Formation and termination of runaway beams during vertical displacement events in ITER disruptions

J. R. Martín-Solís[1], J.A. Mier[2], M. Lehnen[3] and A. Loarte[3]

[1]*Universidad Carlos III de Madrid, Avda. de la Universidad 30, 28911-Leganés-Madrid, Spain*

[2]*Universidad de Cantabria, Avenida de los Castros s/n, 39005, Santander, Spain*

[3]*ITER Organization, Route de Vinon sur Verdon, 13115 St Paul Lez Durance, France*

Background

- Large amounts of runaway electrons can be generated during ITER disruptions, the injection of high-Z impurities by Shattered Pellet Injection actually constituting the most promising candidate for runaway avoidance and mitigation

- Evaluation of runaway current formation and termination during the disruption has been often carried out without including self-consistently the vertical plasma motion eventually hitting the wall

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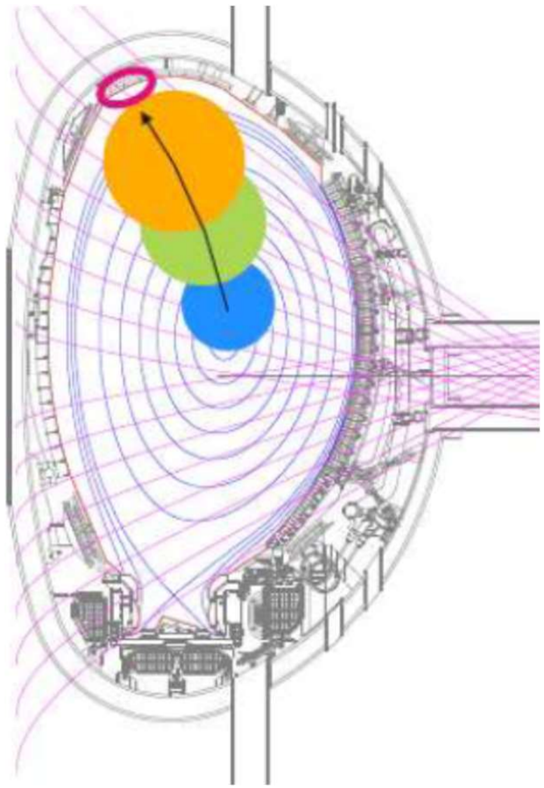
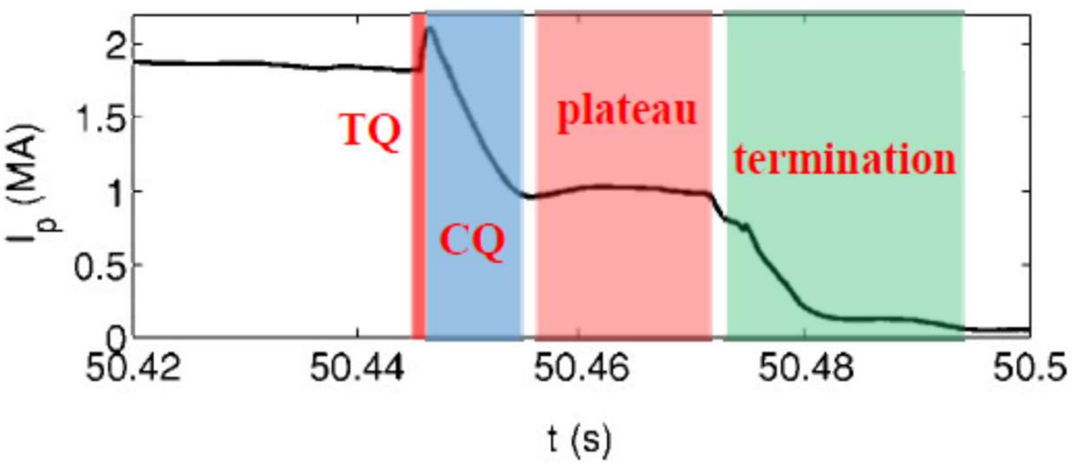
1. During the current quench, the total current decays and runaway electrons are generated until the plasma touches the wall

2. Then, the scraping-off phase starts, the current is terminated, and the runaway energy deposited onto the PFCs





Here, a simple 0-D model which mimics the plasma surrounded by the conducting structures [*D.I. Kiramov, B.N. Breizman, Physics of Plasmas* ***24****,* *100702 (2017)*] and including self-consistently the vertical plasma motion and the generation of runaway electrons during the disruption is used for an *assessment of the effect of vertical displacement events on the runaway current dynamics*

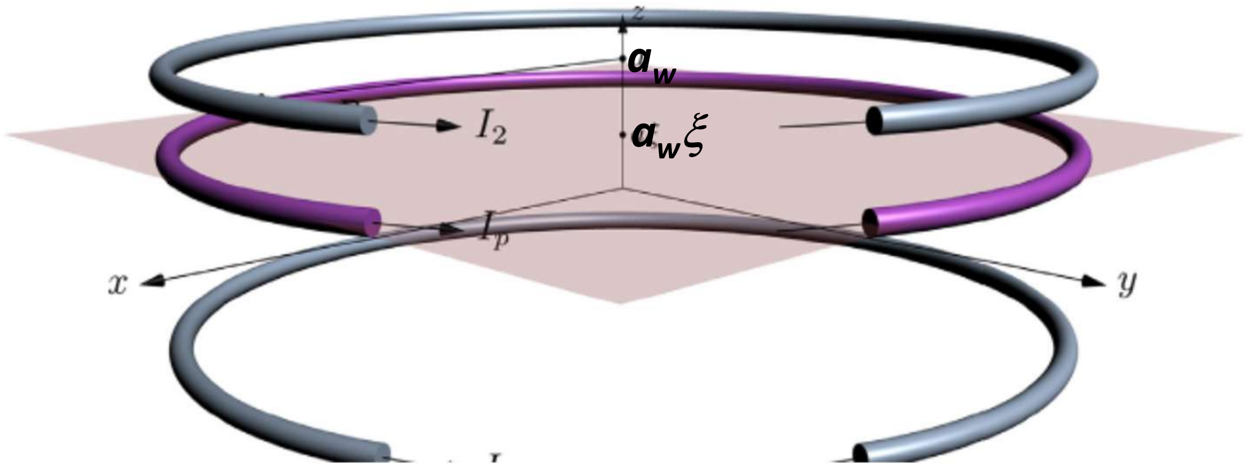
Outline

- *Three-loop model*
- *Runaway formation*
- *Scraping-off and energy deposition*

Three-loop model

(D.I. Kiramov, B.N. Breizman, Physics of Plasmas ***24****, 100702 (2017))*

- Three coaxial circular current loops, inductively coupled, represent the plasma and the chamber wall



* I_1, I_2: currents in the two inmobile loops (wall currents)

* I_p: current in the movable loop (plasma current)

* $\xi = z/a_w$: normalized current displacement

The model also includes a static magnetic field created by two constant circular currents I_e

Circuit equations:

$$L_w \frac{dI_1}{dt} + L_{12}\frac{dI_2}{dt} + L_{wp}\frac{d}{dt}[1-\kappa\ln(1+\xi)]I_p = -R_w I_1$$

$$L_{12}\frac{dI_1}{dt} + L_w \frac{dI_2}{dt} + L_{wp}\frac{d}{dt}[1-\kappa\ln(1-\xi)]I_p = -R_w I_2$$

$$L_{wp}\frac{d}{dt}[1-\kappa\ln(1+\xi)](I_1+I_e) + L_{wp}\frac{d}{dt}[1-\kappa\ln(1-\xi)](I_2+I_e) + L_p\frac{dI_p}{dt} = -R_p(I_p - I_r)$$

$$\kappa \equiv [\ln(8R_0/a_w)-2]^{-1}$$

R_w, L_w: resistance and self-inductance of the wall conductors

R_p, L_p: resistance and self-inductance of the plasma wire

L_{12}: mutual inductance of the wall conductors

mutual inductances of the plasma and wall conductors:

$$L_{1p} \equiv L_{wp}[1-\kappa\ln(1+\xi)] \quad L_{2p} \equiv L_{wp}[1-\kappa\ln(1-\xi)]$$

Force-free approximation:

$$\xi = \frac{I_1 - I_2}{I_1 + I_2 + 2I_e}$$

Runaway generation: avalanche amplification of an initial runaway seed

$$\frac{dI_r}{dt} \approx \left(\frac{dI_r}{dt}\right)_{seed} + \left(\frac{dI_r}{dt}\right)_{\text{secondary}}$$

$$\left(\frac{dI_r}{dt}\right)_{\text{secondary}} \approx \frac{I_r}{\tau_s}$$

$$\tau_s \approx \frac{4\pi\varepsilon_0^2 m_e^2 c^3}{e^4 n_e} a(Z_{eff}) \left(\frac{E_\parallel}{E_R} - 1\right)^{-1} = \frac{m_e c \ln\Lambda \, a(Z_{eff})}{e\left(E_\parallel - E_R\right)}$$

$$E_R \equiv \frac{e^3 n_e \ln\Lambda}{4\pi\varepsilon_0^2 m_e c^2}$$

$$a(Z_{eff}) \approx \sqrt{\frac{3(5+Z_{eff})}{\pi}}$$

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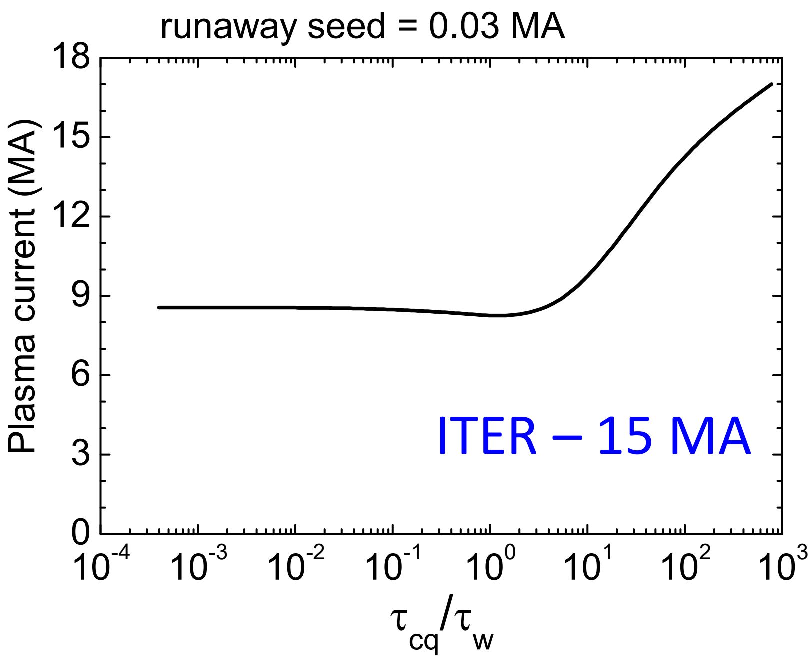
Runaway formation

During the current quench, the total current decays and runaway electrons are generated until the plasma touches the wall

The plasma current and runaway current at each time can be evaluated using the circuit equations, taking into account the generation of the runaway current

Plasma current at the time the plasma hits the wall:



if $\tau_{cq} << \tau_w$ (perfectly conducting wall), no external magnetic energy penetrates and the current at the wall tends to a constant limiting value

if $\tau_{cq} > \sim \tau_w$, penetration of external magnetic leads to an increase of the current at the wall

Vertical plasma velocity and time to hit the wall

From the circuit equation for the plasma current

$$E_{\parallel} = \frac{R_p I_{OH}}{2\pi R_0} = \frac{R_p\left(I_p - I_r\right)}{2\pi R_0} = -\frac{1}{2\pi R_0}\frac{dF}{dt}$$

where *F* is the magnetic flux across the circular contour of the plasma current,

$$F \equiv L_{wp}\left[1-\kappa\ln(1+\xi)\right]\left(I_1 + I_e\right) + L_{wp}\left[1-\kappa\ln(1-\xi)\right]\left(I_2 + I_e\right) + L_p I_p$$

and $E_{\parallel} = \frac{R_p I_{OH}}{2\pi R_0} = -\frac{1}{2\pi R_0}\frac{dF}{dt} = -\frac{1}{2\pi R_0}\frac{dF}{dz}v_p \Rightarrow$ $\boxed{v_p = -2\pi R_0 \frac{E_{\parallel}}{\left(dF/dz\right)} = -\frac{R_p\left(I_p - I_r\right)}{\left(dF/dz\right)}}$

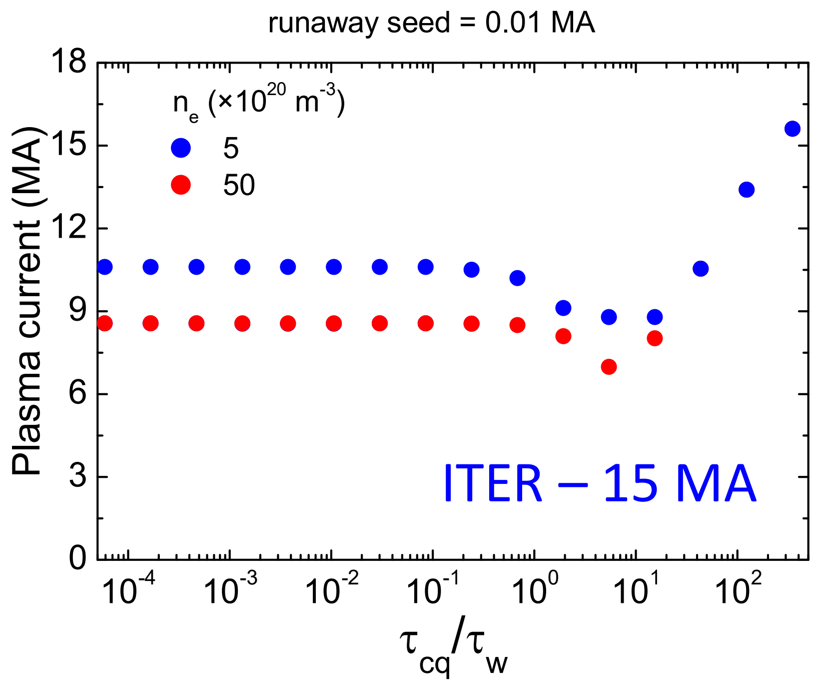
and the time to reach the wall $\boxed{\tau = -\int_{z_0}^{z_c}\frac{\left(dF/dz\right)}{R_p\left(I_p - I_r\right)}dz}$

$$v_p(\xi) = -2\pi R_0 a_w \frac{E_\parallel}{(dF/d\xi)} = -\frac{a_w R_p \left(I_p(\xi) - I_r(\xi)\right)}{(dF/d\xi)} \qquad \left(\xi \equiv \frac{z}{a_w}\right)$$

The velocity is larger for lower runaway currents (larger electric field)

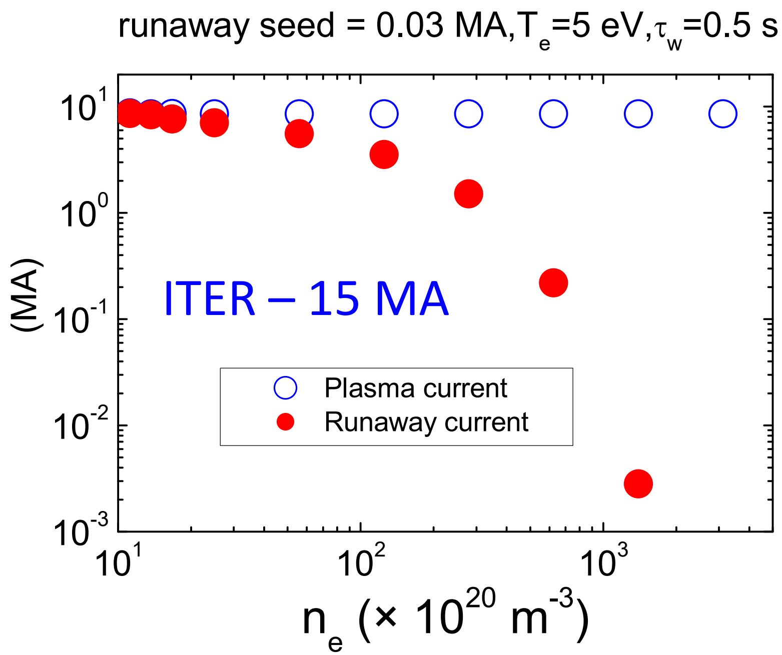
$$\tau(\xi) = -\int_{\xi_0}^{\xi} \frac{(dF/d\xi)}{a_w R_p \left(I_p(\xi) - I_r(\xi)\right)} d\xi$$

Notice that if a large runaway production occurs before the plasma touches the wall, the plasma velocity might be so small and the time to hit the wall increase so much that a large penetration of external magnetic energy could increase the current at the wall

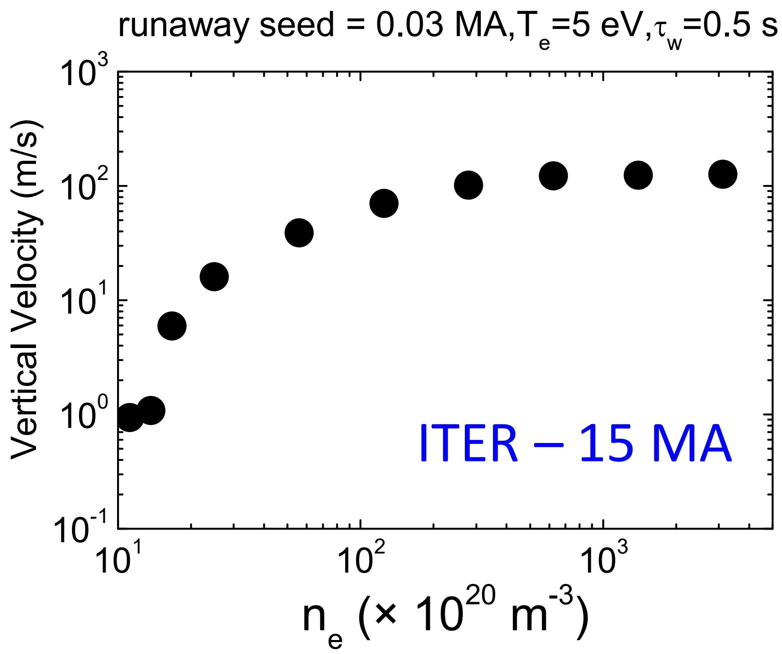


Here we will focus on the case of disruptions with large impurity content for which, for the case of ITER, with a large τ_w , would lead, to the limiting case of a perfectly conducting wall

Plasma and runaway current vs n_e at the time the plasma hits the wall:



- The plasma current is always the same
- The runaway current decreases with density
- The vertical velocity is larger for high densities (lower runaway currents)



Runaway termination (scraping-off)

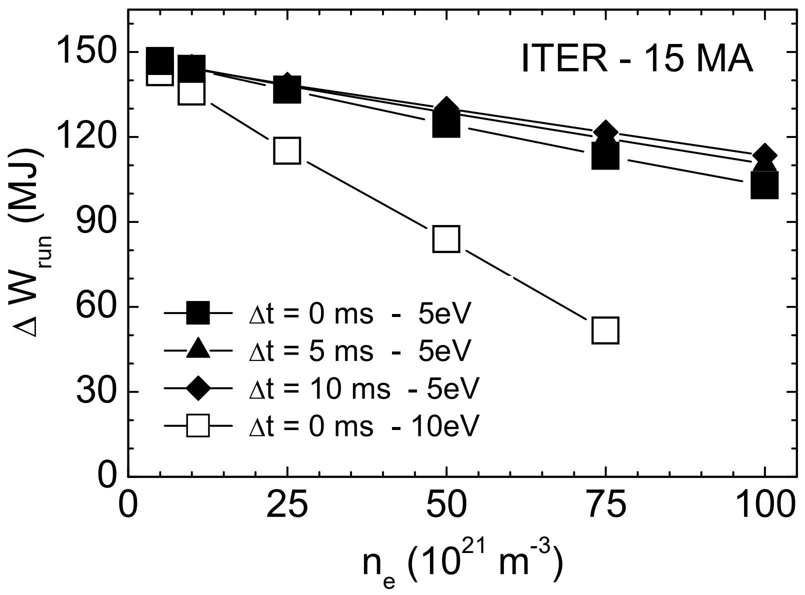
- When the runaway beam touches the wall, the scraping-off phase starts, the runaway energy is deposited onto the wall and the current is terminated
- During this phase, the plasma velocity and electric field can substantially increase leading to the deposition of a noticeable amount of energy on the REs

Simple 0-D description of the scraping-off (M. Lehnen):

$$\frac{dI_r}{dt} \approx \frac{2\dot{a}}{a} I_r$$

$$\frac{dI_r}{dt} \approx \frac{ec\left(E_{\parallel} - E_R\right)}{T_r} + \frac{2\dot{a}}{a} I_r \qquad \left(T_r \approx m_e c^2 \ln \Lambda \sqrt{3\left(5 + Z_{eff}\right)/\pi}\right)$$

Energy deposited on the runaways

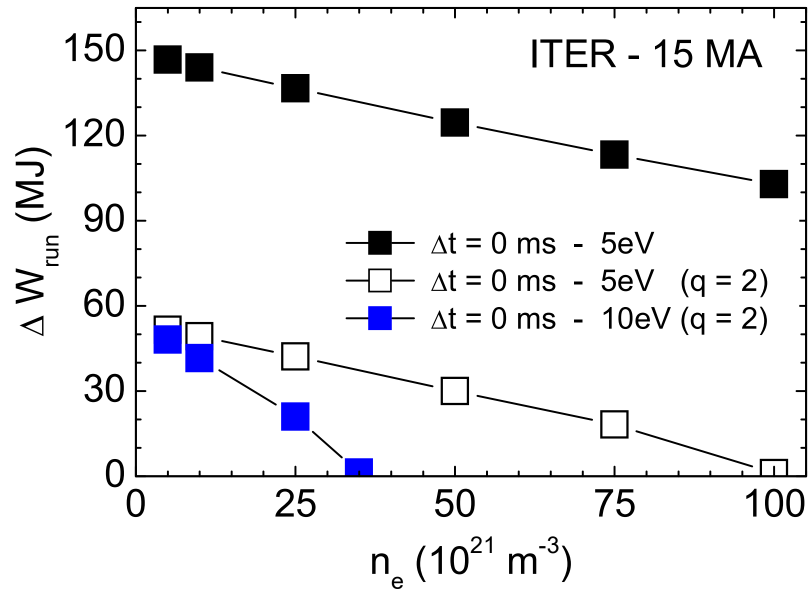


$$\Delta W_{run} = 2\pi R_0 \int I_r \left(E_{\parallel} - E_R\right) dt$$

a density $ne^0 = 5\ 10^{21}\ m^{-3}$ is assumed at the start of the CQ increasing to ne due to a second impurity injection at Δt

an earlier second injection favors a reduction on the amount of energy deposited on the runaways.

larger temperatures during the scraping-off might be efficient in reducing the power fluxes onto PFCs



the plasma reaches the q = 2 limit before the current is terminated and the amount of energy deposited on the runaways at that time can be substantially lower

Conclusions

A simple 0-D model which mimics the plasma surrounded by the conducting structures [*D.I. Kiramov, B.N. Breizman, Physics of Plasmas **24**, 100702 (2017)*], including self-consistently the vertical plasma motion and the generation of runaway electrons, has been used for an evaluation of the runaway electron formation and termination during the disruption

Formation of the runaway beam

In the case of ITER, with a highly conducting wall, the total plasma current when the plasma touches the wall is always the same, but the runaway current at that time can significantly decrease for large enough amount of impurities.

The plasma velocity is larger and the time to hit the wall shorter for lower runaway currents, when larger amounts of impurities are injected

Scraping-off and termination of the current

During this phase, the plasma velocity and electric field can substantially increase leading to the deposition of a noticeable amount of energy on the runaway electrons (more than 100 MJs)

An earlier second impurity injection can reduce somewhat the amount of energy deposited on the runaways.

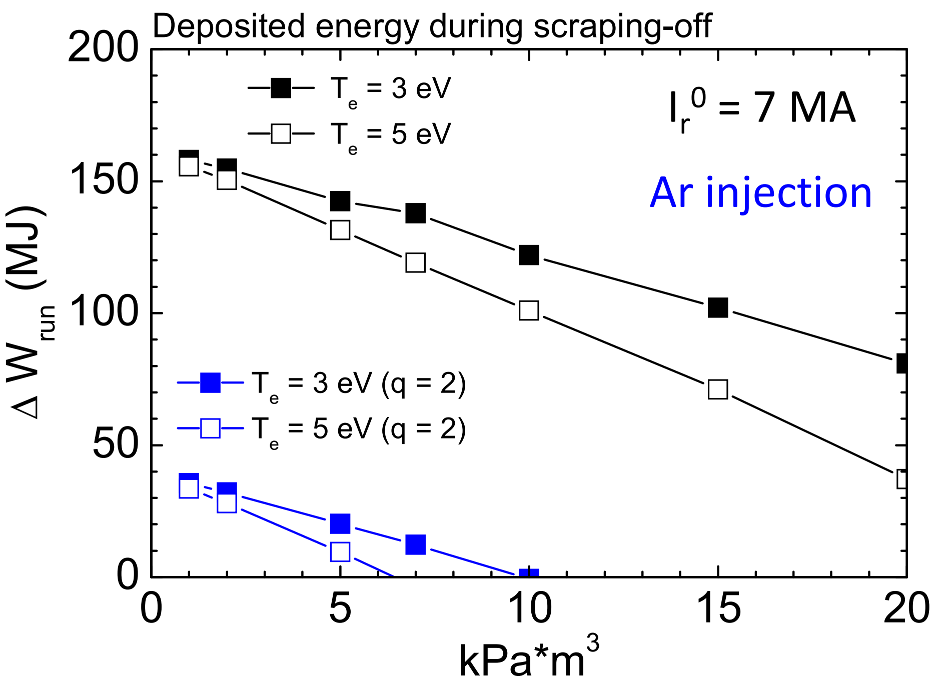
Also larger temperatures during the scraping-off might be efficient in reducing the power fluxes onto the PFCs.

The plasma reaches the q = 2 limit before the current is terminated and the amount of energy deposited on the runaways at that time can be substantially lower

- The previous analysis has not included the effect of the collisions with the impurity ions

- Similar results are obtained when including the effect of the collisions with the free and bound electrons, and with the average and the full nuclear charge of the impurity ions:

*(J.R. Martín-Solís, A. Loarte and M. Lehnen, Phys.Plasmas **22** (2015) 092512)*



$$\left(10^{21}\, m^{-3} \approx 3.5\, kPa \cdot m^{3}\right)$$