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

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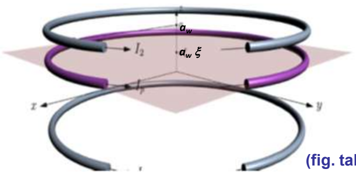
MOTIVATION

- Large amounts of runaway electrons are expected to be generated during ITER disruptions (up to ~ 10 MA) [1], the injection of high-Z impurities by Shattered Pellet Injection actually constituting the most promising candidate for runaway avoidance and mitigation [2]
- 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

Aim: a simple 0-D model which mimics the plasma surrounded by the conducting structures [3], 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*

THREE - LOOP MODEL

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



(fig. taken from [3])

- 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

plus a static magnetic field created by two constant circular currents I_e

Circuit equations:

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

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

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

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

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:

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

Force-free approximation:

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

Runaway generation:

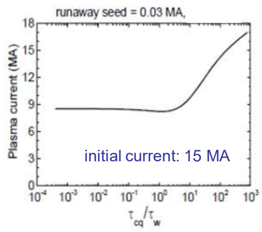
$$\frac{dI_r}{dt} \approx \left(\frac{dI_r}{dt}\right)_{seed} + \left(\frac{dI_r}{dt}\right)_{\text{avalanche}}$$

$$\left(\frac{dI_r}{dt}\right)_{avalanche} \approx \frac{I_r}{\tau_s} \qquad \tau_s \approx \frac{m_e c \ln\Lambda\, a(Z_{eff})}{e\left(E_\parallel - E_R\right)}$$

$$E_R \equiv \frac{e^3 n_e \ln\Lambda}{4\pi\varepsilon_0^2 m_e c^2} \qquad a(Z_{eff}) \approx \sqrt{\frac{3(5+Z_{eff})}{\pi}}$$

RUNAWAY FORMATION

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 energy leads to an increase of the current at the wall

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

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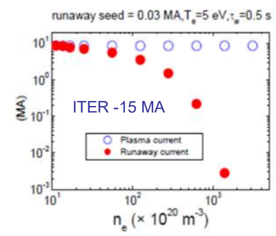
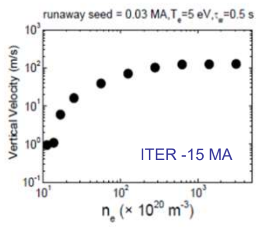
Plasma and runaway current vs n_e at the time the plasma hits the wall

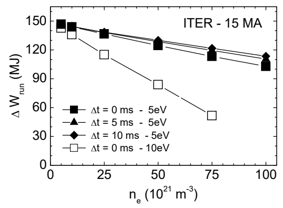




- The plasma current is always the same *(perfectly conducting wall)*
- The runaway current decreases with density
- The vertical velocity is larger for high densities (lower runaway currents)

SCRAPING-OFF AND CURRENT TERMINATION

Energy deposited on the runaways



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

a density ne⁰ = 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 somewhat 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

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

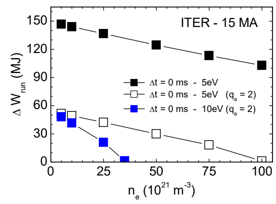
During this phase, the plasma velocity and electric field can substantially increase leading to the deposition of a noticeable amount of energy on the REs [4]

Modelling of the scraping-off [5]:

$$\frac{dI_r}{dt} \approx \frac{ec\left(E_\parallel - E_R\right)}{T_r} + \frac{2\dot{a}}{a} I_r$$

scraping-off term

q_a = 2 limit



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

it is therefore an important question if when the q_a = 2 stability boundary is crossed additional substantial conversion of magnetic into runaway energy may occur [6]

*** For simplicity, the effect of the injection of impurities has just been accounted for increasing the density n_e. Similar results are obtained by a more accurate treatment 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

REFERENCES

[1] MARTIN-SOLIS, J.R. et al., *Nucl. Fusion* **57**, 066025 (2017)
[2] LEHNEN, M. et al., Proc. 27th Int. IAEA Conf. (Ahmedabad, 2018) (Vienna: IAEA) CD-ROM file EX/P7-12
[3] KIRAMOV, D.I. and BREIZMAN, B.N., *Phys.Plasmas* **24**, 100702 (2017)
[4] LEHNEN, M., Private Communication (2018)
[5] KONOVALOV, S. et al., Proc. 26th Int. IAEA Conf., (Kyoto, 2016) (Vienna: IAEA) CD-ROM file TH/7-1
[6] PAZ-SOLDAN, C., et al., Plasma Phys. Controlled Fusion **61** (2019) 054001

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