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Empirical Evaluation of the Radiative Cooling Coefficient for Krypton Gas in the FTU Plasma

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ABSTRACT

For future fusion reactors, a careful balance must be achieved between the cooling of the outer plasma via impurity radiation and the deleterious effects of inevitable core penetration by impurity ions. We have injected krypton gas into the Frascati Tokamak Upgrade (FTU) plasma. The measured visible bremsstrahlung and bolometric signals from krypton have been inverted and the resulting radial impurity density profile and power loss profile for krypton gas are extracted. Using the measured electron density and temperature profiles, the radiative cooling coefficient for krypton is derived. The level of intrinsic impurities (Mo, Cr, Mn and Fe) in the plasma during the krypton puffing is monitored with a VUV SPRED spectrometer. Models for krypton emissivity from the literature are compared to our measured results.

I. The Experiment

The Frascati Tokamak Upgrade (FTU) is a high magnetic field, high electron density tokamak (Fig. 1). The major radius of the torus, R, is 0.93 m and the minor radius, a, is 0.3 m. Two krypton (Kr, Z=36) injections were made in June of 1997. For those shots (13050 and 13060) the plasma current, I_p was 500kA, the toroidal field, B_T was 5.2T and the average electron density of the plasma was low for the FTU parameter space, $\langle n_e \rangle = 5\text{x}10^{19}$ m^{-3}.

Fig. 1 The Frascati Tokamak Upgrade (FTU).

FTU characteristics	
R^{maj}	0.93 m
a	0.3m
B_T (max)	8 T
I_P (max)	1.6 MA
$\langle n_e \rangle$	0.3 to 3×10^{20} m^{-3}
T_e	0.7 to 8 keV
ECRH	400 kWatts
LH	1 MWatt

Large volumes of Kr were introduced to the plasma for both shots. The result was that more than 230 msec after the injection, the plasma disrupted. Figure 2 shows the time history of soft x-ray emission from the core of the FTU plasma during shot 13060. The Kr was injected at t=0.80 seconds and the plasma disrupts at t=1.03 seconds.

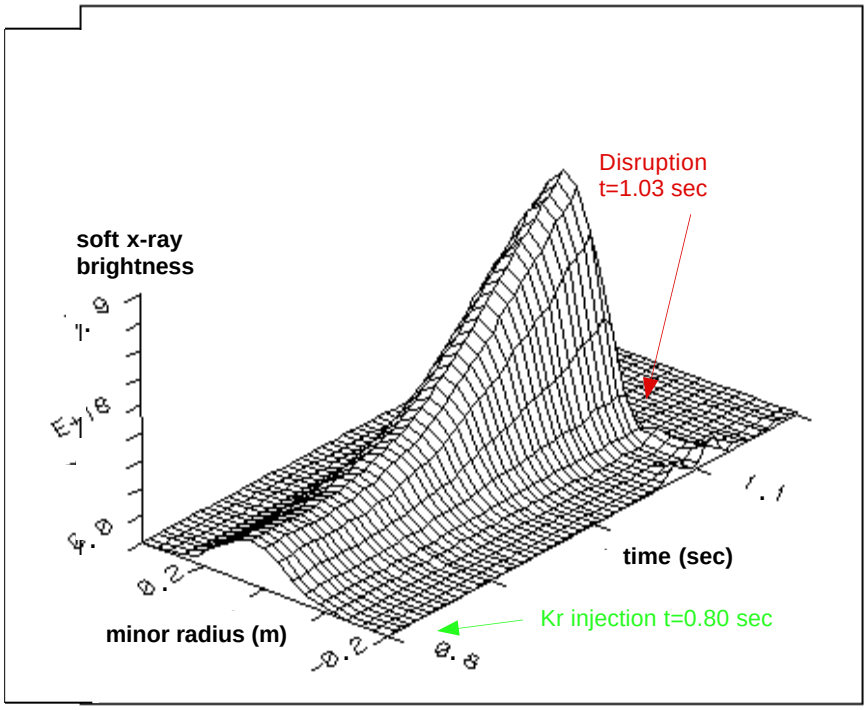

Fig. 2 Temporal and spatial profiles of the soft x-ray emission in the FTU plasma (shot 13060). The Kr was injected at t=0.80 seconds.

The time chosen for the analysis in the present work was t=1.0 seconds. The Kr had been in the plasma 200 msec, and the disruption was 30 msec away; the diagnostic systems considered in this work have a time resolution on the order of ≅1 msec.

II. The Model

We have developed a very simple, analytic model which uses the measured power losses from bolometry and visible bremsstrahlung to derive the density profile and radiative loss coefficient for krypton gas in a high temperature, low density plasma. With this result, we can assess the radiative patterns of Kr and its penetration behaviour in ohmically heated plasmas. With the empirical value for the Kr radiation coefficient, we can test different theoretical predictions for the efficiency of Kr as a cooling channel in a hot plasma. We may also be able to say something interesting about the transport of a high-recycling impurity in a tokamak plasma.

The total power radiated from the plasma and the total power lost by free-free transitions (bremsstrahlung) is given by

$$P^{Rad}(r) = n_e N_{Kr} Q_{Kr}(T_e(r)) + n_e \sum_i N_{Z_i} Q_{Z_i}(T_e(r))$$

$$\varepsilon^{Brems}(r) = n_e N_{Kr} < Z_{Kr}^2 > f(T_e(r)) + n_e \sum_i N_{Z_i} < Z_{Z_i}^2 > f(T_e(r))$$

where $Q_z(T_e)$ is the radiative cooling coefficient for impurity species Z, $<Z>$ is the average charge on an impurity ion at temperature T_e, f is a slowly varying function of temperature and the sums over i run over all other impurities in the plasma (Cr, Mn, Fe, Ni, Mo and oxygen). Note, n_e, N_{Kr}, $<Z^2_{Kr}>$, etc. are functions of minor radius.

<u>Observations</u>:

- The temperature in the plasma changes from 1.8 keV before the Kr injections to 1.5 keV afterwards.

- During this time, the level of intrinsic impurities is monitored with a VUV SPRED spectrometer and found not to change (Fig. 3).

Since the level of intrinsic impurities and the function $f(T_e)$ do not change significantly during the Kr injections, the signals from P^{Rad} and ε^{Brems} at some time after the injections can be subtracted from the signal at a time before the injection to yield the contribution from Kr alone

$$P^{Rad}(r) = n_e N_{Kr} Q_{Kr}(T_e(r))$$

$$\varepsilon^{Brems}(r) = n_e N_{Kr} < Z_{Kr}^2 > f(T_e(r))$$

The experimental values of P^{Rad} and ε^{Brems} are obtained by means of Abel inversion of the signal from a 13 channel bolometer array and a 12 channel visible bremsstrahlung array.

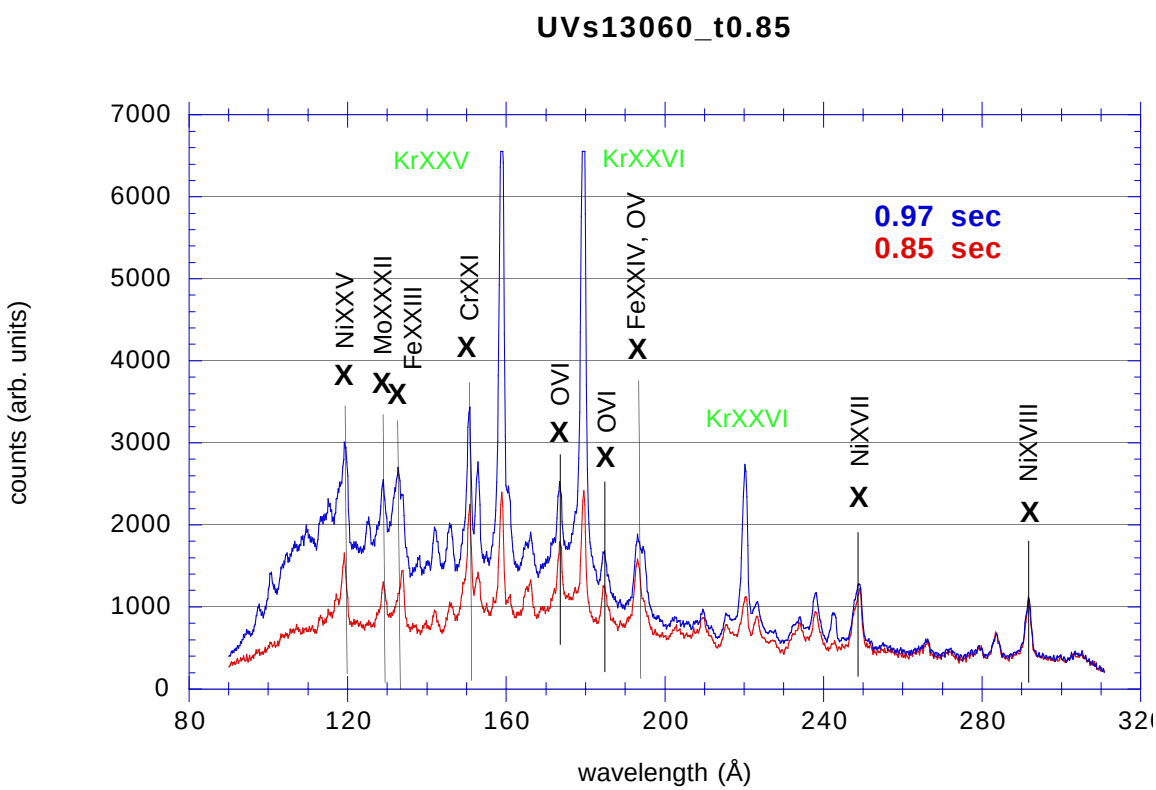

Fig. 3 The SPRED spectrum from shot 13060 at a time before and after the Kr injection. The lines marked with 'X' are from intrinsic impurities and do not change in time.

III. Bremsstrahlung Data

Bremsstrahlung data is from a vertical (12 chord) array. This array looks directly into a port at the bottom of the machine and thus, sees no reflected light. The data from this array at three times during shot 13060 are shown in Fig. 4. The Kr was injected at 0.8 seconds.

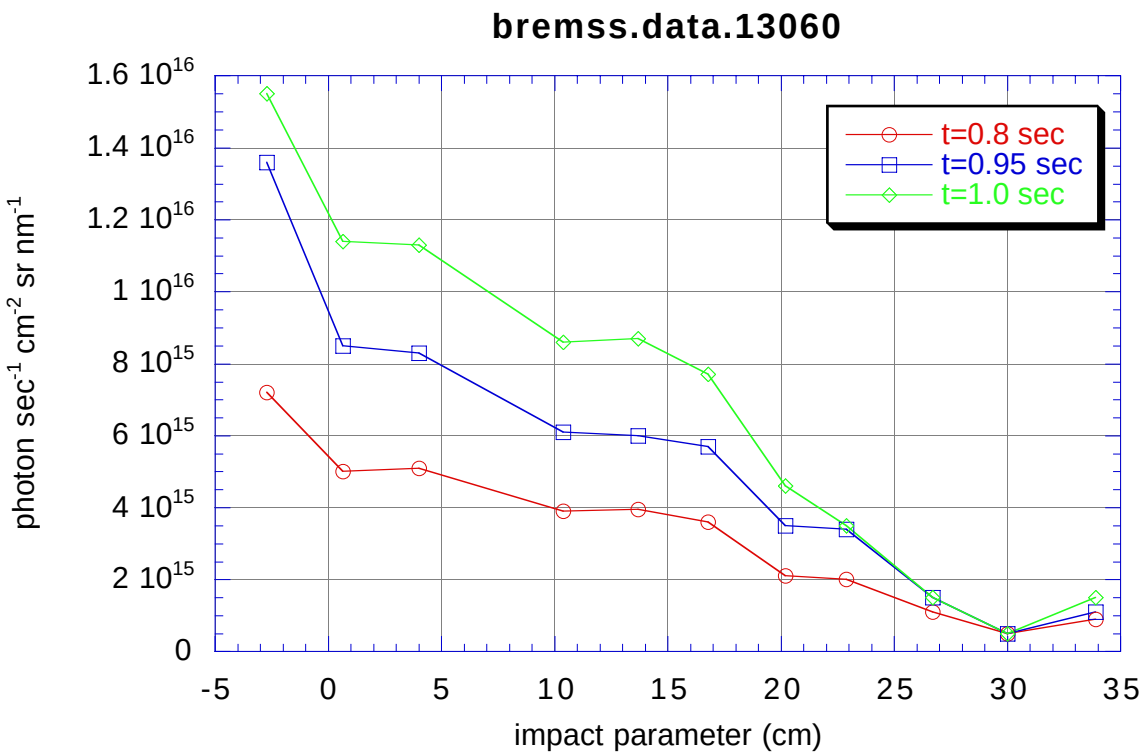

Fig. 4 Brightness seen as a function of viewing chord for the vertical bolometer array.

We have, according to the definition of Z_{eff},

$$n_e'(r)Z_{eff}'(r) = n_D(r) + \sum_{i,j'} n_{i,j'}(r)Z_i^2(r)$$

and with the assumption that the concentration of intrinsic impurities is constant during the time Kr is in the plasma

$$n_e(r)Z_{eff}(r) = n_D(r) + \sum_q N_{q,Kr}(r)Z_{q,Kr}^2(r) + \sum_{i,j'} n_{i,j'}(r)Z_i^2(r)$$

where the primed quantities are for the time before the Kr injection, the sum over j is over all impurity species other than Kr, the sum over i is over all charge states of each impurity, and the sum over q is over all the ions of Kr.

Thus, taking the difference between the two times,

$$\boxed{n_e(r)Z_{eff}(r) - n_e'(r)Z_{eff}'(r) = N_{Kr}(r)\left\langle Z_{Kr}^2(r)\right\rangle}$$

where the quantity $\langle Z^2_{Kr}\rangle$ is the average charge on a Kr ion at some temperature, T_e (see below).

The bremsstrahlung losses from the plasma are given by

$$\varepsilon_{ff}(r) = \frac{n_e^2(r)Z_{eff}(r)}{\kappa} g_{ff} \frac{1}{\lambda^2\sqrt{T_e(r)}} \exp\left(-\frac{1240}{T_e(r)\lambda}\right)$$

where T_e is in eV, λ= 540nm and κ contains various physical constants.

By substituting for Z_{eff}(r) and Z'_{eff}(r) in the equation above, the bremsstrahlung losses from Kr are given by

$$\varepsilon_{ff}(t) - \varepsilon_{ff}(t') = \frac{\overline{n_e}}{\kappa\lambda^2}\left[\overline{g_{ff}}\,\frac{1}{\sqrt{T_e(r)}}\exp\left(-\frac{1240}{T_e(r)\lambda}\right)\right] N_{Kr}(r)\langle Z_{Kr}^2(r)\rangle$$

where t' is before the injection, t is after the injection and the quantity in the brackets is the slowly varying function, $f(T_e)$, mentioned above.

<u>Comments</u>:

- For the electron density, temperature and the Gaunt factor, the quantities with the overbars are found by assuming an average value of the density and temperature for the time before and after the injection.

- The quantity ε_{ff} is the volumetric power lost due to free-free transitions. The measurements are, of course, line-of-sight integrated and must be inverted. In this case, the difference in the signal at a time before and after the injection is fit to a sum of Zernicke polynomials, and then the inversion is performed.

Data from shot 13060

	t=0.80 sec	t = 1.0 sec	
n_e(r=0)	0.9×10^{20} m^{-3}	1.3×10^{20} m^{-3}	+40%
T_e(r=0)	1.8	1.5	-16%
$g_{ff}(T_e)$	4.12	4.02	-2%

Thus, using an inversion of the difference in the bremsstrahlung data before and after the Kr injection, the experimental T_e and n_e profiles, and the tables of Post *et al.* (ADNDT, 1977) for $\langle Z^2_{Kr}\rangle$ as a function of T_e, we find the Kr density profile directly.

The resulting Kr density profile is shown in Fig. 5.

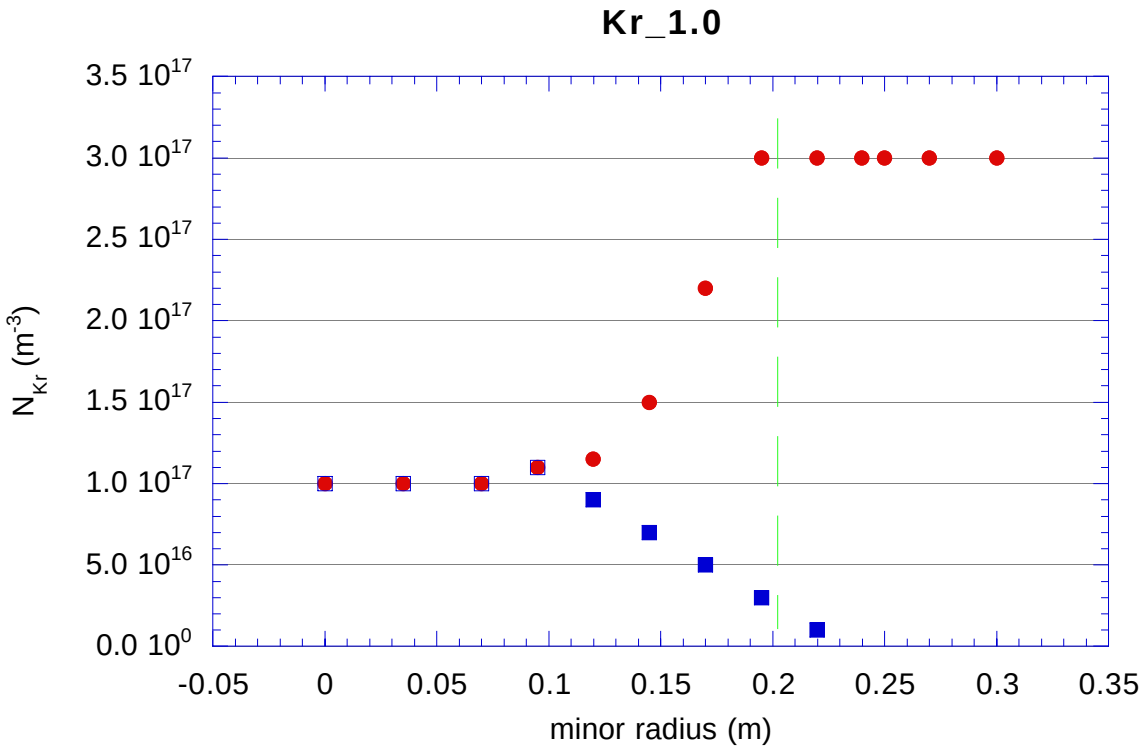

Fig. 5 The radial profile of Kr at t=1.0 sec in shot 13060 (red circles). The blue boxes are an artificial, decreasing profile (discussed below). The green vertical line indicates the limit at which the inverted data are reliable.

<u>Observations</u>:

- The profile indicates that at t=1.0 sec, the Kr concentration in the core plasma ($r < 10$ cm) is 0.1% of the central electron density.

Observations (continued):

- The profile is clearly increasing outwards from the center of the plasma up to the limit of the data. This is consistent with the observations that:

(1) Kr is a high-recycling impurity. Its source at the plasma's edge does not decay in time, but rather remains quite strong.

(2)It has been observed that there is a transport barrier in the plasma near the half-radius of the FTU (Pacella *et al.*, Plas. Phys. and Controlled Fusion, 1997). This is the position where the large gradient in N_{Kr} exists.

A density profile that decreases with radius (consistent with a typical high-Z intrinsic impurity density profile) is indicated by the boxes in Fig. 5. This profile yields results for the Kr radiative cooling coefficient, derived in the section below, which are not consistent with theoretical models (see following section).

IV. Bolometry Data

The data from the bolometer array at three times during shot 13060 is shown in Fig. 6.

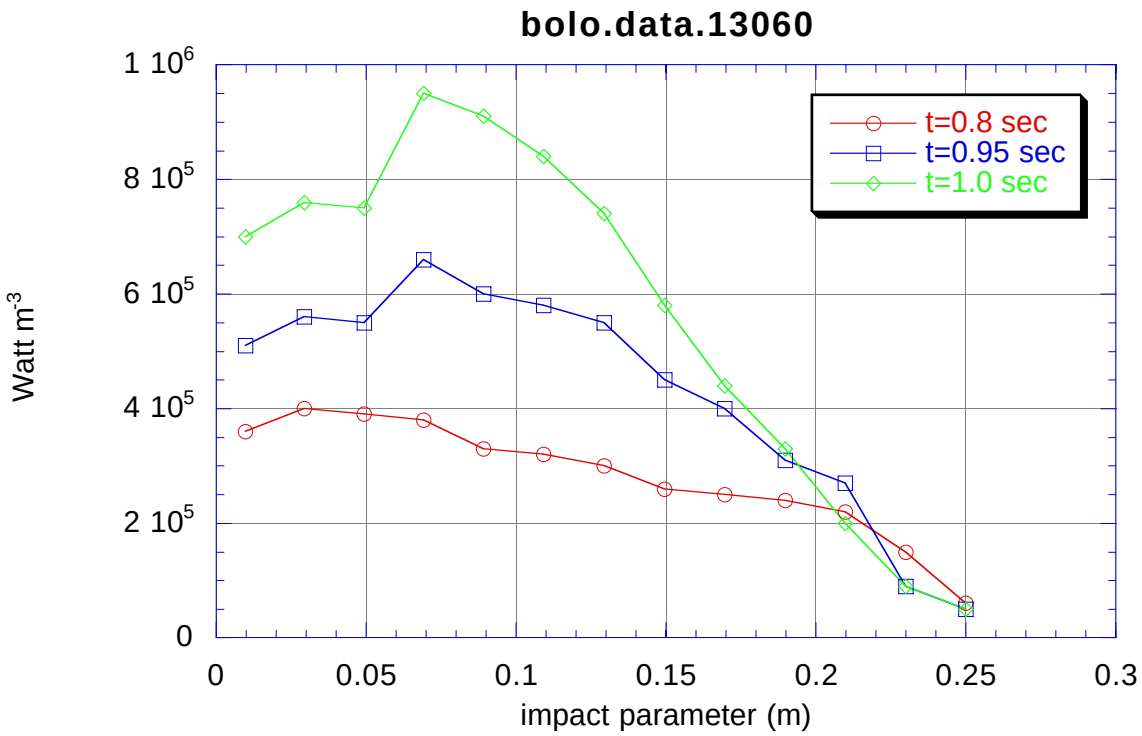

Fig. 6 Brightness seen as a function of viewing chord for the horizontal bolometer array.

Comments:

- Unlike the bremsstrahlung array, this bolometer array looks horizontally into the plasma and sees the molybdenum tile limiter on the inner wall. (The vertical bolometer array is unavailable for this shot).

- The four chords which have impact parameters from 7 cm to 13 cm clearly see an unusual radiation pattern after the Kr is injected. This radiation is a MARFE.

- The H_α diagnostic array, and a horizontal bremsstrahlung array, which have the same lines of sight as the bolometer array, see the same MARFE.

Hence, the data for those four chords has been smoothed to map monotonically from the chord with impact parameter ρ=15 cm to the chord with ρ=5 cm.

- If the data is not smoothed in such a manner, the inversion of the data yields *negative* volumetric power losses in the core plasma.

- The inversion of the difference between the smoothed data after the Kr injection and the bolometric data before the Kr injection yields an excellent fit to the (smoothed) bolometric signal when integrated. Thus, the procedure is self-consistent.

The inverted data gives us the volumetric radiative loss profile, $P^{Rad}(r)$. With the electron density profile (measured by DCN), the electron temperature profile (measured with ECE) and the Kr density profile derived above, we compute the radiative cooling coefficient for Kr

$$Q_{Kr}(T_e) = \frac{P^{Rad}(r)}{n_e(r)N_{Kr}(r)}$$

The result is shown in Fig. 7.

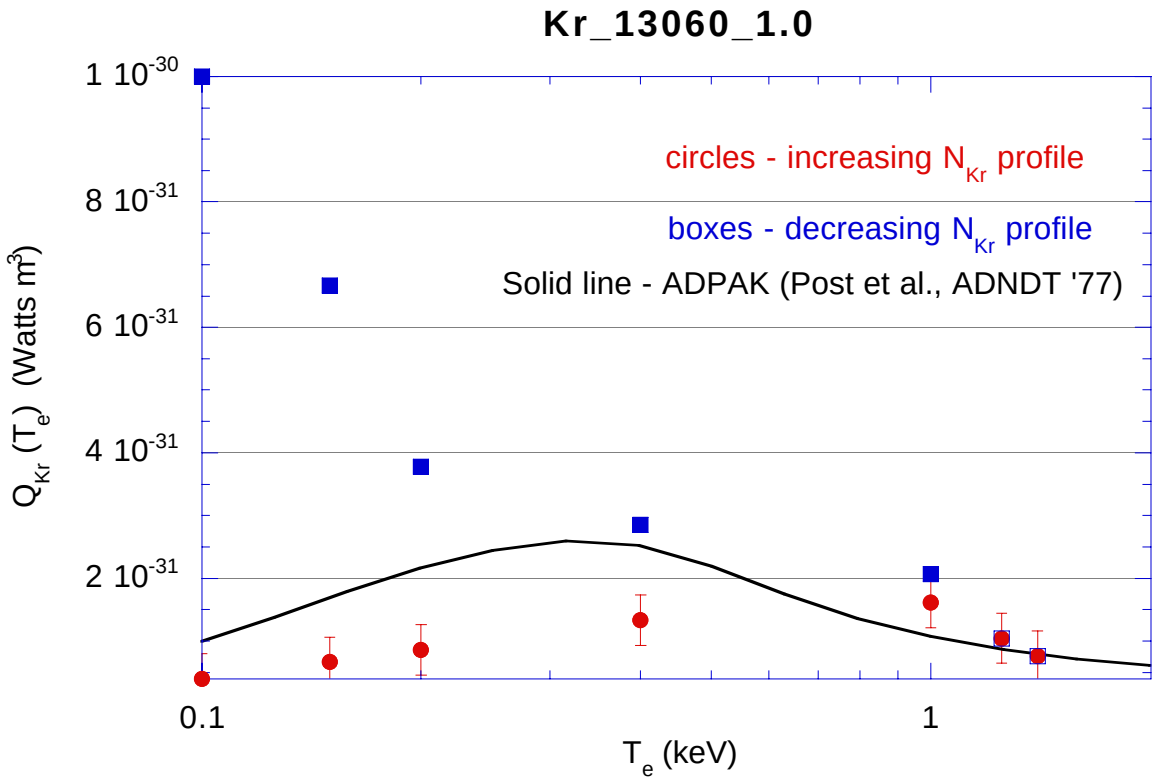

Fig. 7 Kr radiative cooling coefficient for the experimentally derived Kr profile (red circles), for the artificial, decreasing Kr profile (red squares) and from the average-ion model of Post *et al*. (solid line).

V. Conclusions

- We have measured the radiative cooling coefficient of krypton in a tokamak plasma. The amount of Kr was so large as to cause a disruption of the plasma after 200 msec (Fig. 2); the large amount of Kr means that the measured bolometric and bremsstrahlung signals are due (almost exclusively) to Kr (Fig. 3).

- From 300 eV to 1.5 keV good agreement is achieved between our derived cooling coefficient and the theoretical results of Post *et al.*

- The profile of Kr, N_{Kr}(r), is obtained from the bremsstrahlung data, and is seen to be peaked in the outer part of the plasma. This profile is the only one that yields a cooling coefficient in (qualitative) agreement with the theoretical results of Post *et al.*

    - A transport barrier at the half-radius (where the T_e and n_e gradients are very large) explains the shape of the profile.

    - The same shape of the Kr profile is seen at times earlier than, and subsequent to, the time we have chosen for analysis.

This work describes a preliminary analysis of two Kr injections at FTU. Agreement between the results of our model and the theoretical predictions of Post *et al.* has been achieved within the experimental uncertainties and the approximations used in the analysis. Future experimental work will include further Kr injections with a smaller volume of gas as well as spectroscopic diagnostics of line transitions in individual ions. Future developments in the analysis will incorporate the measured time variation in the electron temperature and density profiles and an inversion of the bolometric and bremsstrahlung signals at times before and after injection, separately.

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