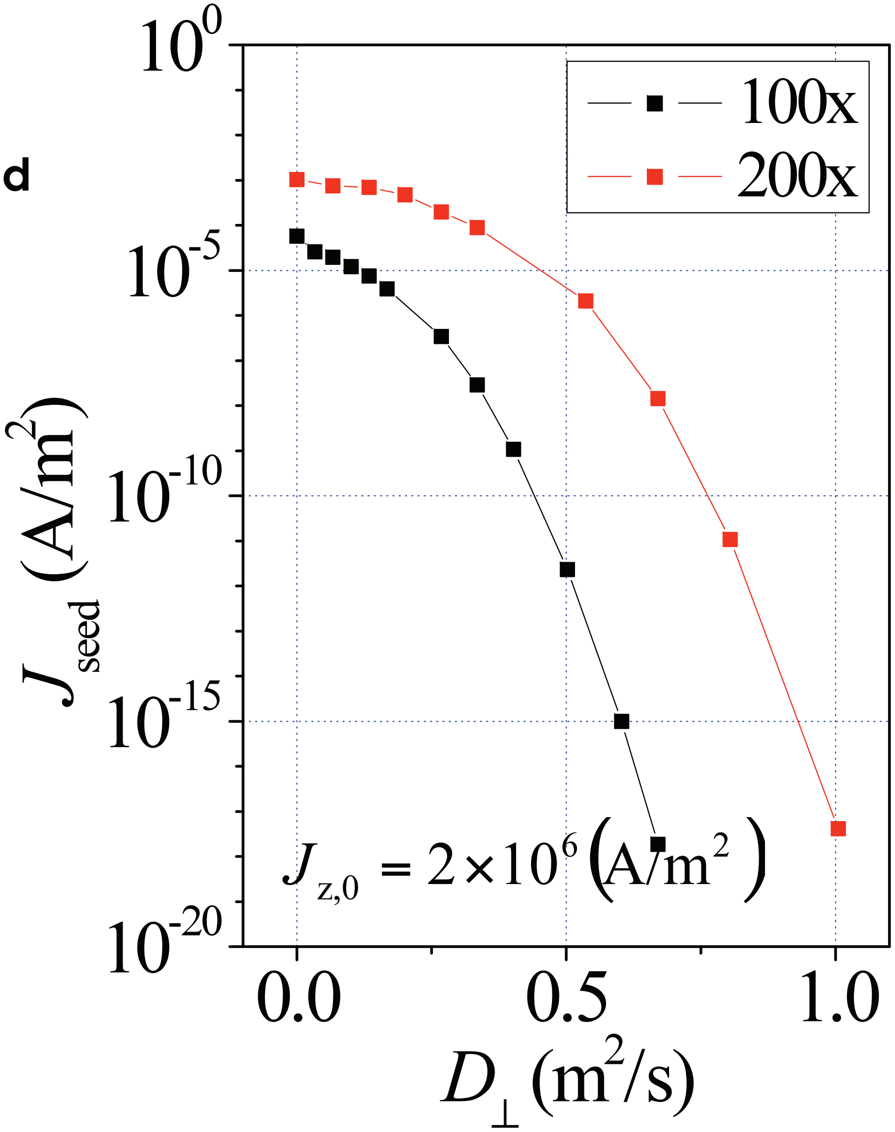
- **Less particle diffusion leads to sharper *J* profile and larger runaway electron seed.**

Dreicer runaway electron generation is negligibly small under nominal DIII-D conditions

- **Assume $D_\perp$=0-1.0m²/s and study the magnitude of J_{seed}**
- **For 100x and 200x cooling cases, the Dreicer seed of runaway electron is weak.**

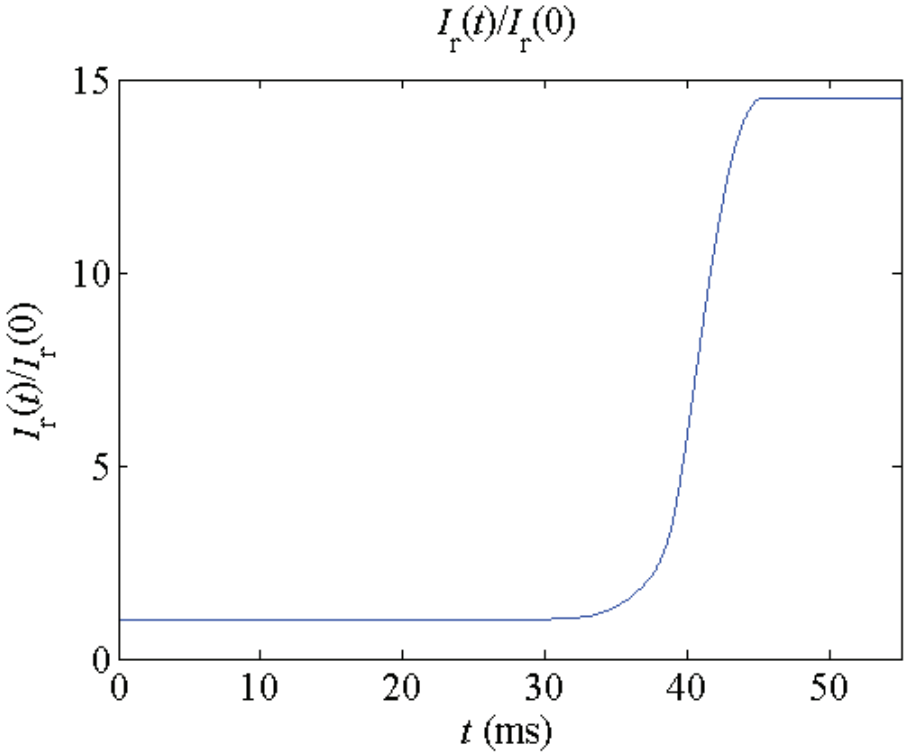
$$\boxed{\frac{J_{\text{seed}}}{J_{z,0}} < 10^{-9}}$$

- **E~E_{crit}, no significant exponential gain (~3-fold increase for DIII-D)**



Preliminary ITER simulations also indicate small Dreicer runaway currents

- J_{seed} is small in ITER, similar to DIII-D
- $E \sim E_{crit}$, no significant exponential gain
- Simulation suggests <15-fold increase of runaway current for ITER 150x densification case
- Total runaway current generated in ITER is negligible + ?????



Conclusion

- FCQ provides an efficient way to study the physics of plasma disruption mitigation in tokamak devices (DIII-D, ITER, etc.).
- Simulation suggests a range of 100x-200x density increase for desired current quench time (10-20ms on DIII-D, 30-50ms on ITER) – beyond the current capacity of MGI, may require liquid jet or pellet train injection.
- INSIGNIFICANT RUNAWAYS FORM from the Dreicer seed in DIII-D and ITER, may include "hot tail" runaway study in the future.
- Results in agreement with NIMROD simulation for similar DIII-D and ITER conditions (Ref. V. Izzo APS 2008 poster).
- An effective route to fast current quench while avoiding runaway electron generation is possible.