Influence of ICRH on runaway electron generation in ASDEX Upgrade: first experimental attempts.

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Introduction. Tokamak plasmas are subject to disruptive events. During such incidents, part of the electrons can be accelerated to relativistic energies and can cause serious damage to the device [1]. Typical variants of action against these runaway electrons (e.g. massive material injection via gas or shattered pellets) are not yet demonstrated to completely solve the problem in a reactor. In our experiments in ASDEX Upgrade, we have tried to avoid runaway beam generation with radio-frequency (RF) waves in the Ion Cyclotron Resonance Frequencies-(ICRF, 30 MHz) [2]. The main idea is to provoke higher radial transport by introducing RF waves in the system during the generation phase of the runaway beam. The ICRF system has two pairs of antennas which can be independently configured and give the flexibility to change the injected wave spectra (figure 1a,b). The spectra itself has a complicated structure and was calculated with TORIC code [3].

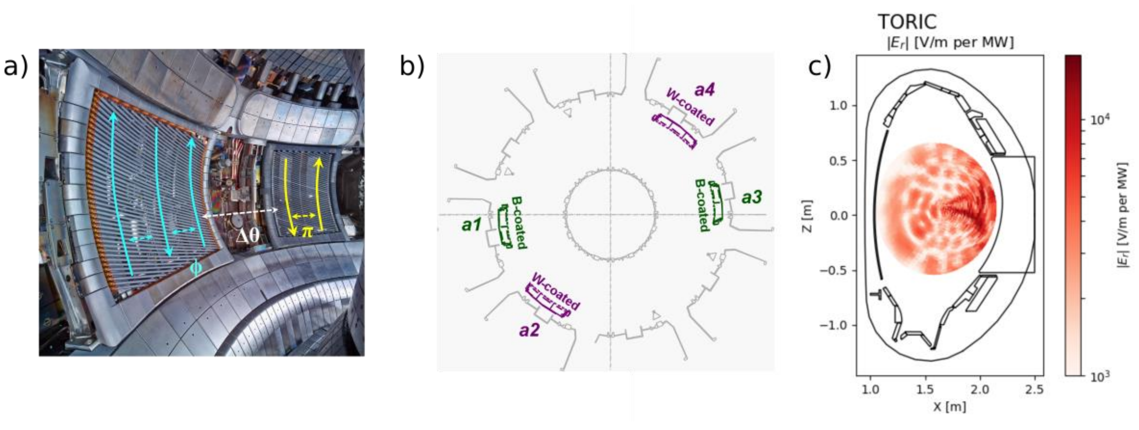

Figure 1. a) Photo of ICRH system in AUG; b) Position of the antennas from the top; c) Example of the radial field distribution for one of the runaway discharges (#35444).

The typical example of the radial electric field amplitude produced by ICRH antennas in the experiment is shown in Figure 1c (#35444). Such a field leads to a complicated picture of the resonances and the electrons can diffuse radially along the resonance lines as shown in Figure 2. The resonances here are the ones that are most sensitive to perturbations and can be found from the condition: $\omega - n\omega_{\varphi}(P_{\varphi}, \gamma, J_{\perp}) - l\omega_{\theta}(P_{\theta}, \gamma, J_{\perp}) = 0$, as discussed in Ref. [1]. Examples of such drifts are shown in the figure for outward electron drift (red trace) and inward electron drift (green trace) along the resonances for two different starting electrons. The problem is challenging for analysis and it is not clear which contribution wins. In this representation the toroidal magnetic momentum P_{φ} is connected to the radial direction drift and the relativistic γ factor to the electron energy. The increase of these two quantities is shown by arrows. This was the motivation for our first experimental studies.

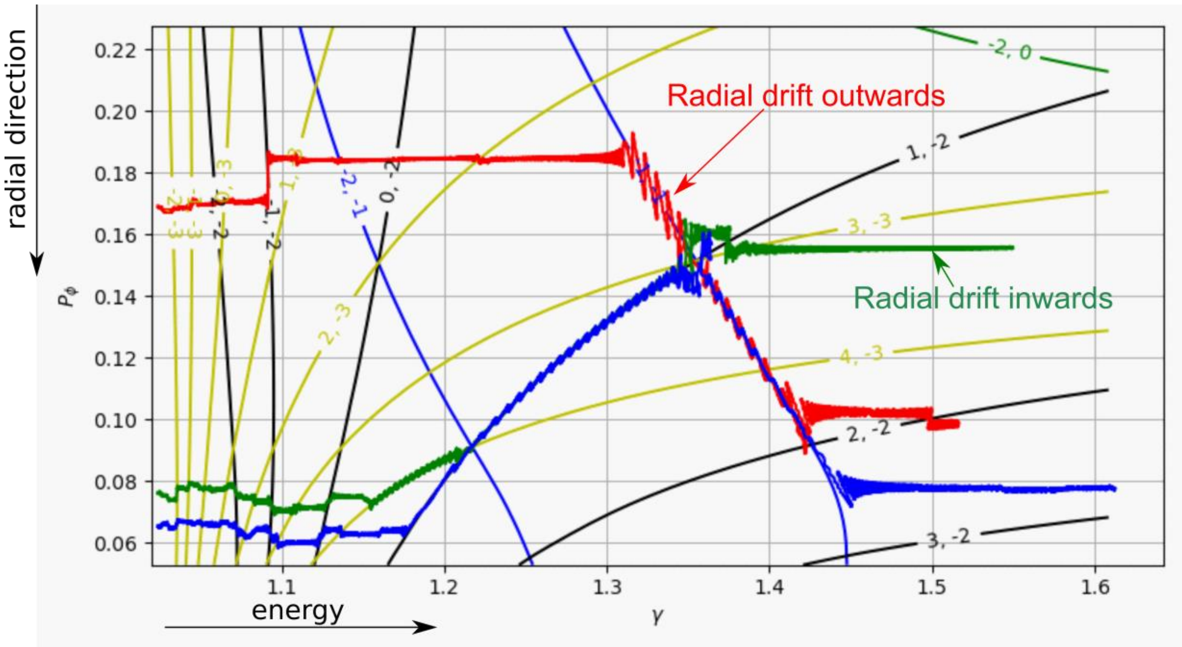

Figure 2. Resonances of the electrons are shown as a function of canonical momentum (radial position) and relativistic gamma factor (energy). Examples of radial drift inwards (green) and outwards (red) are shown. The last case (blue) shows the electron which stays basically at the same radial location.

The experiments were designed to make identical plasmas with and without ICRH in the disruption phase. For this purpose, ICRH power is stepwise raised to its maximum well before the disruption and stays constant afterward. In the first type of discharge, it was kept until the automatic switch-off of the ICRH system, we call this “with ICRH” in the following. The other type has an ICRH power switch-off just before the disruption at 0.99s or 0.995s, which will be called “without ICRH” in the following. The disruption was provoked by the Massive Gas Injection (MGI) system at 1s. Direct measurements show that the tungsten concentration in the core, core temperature, and other parameters were similar in all discharges (figure 3). The current result is the following:

- From 9 reference discharges without ICRH in the generation phase, which should always have runaways, 2 were without runaways.
- From 11 discharges with ICRH, 6 were without runaways and another 5 had runaways. Although this sounds promising, we did not succeed in finding a particular recipe for ICRH that would always avoid runaway generation. There were cases where the runaways were prevented, but it does not work for an identical attempt a few discharges later.

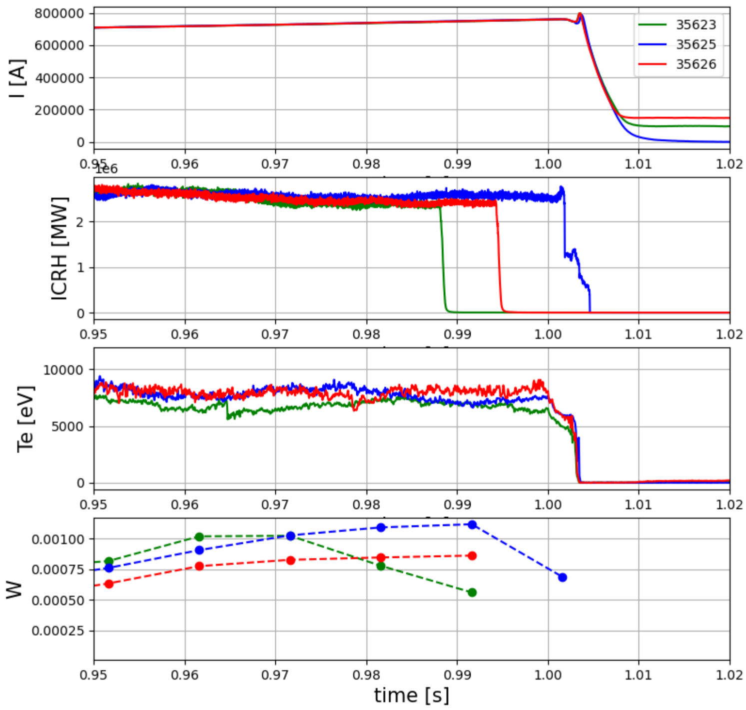

Figure 3. Main plasma parameters are shown for typical runaway discharges: Plasma current, ICRH power, electron temperature and core tungsten concentration (grazing incidence analysis of tungsten lines).

One of the main problems was the reproducibility of runaway scenarios.

Statistical analysis: Statistical analysis in our situation can be done only by considering all cases together due to the small number of experiments. It should be noted that in this case some of the discharges have different antenna phasing but belong to one statistical group. In our case, the two-proportion Z-Test was applied to check the null hypothesis that two sets are equal. The first set is the discharges without ICRH ($N_1 = N_{with\_ranaways}$ /7/ + $N_{no\_runaways}$/2/ =9) $p_1 = \frac{2}{9}$. The second set is the discharges with ICRH ($N_2 = N_{with\_ranaways}$ /5/ + $N_{no\_runaways}$/6/ =11) $p_2 = \frac{6}{11}$.; $p_x = (p_1N_1 + p_2N_2)/(N_1 + N_2)$. $z = (p_1 - p_2)/\sqrt{p_x(1-p_x)(1/N_1 + 1/N_2)} = -1.468$ The result p-value for this z can be found in the table [4] and is larger than the threshold: $p_{value} = 0.142 > 0.025$. Thus, one can neither reject nor confirm the null hypothesis, and a larger number of experiments (approx. two-three times larger compared to the executed) is required to clarify the influence of ICRH on runaways with statistics.

Conclusions. In the paper, we report the details of the first experiments and show how different potentially important factors, for example, possible differences in tungsten concentration, were excluded by the design of the experiments. Despite all our attempts, we did not succeed in finding a particular recipe for ICRH that would always avoid runaways. This is partially due to the limited statistics together with the reproducibility of runaway scenarios in the particular session. At the same time, there is room for further improvements. It is in principle possible, but challenging, to modify ICRH automatic switch-off and prolong the ICRH phase into the disruption. This should make possible more stable experiments, compared to the present situation with larger ICRH power (figure 4).

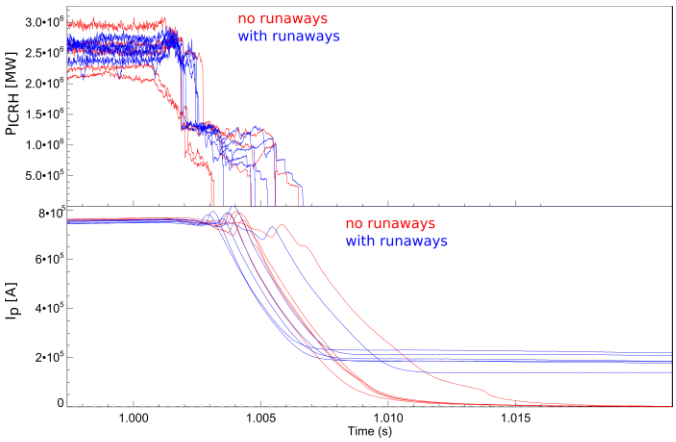

Figure 4. ICRH power and plasma current for all discharges used in the publication for the analysis. Discharges with runaways are shown in blue. Discharges without runaways are red.

References

[1] B.N. Breizman et.al., Nucl. Fusion **59** (2019) 083001

[2] V. Bobkov et al., Nucl. Fusion **56** (2016) 084001

[3] M. Brambilla and R. Bilato, Nucl. Fusion **49** (2009) 085004

[4] For calculation of p-value from z-value there are two standard variants

a) from the table https://www.statology.org/p-value-from-z-score-by-hand/

b) online https://www.statology.org/z-score-to-p-value-calculator/