

## GENERATION OF FAST ELECTRONS IN TJ-II

L. Rodríguez-Rodrigo, F. Medina, M.A. Ochando, A. López Fraguas and  
TJ-II Team

Asociación EURATOM-CIEMAT, Madrid, Spain.

### I-Introduction

Electron Cyclotron Resonance ( $f = 53.2$  GHz, 2nd harmonic,  $P_{\text{ECRH}} = 250$  kW, pulse length of  $\Delta t = [100 - 250]$  ms) heated plasmas have been produced in TJ-II for a wide range of magnetic configurations [1]. During the coils current ramp-up and ramp-down phases, runaway electrons are generated and hard x rays (HXR) fluxes have been detected in most of the discharges during the first year TJ-II campaign. To prevent high x ray doses and damage to the wall of the device, a mechanical paddle has been installed inside the vacuum chamber that cuts the poloidal magnetic surfaces a few milliseconds both before and after the fields flat-top. Accelerated electrons which follow the magnetic field lines would then be stopped. Otherwise, fast electrons, still confined during the steady-state phase, absorb part of the ECRH injected power, as it has also been observed in other devices [2].

Nevertheless, for some operation regimes in discharges where no runaways were present, photons with energies up to 200 keV have been detected during ECRH.

In this work the obtained results are analysed for different configurations and in some cases with and without paddle in an attempt to experimentally give a description of runaway generation process and its consequences for the discharge.

### II-Electric fields during current variations in magnetic coils and runaway generation.

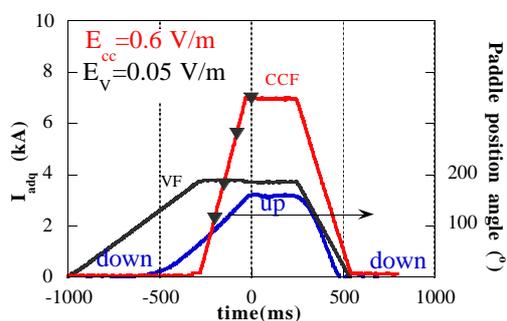


Figure 1: Central (CCF) and vertical (VF) field coil currents. The triangles correspond to the magnetic flux surfaces on figure 2. Paddle (illustrated in figure 3) movement up and down during the discharge.

In the TJ-II stellarator (low magnetic shear,  $R_0 = 1.5$  m  $\langle a \rangle = 0.10 - 0.20$  m) [1], the magnetic field  $B_0 = 0.95$  T is generated during the flat top of current in a system of central, toroidal and vertical coils. The central conductors, which provide the flexibility of the TJ-II device, consist of a circular solenoid and two helical coils which are wrapped around the central solenoid. The time evolution of currents starts at  $t = -1$  s. Only vertical and central coils induce toroidal loop voltages in TJ-II. The flat top in current is well reached at  $t = 0$  s for all the coils and can last 0.5 s. At  $t = 0.04$  s electron cyclotron heating wave is injected (see figure 1). Depending on the configuration, the ramp up of current in the vertical field coils induces an electric field up to  $E_v \sim 0.1$  V/m during 0.72 s for the highest nominal currents. When the flat top of the vertical field is reached, the main accelerating electric field is then induced by current ramping in the central coils. The value of this electric field can reach  $E_{cc} \sim 1$  V/m during 0.25 s. During the ramp down of the currents, that is not critical for plasma generation, an electric field of about 3 V/m is induced during 0.1-0.2 s. Figure 1 illustrates the values of current coils for a set of currents of one discharge of the large flexibility ( $I_c = 10$  kA,  $I_{hx} = 5.0$  kA,  $I_{vf} = 6.5$  kA, so called configuration 100-50-65) diagram and corresponds to the operational protocol used in all TJ-II campaigns. The TJ-II coil set-up forms during the flat top closed and nested magnetic surfaces that have been calculated for many points of the configurational diagram and measured out at low magnetic field [3]. Furthermore, closed and nested magnetic surfaces appear during the ramp up of current in central coils. Figure 2 shows the Poincaré diagram of the closed magnetic surfaces for a configuration 100-32-60, for three different moments of the ramp-up and for the beginning of the flat top. It can be seen that the

magnetic axis enters the vacuum chamber about 0.2 s before the steady-state phase allowing free electrons to be accelerated and confined. Consequently, if the energy reached by those fast electrons is high enough they can generate X rays by bremsstrahlung on the puffed gas, the plasma or the wall.

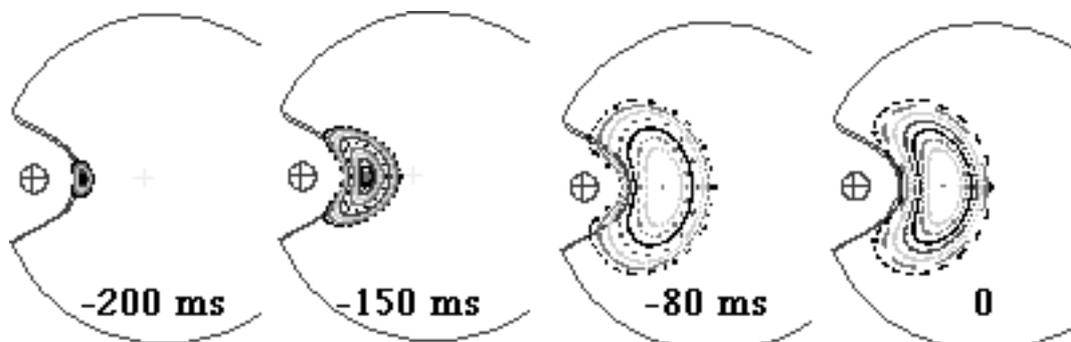


Figure 2: Evolution of the magnetic flux surfaces with the ramp-up of the currents in the central coils as show in figure 3.

To prevent the acceleration of runaway electrons a mechanical paddle has been installed in a top port in TJ-II (figure 3). It consists in a pneumatically operated shutter that is introduced in the vacuum chamber twice. The downer position is the rest one. During the ramp up of currents it rotates up pushed by the pneumatically activated piston. It stays up during the gyrotron pulse and rotates down when currents fall down. Duration of movements down and up, given by a resistor, can be regulated by the valves and the trigger timing.

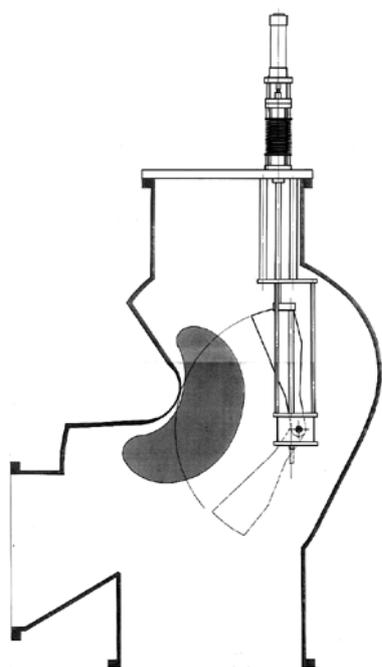


Figure 3: Mechanical paddle interfering poloidally the magnetic surfaces.

During the first operation campaign of TJ-II hard x ray fluxes were obtained before and during the flat top of the discharge as shown in figure 4a. Confinement time  $\tau_{\text{run}}$  of lost electrons has been deduced from the fall down of the hard x ray signal.

### III X ray measurements

The experimental set-up for hard x ray measurements consists of two NaI(Tl) detectors mounted on phototubes. One of them is operated with the phototube in current mode and gives the time behaviour of the hard x ray flux incoming from all the device. The other one, shielded and collimated, works in pulse height analysis (PHA) mode and gives energy of photons generated by fast electrons. Both detectors receive photons crossing the vacuum chamber wall or generated inhere. The wall is a stainless steel filter that stops photons of less than 100 keV. For medium energy photons a planar Ge detector working in PHA has a tangential access to the inner part of the vacuum vessel through a quartz window which stops photons below 20 keV. X rays from thermal electrons are measured by a Si(Li) detector connected to the vacuum chamber and collimated to see a central plasma chord [4].

#### a-Hard x rays

The dependence of  $\tau_{\text{run}}$  on the magnetic configuration volume is shown in figure 4b. Maximum energy for those electrons has been deduced from hard x ray spectra and gives values about 1.5 MeV which means that time acceleration is about 20-70 ms depending on the loop voltage induced,  $V_{\text{loop}}$ . In these cases higher  $V_{\text{loop}}$  is also higher volume [1], so  $\tau_{\text{run}}$  seems to corresponds to the drift time of accelerated electrons once  $V_{\text{loop}}$  is nul.

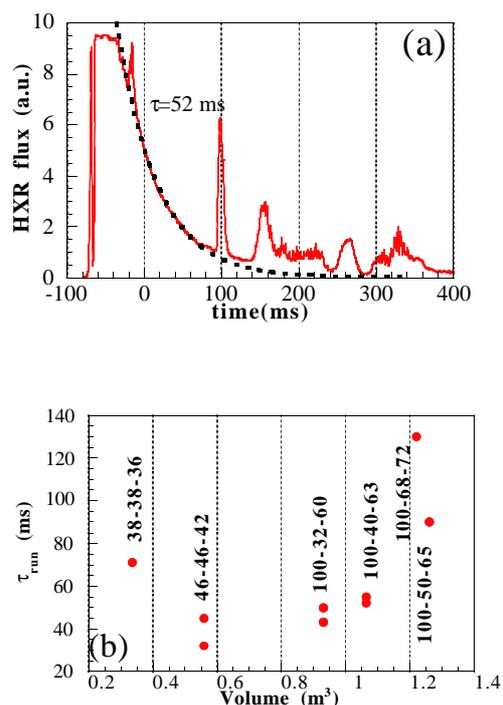


Figure 4: (a) Hard x ray flux, HXR, produced by the ramp up of currents. e-falling curve fitting of the HXR flux is the dotted line. (b) The deduced runaway electrons confinement time,  $\tau_{run}$ , as a function of the volume for each magnetic configuration.

electrons production is observed when line density rises above  $0.5 \times 10^{19} m^{-3}$ . Nevertheless, even for high density plasmas and microwave absorption in the range of 80% - 90%, the x ray flux never disappears completely, although its mean energy gradually decreases.

An estimation of the confinement time of these fast electrons, of the order of 3-4 ms, is done from the falling time of the flux traces when density is high enough.

As well, a Si(Li) detector (spectral range from 1.5 to 10 keV) has observed significant deviations from the maxwellian distribution at energies of the order of a few times the thermal one (see figure 9). In selected discharges with modulated density, the deviation from the maxwellian distribution is favoured by the decrease of density. This effect can only be observed when first pass absorption is of the order of 40% - 60%, as deduced from ray tracing calculations.

## b-Runaway electron control

Runaway electrons were suppressed using the mechanical paddle as shown in figure 5 where the paddle position is plotted together with the hard x ray flux. As a general observation, in discharges with very high flux, microwave absorption is marginal. In figure 6 the strong decrease of the mean energy of fast electrons can be observed.

## c-Measurements without runaway electrons

Even when runaways were suppressed there is always present a flux of x rays (x ray energies up to 200 keV and mean energy about 40 keV have been measured in typical discharges, on the other hand, for delayed discharges and discharges of very low density the mean energy of these fast electrons increases up to 100 keV) associated with fast electrons originated from the ECRH. This flux starts at the onset of the discharge even if it is delayed a time longer than the measured runaway confinement time (see figure 7). Also, the time evolution of the x ray flux and mean energy show a behaviour that is clearly correlated with density: they are higher for lower density (see figure 8). This dependence with density is non linear and a strong reduction of fast

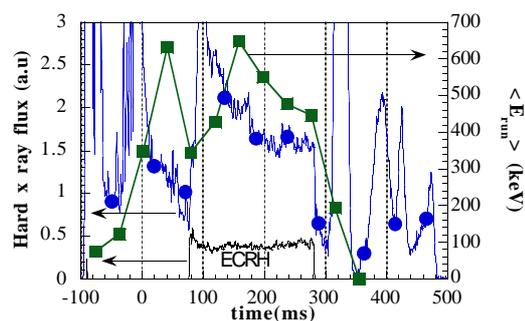


Figure 5: Discharge with runaway generation. There is no plasma breakdown.

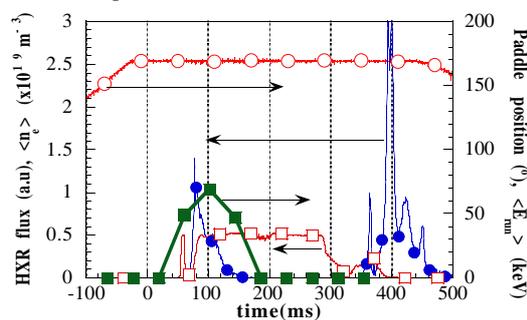


Figure 6: Paddle effect on runaway electrons. Open circles represent the paddle position angles. Runaway electrons are suppressed, only fast electrons generated by ECRH are present at the beginning of the discharge. Final HXR flux corresponds to the coil current ramp-down.

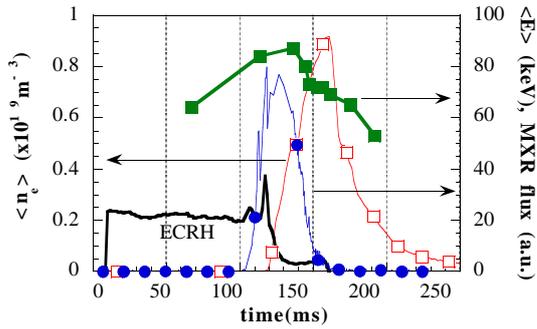


Figure 7: Time evolution of intermediate energy flux, MXR, (close dots) and mean energy (full squares) of fast electrons generated by ECRH. The onset of the discharge is 120 ms delayed.

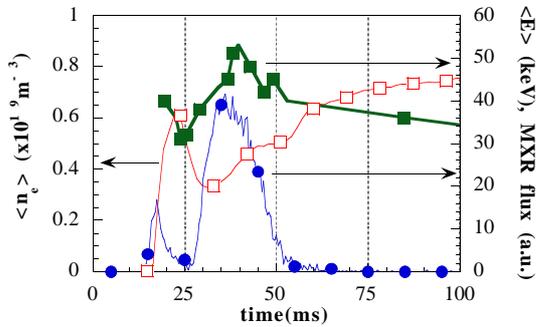


Figure 8: Time evolution of intermediate energy flux, MXR, (close dots) and mean energy (full squares) of fast electrons generated by ECRH in a typical discharge. The discharge lasts 150 ms more and the fast electrons mean energy falls to 20 keV.

high energy electrons are not a separate population that compete with thermal electrons in absorbing the non absorbed power in first pass, but are thermal electrons pumped to higher energies. If true, they would be a non negligible sink energy channel because they get uncoupled from the plasma bulk and lost faster than thermal particles (estimated global particle confinement time is about 8 ms [6]). Further investigations are on the way to obtain a more detailed information on the relevance of superthermal and fast electron populations as a power loss channel.

References

- 1-C. Alejaldre et al., Plasma Phys. Control. Fus., **41**, A539 (1999).
- 2-A.C. England et al., ORNL/TM-10988, (1989).
- 3-E. Ascasibar et al., J. Plasma Fus. Res. **1**, 183 (1998).
- 4-F. Medina et al., Rev. Sci. Instrum. **70**, 642 (1999).
- 5-F. Medina et al., Plasma Phys. Control. Fus., **40**, 1897 (1998).
- 6-F.L. Tabarés et al., at this conference.

IV-Discussion

As is well known, in ECRH plasmas, superthermal electrons generation is favoured by low first pass absorption. This fact was interpreted on the basis of both, first pass absorption at high field by high energy resonant electrons (plasma transparency) and by the successive delocalized absorptions of the reflected microwave beam [5]. To try to elucidate whether or not these fast electrons (mean energy 30-50 keV) may gain a substantial part of the incident power mainly due to plasma transparency, the launching angle of the microwave beam has been changed in a series of discharges with about the same electron density. What is seen is that the energy confinement time is modified as shown in figure 10. The radiation losses normalized to the average electron density are also displayed and although not shown, the flux of intermediate energy x ray detected (20-200 keV) seems to present a similar behavior than the confinement time. This may indicate that once the plasma is established,

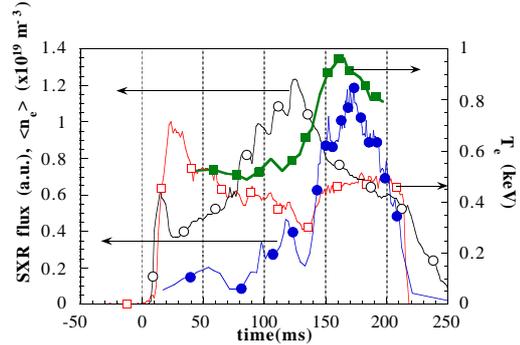


Figure 9: Time evolution of soft x ray flux, SXR, (close dots) and mean energy (full squares) of fast electrons generated by ECRH. Central electron temperature is represented by open squares.

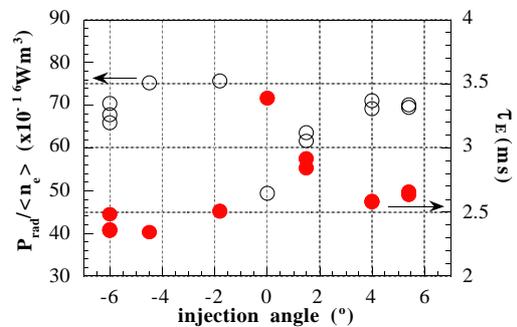


Figure 10: Influence of the ECRH launching angle on energy confinement time and radiated power per particle.