Assessment of the runaway electron energy dissipation in ITER

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Motivation & Goals

- ✓ **Substantial fraction of the plasma current can be converted into runaway electrons in ITER disruptions!**
- ✓ **W_k/W_m~5-10% depending on the amplitude of the RE current and on the particular form of the RE distribution function**
- ✓ **Previous studies predicted large – up to or more than 100% of W_m converted into W_k at RE termination – HUGE energy deposited to the wall with lost REs**

MAGNETIC ENERGY CONVERSION in "REALISTIC" conditions

- ✓ **Get rid of oversimplifications: RE kinetics into DINA**
- ✓ **Emphasize on MITIGATED CQ+RE scenarios**

CQ simulations with DINA-Disruption Simulator

DINA-DS updates includes

Interface with **new RE kinetic module** providing ***j_{re}, dj_{re}/dt***

Passive structures optimized for accurate simulations of eddy currents (Lukash, this conference)

T_e in halo region from improved power balance (Kiramov EPS 2016)

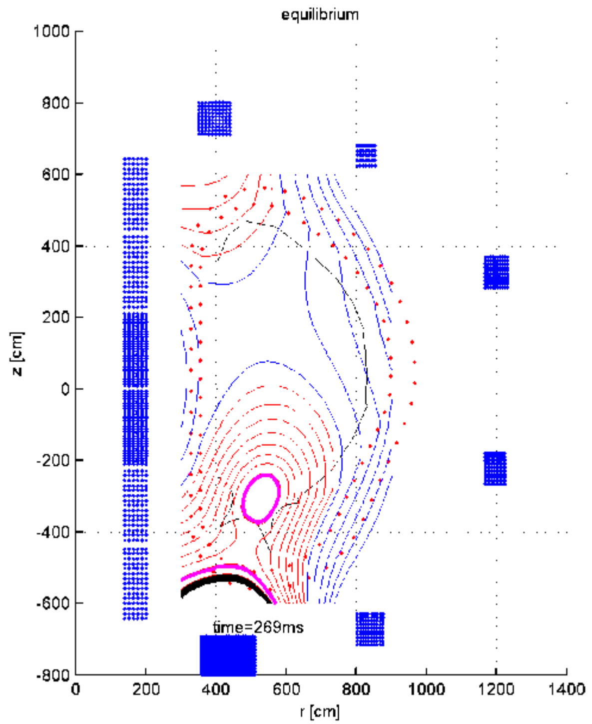
Secondary impurity injection to suppress REs is simulated as an instant rise of impurity density (uniform)

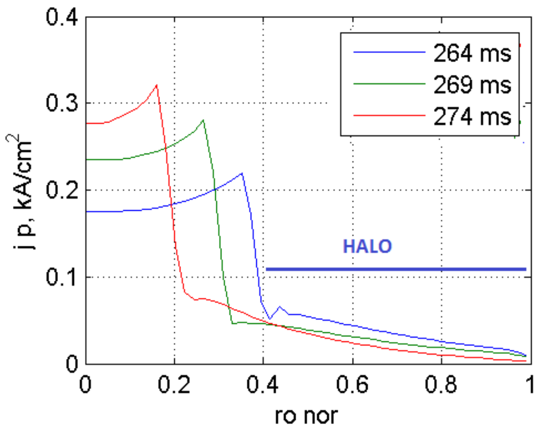
Knowing the RE distribution function allows direct evaluation of the RE kinetic energy deposited to the wall during VDE:

$$W_{re\_VV} = 2\pi R_m \int_{t_0}^{t} (T_{re} n_{re}) \dot{S}_p dt$$

$$W_{re\,kin}(t) = \int_{plasma} \int_{t_0}^{t} j_{re} (E - E_0) dt\, dV$$

Scraping off the plasma during VDE leads to generation of the halo currents in the area shown by red lines in the right figure, and "skin" RE current





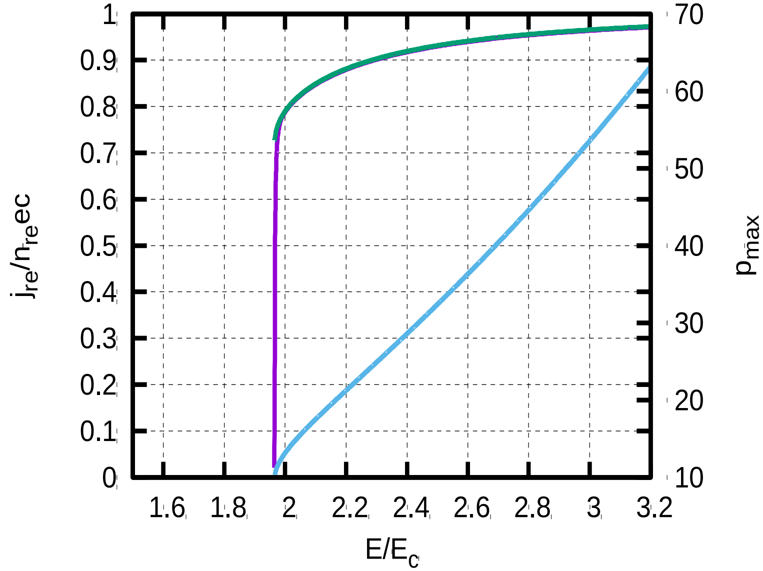
Semi-Analytic Model for RE Kinetics

For *E close to E_0*, Aleynikov, Breizman, PRL-2015

$$F(p,\theta,t) = \delta(p - p_{\max}) \frac{A}{2\sinh A} \exp(A\cos\theta)$$

$$A = \frac{2E}{Z+1} \frac{p^2}{\sqrt{p^2+1}}$$

$$j_{re} = ecn_{re} \frac{p_{\max}}{\sqrt{p_{\max}^2+1}} \left(\frac{1}{\tanh A_{p_{\max}}} - \frac{1}{A_{p_{\max}}} \right)$$



For higher field, *$E>E_a$* – RE avalanche [Rosenbluth, Putvinskii NF-1997] + corrected high Z impurity effect [Zhogolev IAEA 2014]

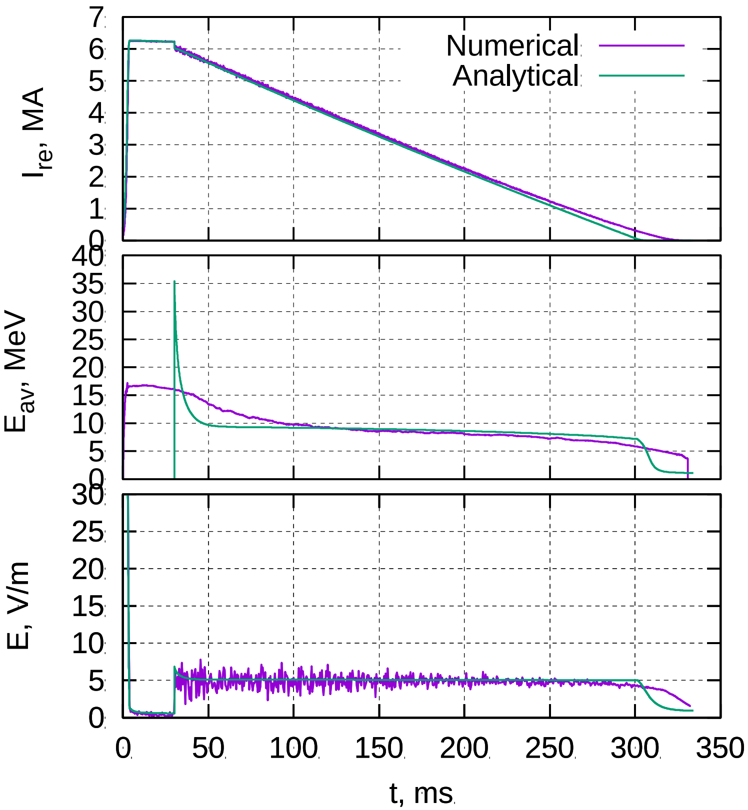
E-field diffusion equation (cylinder)

$$\frac{\partial(\sigma E)}{\partial t} + \left.\frac{\partial j_{re}(E,t)}{\partial t}\right|_{E=const} + \frac{\partial E}{\partial t}\frac{\partial j_{re}(E,t)}{\partial E} = \frac{1}{\mu_0}\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} E$$

RE avalanche

"Shaping" factor for near-threshold model

RE evolution with Semi-Analytic model & with full Monte-Carlo simulations



1 t=0, RE seed I_{re_s}=80kA initiates avalanche

2 t~15ms – Ire saturates (plateau)

3 t=30ms – Ar injection initiate RE current linear decay

Calculated RE current decay is in fairly good agreement with Monte Carlo simulations [Aleynikov, FEC 2014]

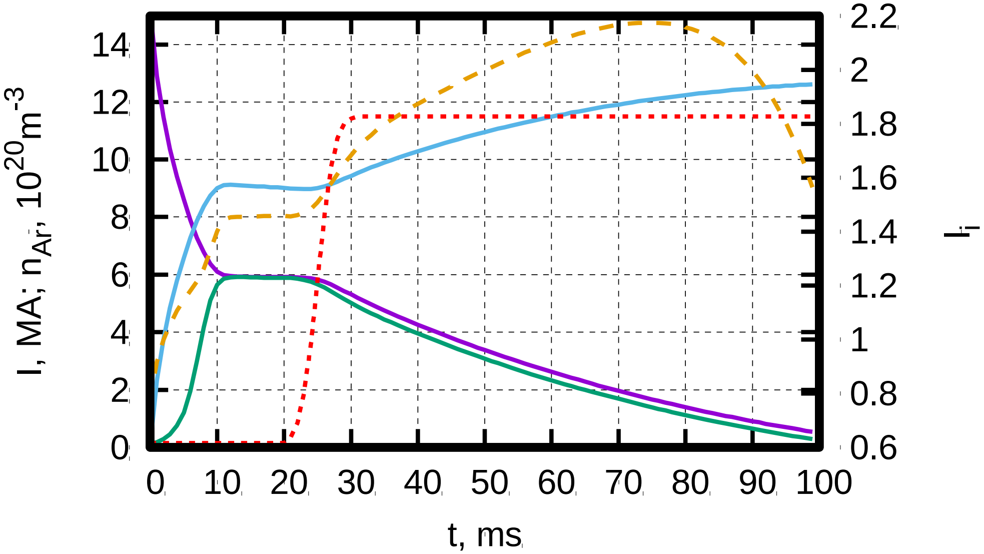
Difference in averaged kinetic energy of REs is due to the long relaxation time of the *F(p,ϑ,t)* over momentum, *p*

A mitigation of the RE current with Ar MGI. The Ar density of $3*10^{20}m^{-3}$ is introduced as a flat profile instantly at t = 30ms

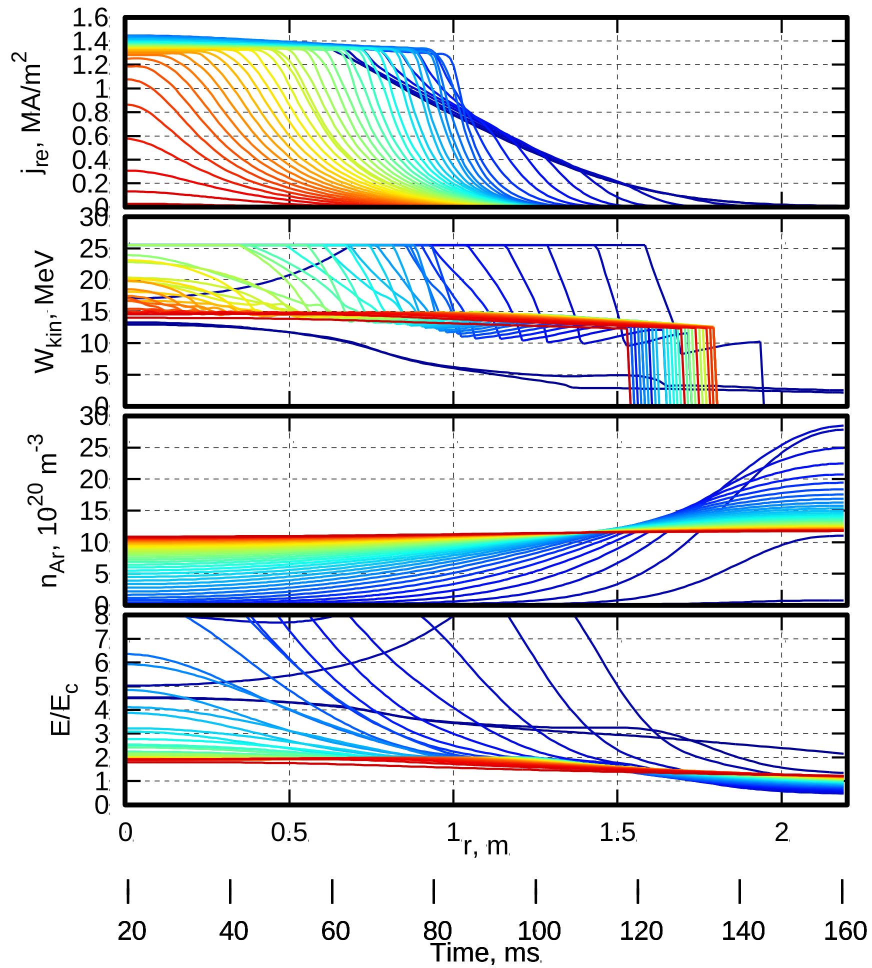
Simplified kinetic description of the REs is valid when plasma parameters and electric field vary slowly in time. In mitigated scenarios

$$\tau = 18ms / n_e[10^{20} m^{-3}] \sim 1\text{ms}$$

Simplified 1D simulations of RE mitigation with impurity injection



Total current (purple), RE current (green), wall current (blue), internal inductance (orange dashed) and injected Argon density (red dotted).

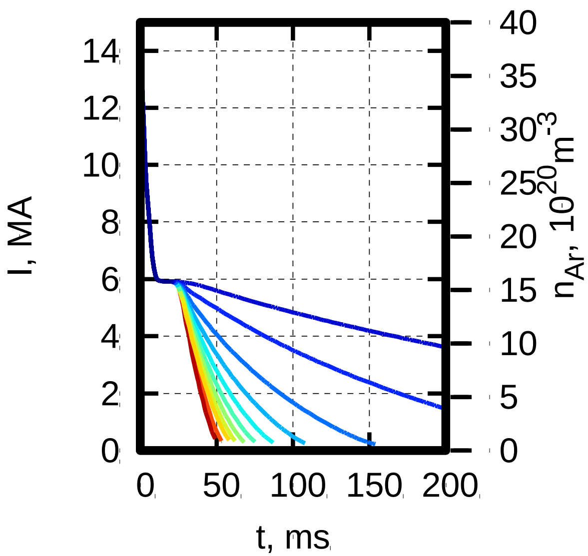


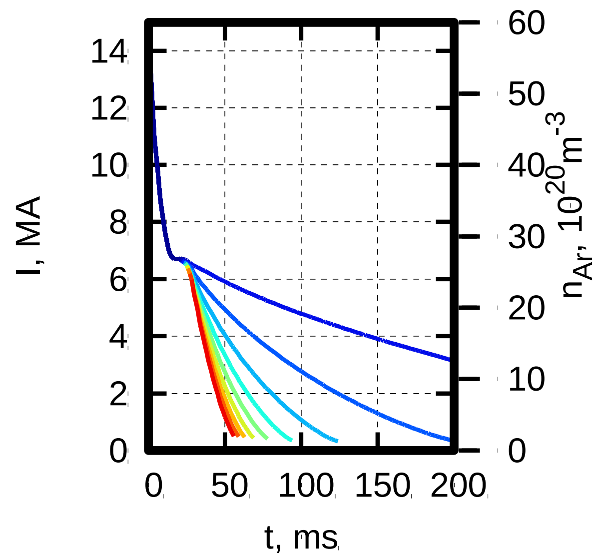
Evolution of the plasma profiles during CQ

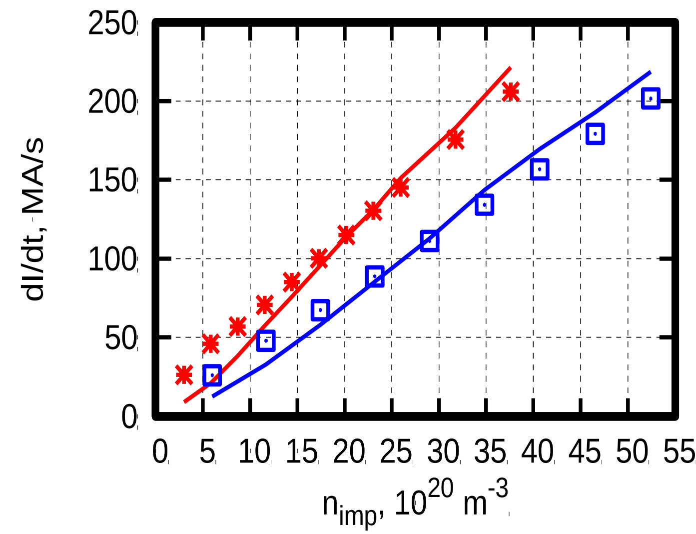
RE profile evolution effect in simplified 1D analysis

$$\frac{dI}{dt} \approx -\frac{2\pi R}{L_i} E_0 = \frac{4\pi}{l_i \mu_0} E_0$$

Total current decay rate as a function of impurity amount: Argon (red) and Neon (blue) in simplified 1D simulations with accounting for the evolution of $J_{re}(r)$ profile. Dots – analytical estimates



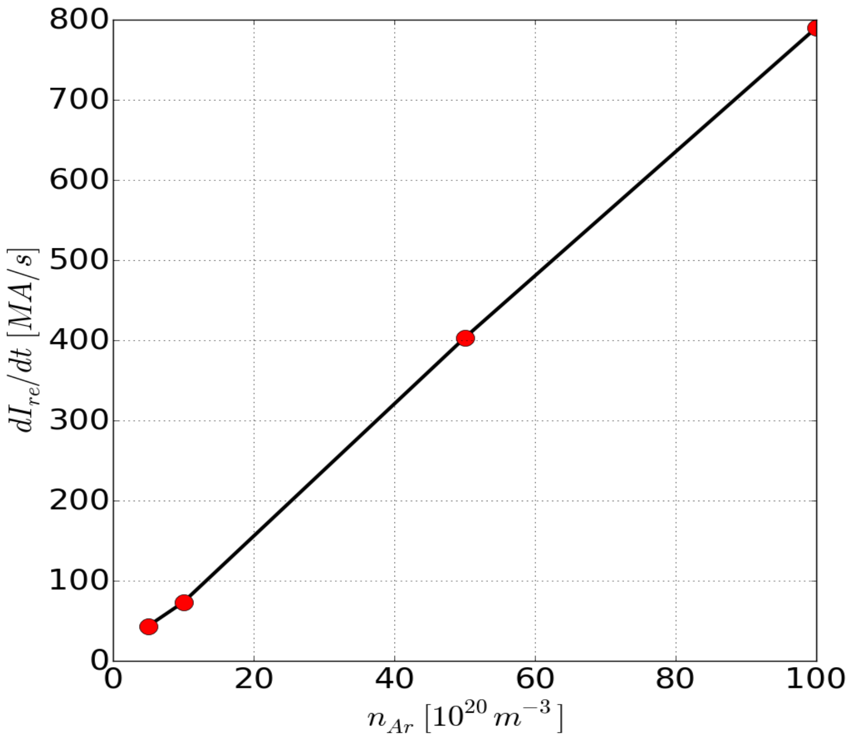




Total current evolution for various impurity amount. Left plot – Argon [5; 30], right plot Neon - [10; 60] (in $10^{20} m^{-3}$)

$dI_{re}/dt \approx (5 \div 6) N_{Ar}[10^{20}]$

Linear RE current decay was confirmed in DINA CQ simulations without VDE



Calculated RE current decay was found to be in a perfect agreement with estimated in simpler 1D simulations. $dI_{re}/dt=8n_{Ar}\{10^{20}m^{-3}\}$ MA/s scaling agrees with earlier predictions of [Aleynikov et al., FEC-2014]

DINA simulations of mitigated CQ with REs in ITER

1. Start from 15MA reference scenario

2. Ar injection (N_{Ar}=1*$10^{19}m^{-3}$, uniform) forced TQ. Impurity amount corresponds to estimated minimum for the thermal load mitigation. At the same time it is close to the maximum permissible for EM loads.

3. Start CQ with I_{re_seed}=80kA (uniform) Vertical position control is off

4. Secondary Ar injection in RE plateau (instantaneous Ar density rise)

5. RE loss is due to the vertical plasma displacement only.

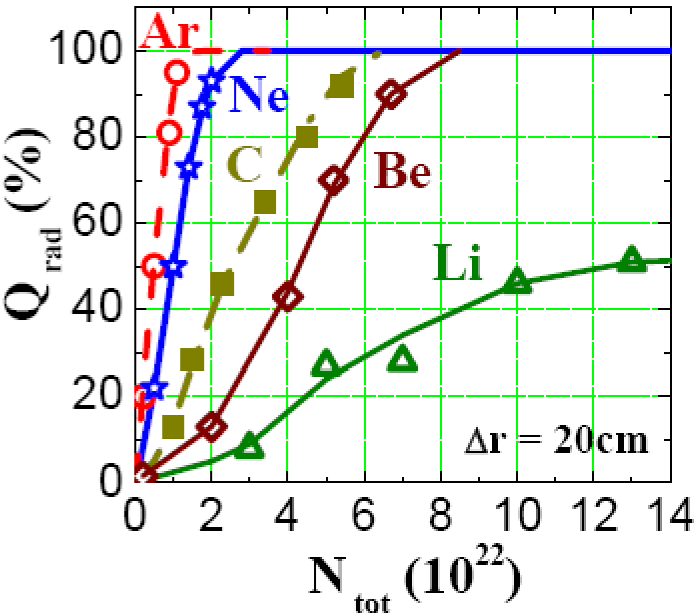
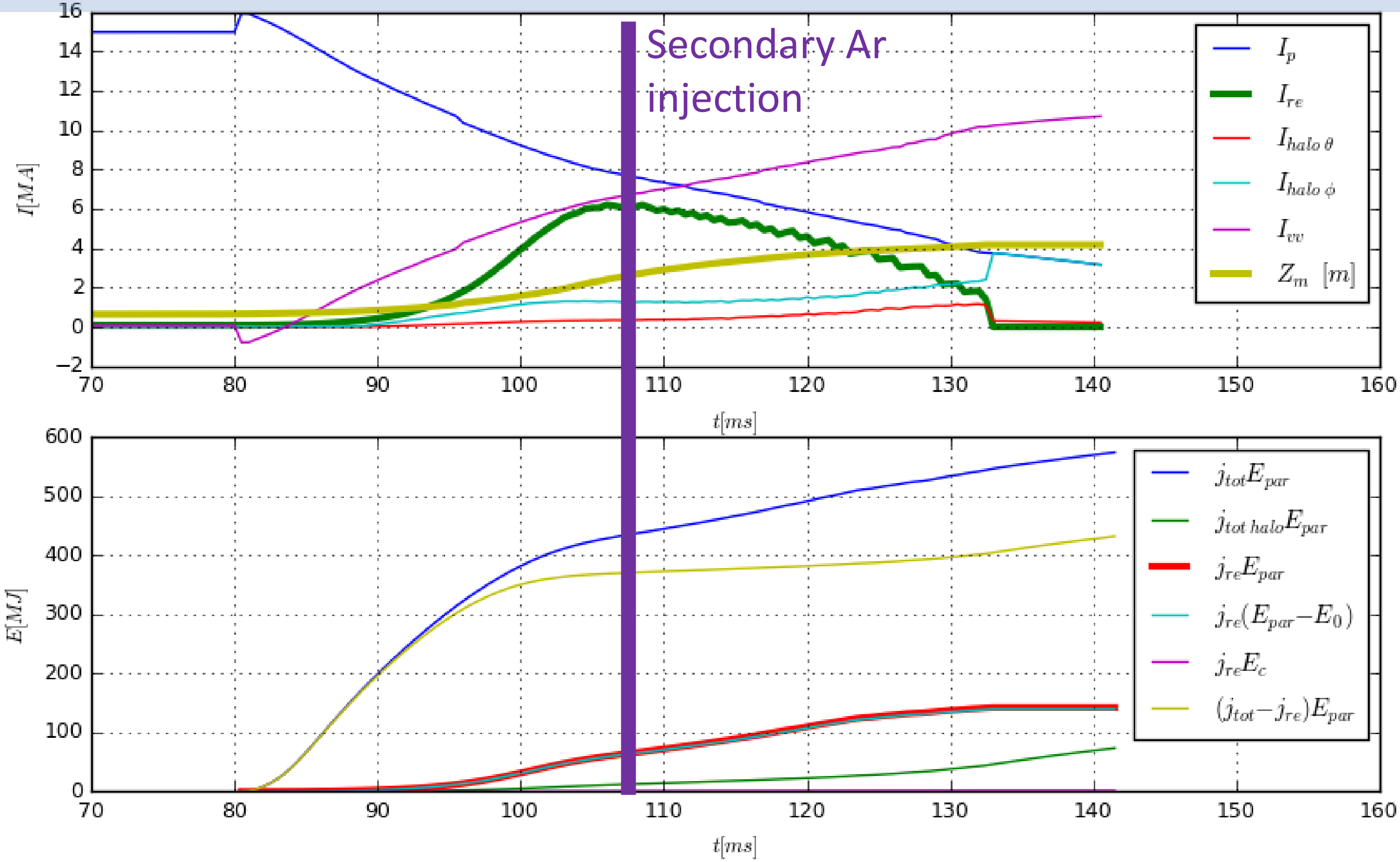


Fig. 4 Dependence of radiated power fraction versus number of different impurities at radiating layer width 20 cm

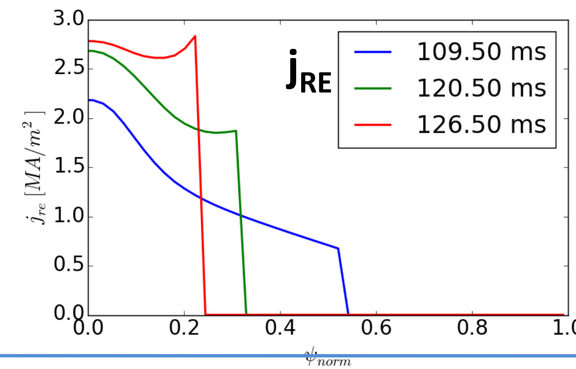
From Leonov, EPS-2011, P2-108

CQ without secondary MGI

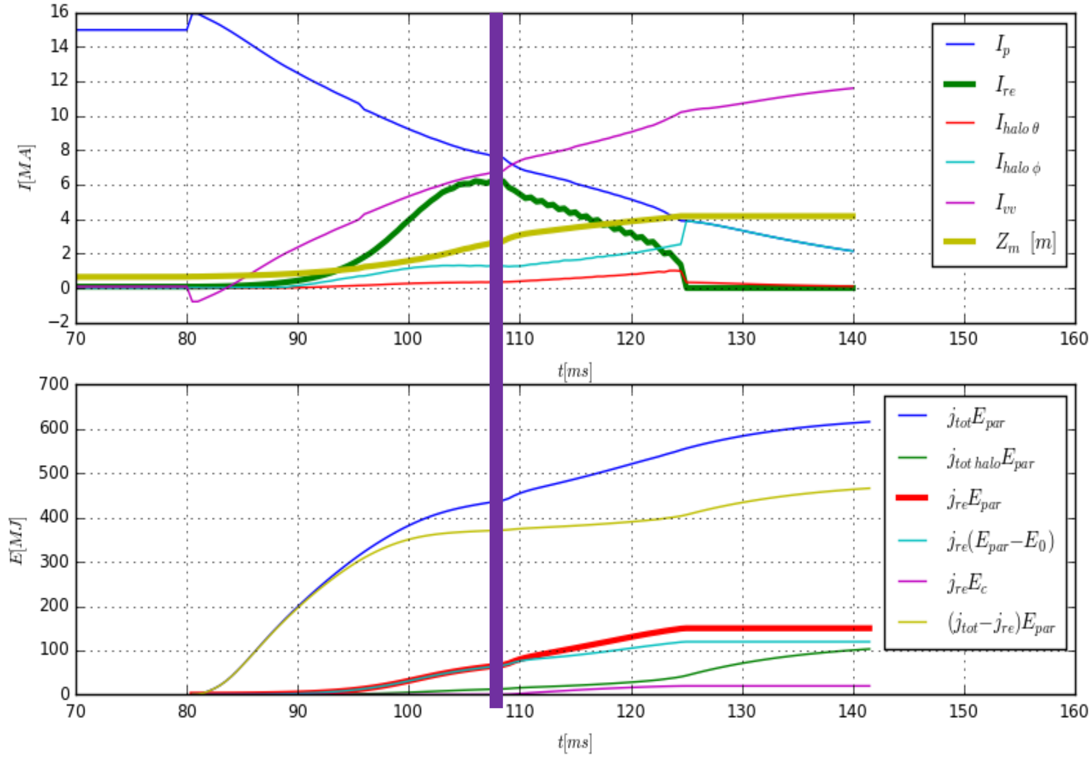


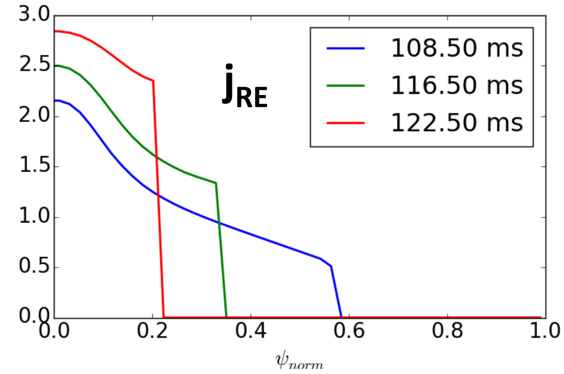
REs are always in the avalanche regime, scrapping off the plasma is accompanied by growth of J_{re} in the center

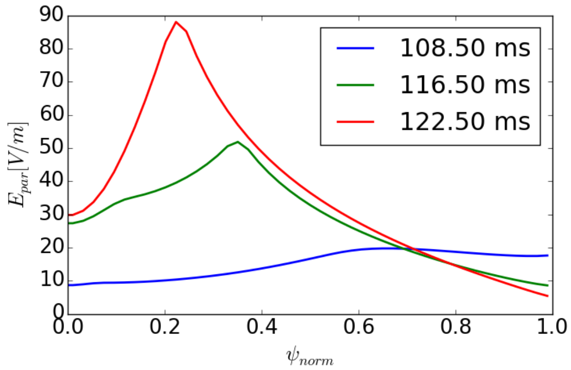
RE are lost to the wall during VDE. ~100MJ



Secondary MGI with $N_{Ar}=10^{21}m^{-3}$





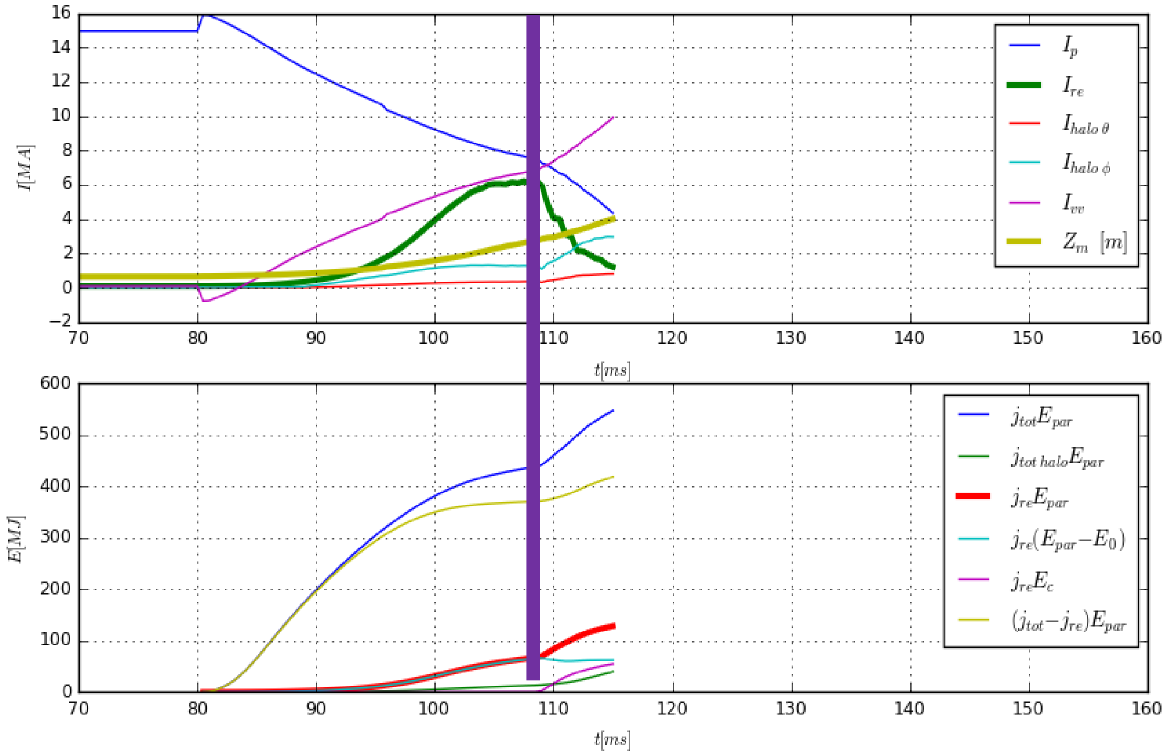


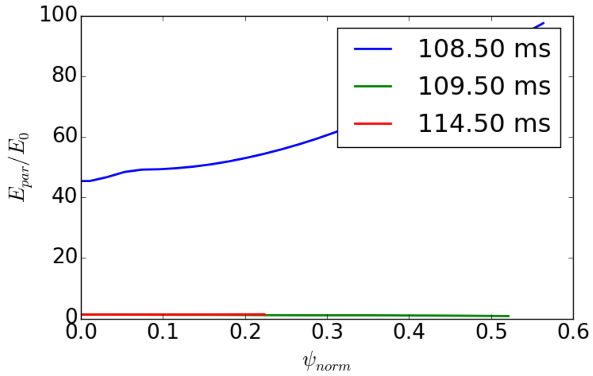
Rising Ar density -> rise VDE velocity -> rise $E_{||}$

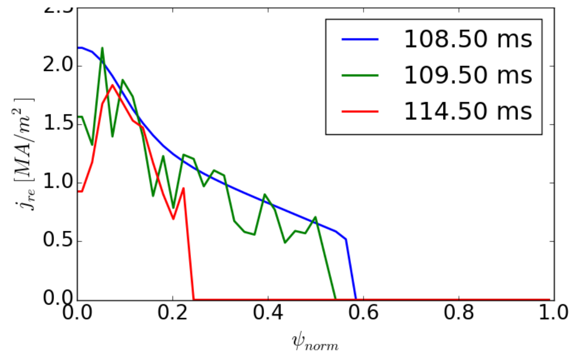
$E_{||}$ tends to "run away" from E_0~N_{Ar}

REs are still in avalanche mode → no mitigation

At n_{Ar}>$10^{22}m^{-3}$ mitigation get visible but not sufficient



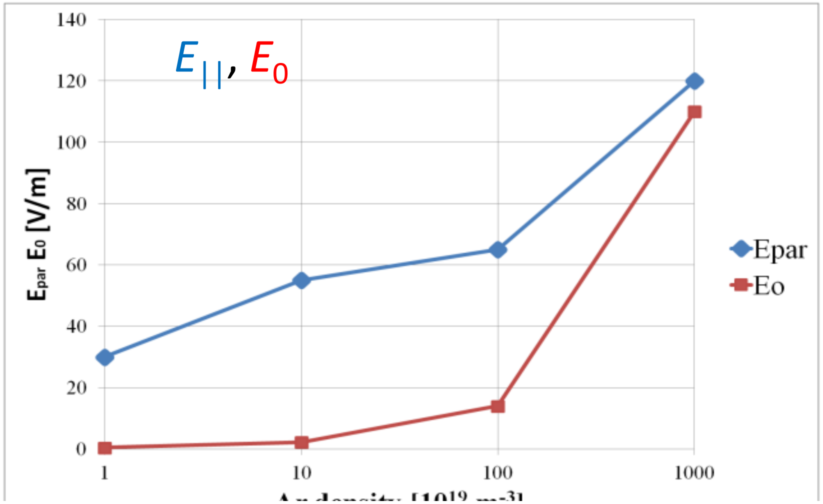


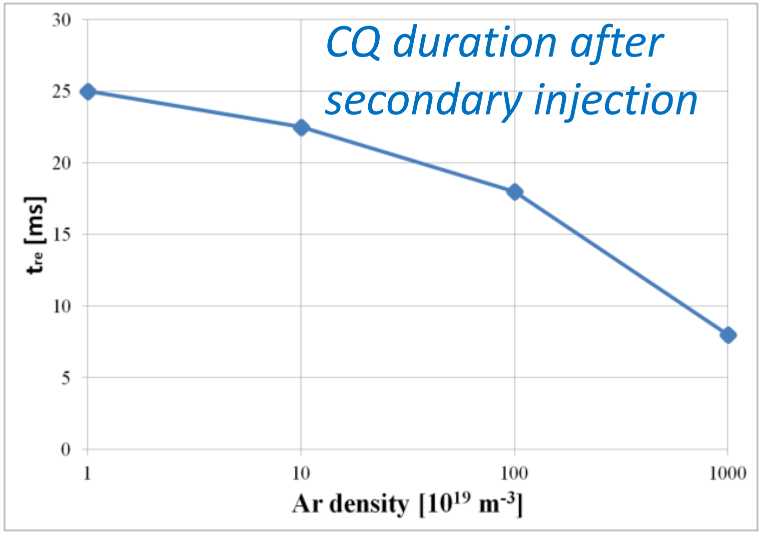


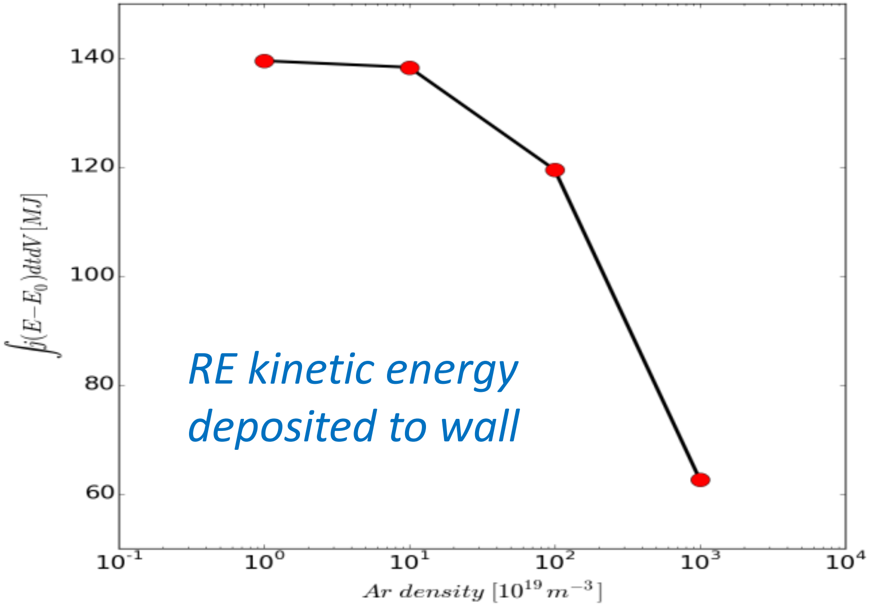
RE current decreases in the plasma center, but not fast enough -> 50MJ RE kinetic energy still goes to the wall

Required Ar amount ~50% of full capacity of ITER Ar/Ne RE-Suppression MGI

Upward VDE vs Ar density scan







Rising impurity density gives rise to induced $E_{||}$ along with critical E_0

Accelerating the VDE requires higher RE current damping rate for successful mitigation

Close to permissible amount of Ar impurity necessary for RE mitigation with secondary MGI

In addition

1**. Halo currents ON vs OFF – almost similar conversion**
In "On" case $E_{//}$ is smaller but CQ is longer
In "Off" case $E_{//}$ is higher but CQ is shorter

2. **Rising I_{seed} to slow down VDE** results in rise of plateau current and of the energy deposited to wall

3. **Extremely fast** (few ms) response time and injection of impurity **amount close to** the technical **limit** (~,> 50%) is necessary to kill existing RE beam

SECONDARY INJECTION IS HARDLY FEASIBLE for RELIABLE RE MITIGATION in ITER

"Do you really want to hurt me?"

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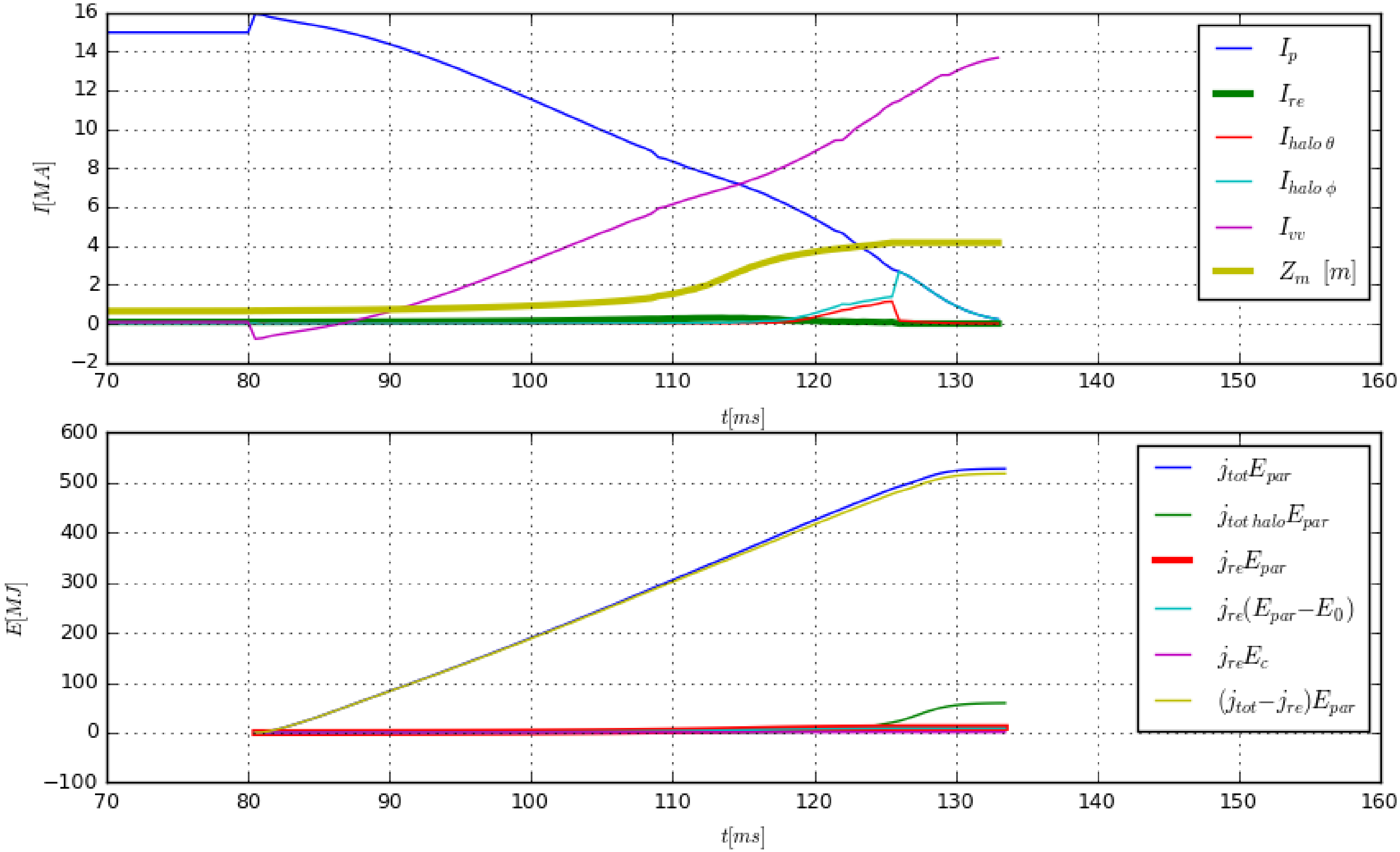
Alternatives

Runaway Electrons

AVOIDANCE instead of **SUPRESSION**

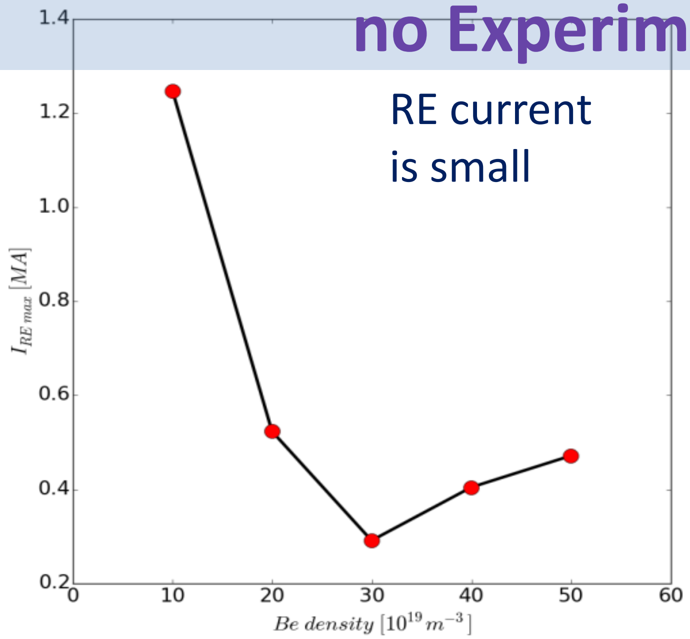
TQ mitigation with light impurities – Be can help

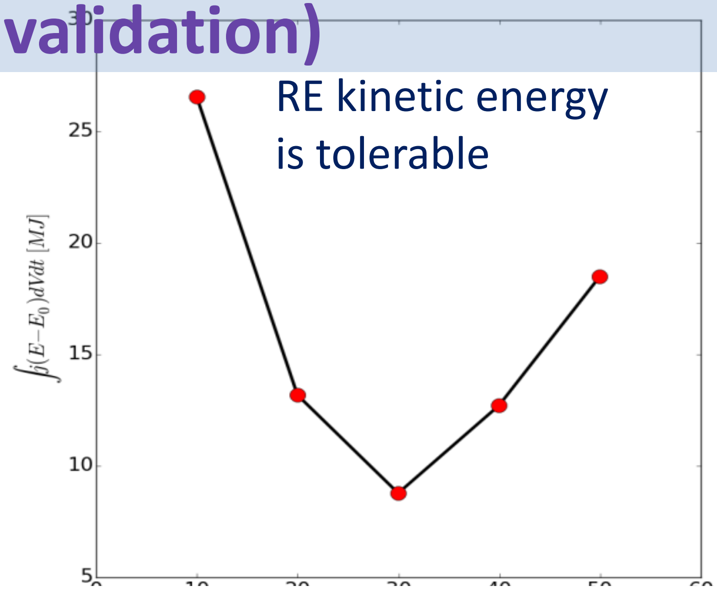


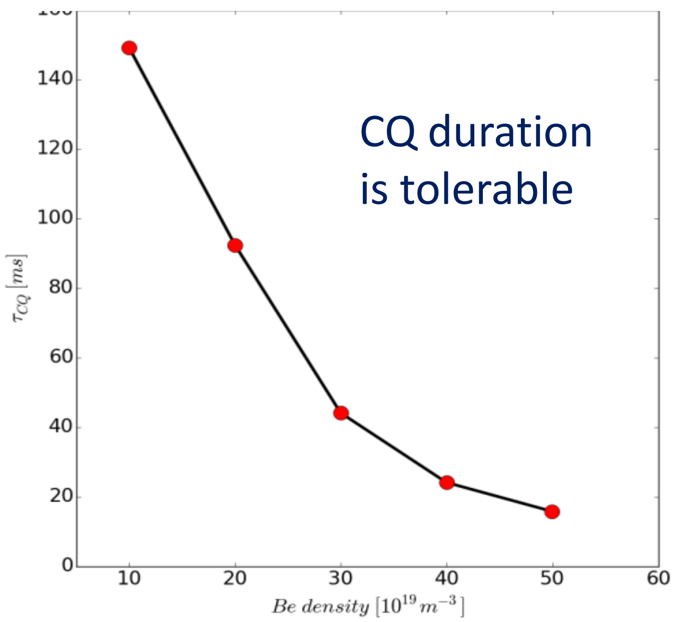
High post-TQ Te HAMPERS RE generation

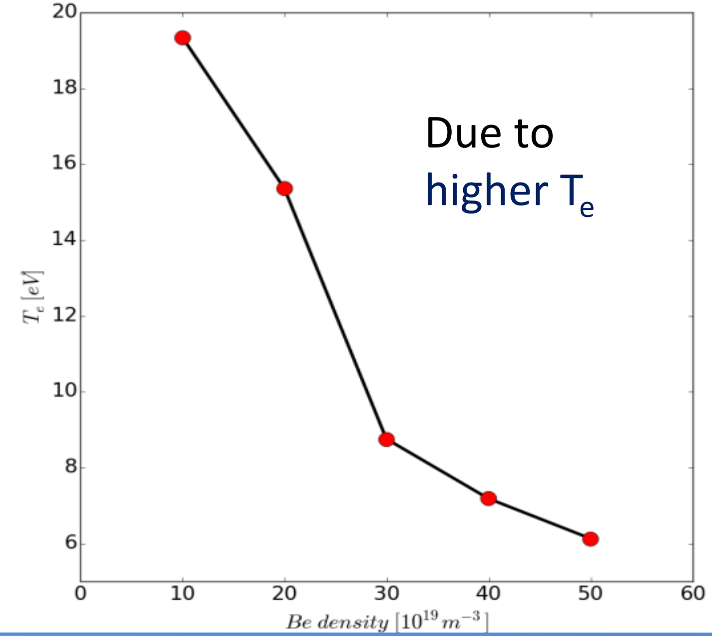
Long CQ -> more flexibility for secondary injection (to mitigate halo currents)

Be injection looks promising from modeling (but there is no Experimental validation)

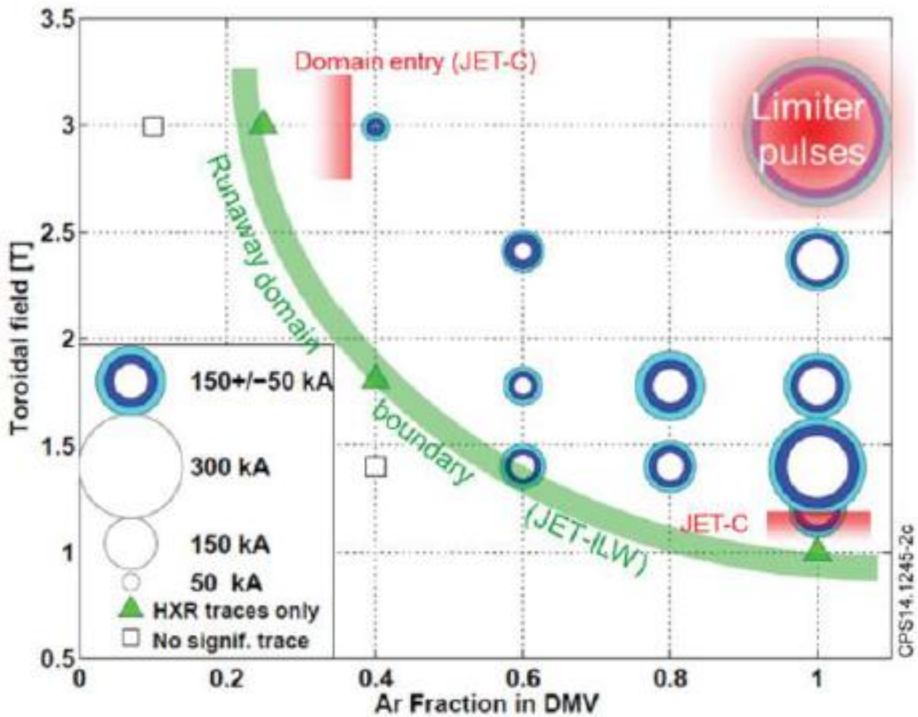








D2 admixture to Ar/Ne is very promising experimentally but an explanation is necessary



JET runaway generation domain as function of magnetic field and fraction of Ar in the D2 mixture [C. Reux et al., *Nucl. Fusion, p. 093013, 2015]*

Understanding of the RE generation at Thermal Quench is of principal importance.

Consistent simulations of RE+ MHD + atomic processes + … is necessary.

SUMMARY

1. **Significant conversion of the plasma magnetic into RE kinetic energy is expected in ITER disruptions mitigated by the high-Z impurity injection**
2. **Secondary injection of impurity in RE plateau is not effective for RE suppression in vertically unstable CQ plasma**
3. **ITER DMS is to be aimed on the RE avoidance rather than suppression. Be (or other light impurity) injection for Thermal Load mitigation looks beneficial for consistent DMS scenario.**
4. **Rigorous kinetic analysis of the RE formation at TQ stage of disruption is necessary for development reliable ITER DMS strategy**

Disclaimer: "*ITER is the Nuclear Facility INB no. 174. This paper explores new directions for management of disruptions that are not yet introduced into the ITER technical baseline. The nuclear operator is not constrained by the results presented here.* "