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ABSTRACT
New automatic analysis methods allow the analysis of large amounts of data without human interaction. Tokamak machines, such as JET, are perfect candidates to apply data mining techniques in order to obtain results with a high statistical relevance. In this paper, an automatic technique to analyse the pedestal edge gradient is introduced. This technique does not require human intervention and therefore can be applied to many pulses. The pedestal edge gradient is the temperature gradient corresponding to the external transport barrier at the edge of H-mode plasmas. This gradient is quantified using the temperature profiles obtained from the ECE diagnostic. An automatic technique to locate events in plasma pulses is applied in order to locate ELMs and then, the evolution of the edge pedestal gradient is analysed during the ELMs. The degradation of the edge pedestal gradient during an ELM is quantified using the edge pedestal gradient 2ms before it as a reference of the amplitude of the gradient. This technique has been applied to a JET database containing more than a thousand pulses for a total of more than 46000 ELMs.

1. INTRODUCTION
When the power injected into Tokamak plasmas is above a certain threshold (and the right conditions are met), the plasma confinement moves from the L confinement mode (Lmode) to the H confinement mode (H-mode). One of the most important characteristics of the Hmode [1] is the existence of a transport barrier at the edge of the plasma. This barrier is known as External Transport Barrier (ETB) [2]. The ETB appears in the plasma temperature and density profiles as a high steep gradient close to the plasma edge. Figure 1 shows an example of the electron temperature profile of the plasma in both L-mode and H-mode for JET Pulse No: 73569. The ETB in fig.1 is located in the H-mode plasma close to the major radius of 3.8m. It is the highest gradient between consecutive radial coordinates of the electron temperature profile. In this paper, this gradient is called Edge Temperature Gradient (ETG). It is measured as the difference of the electron temperature between two consecutive electron temperature points at the ETB.

The Electron Cyclotron Emission (ECE) diagnostic [3] of JETdetermines the electron temperature profile of the plasma. At each time, it measures the electron temperature at 96 radial positions. The standard acquisition has a bandwidth of 5kHz. The fast acquisition system has a bandwidth up to 400kHz. Using a sampling rate of 250kHz, it provides up to 3s of data collection.

Another characteristic of H-mode plasmas is the presence of Edge Localized Modes (ELMs). ELMs are instabilities at the plasma edge of H-mode plasmas [4]. At each ELM burst, the ETB is reduced and the plasma confinement degrades. ELMs can be automatically (without human intervention) located in discharges by using data mining techniques as described in [5]. The automatic methodology was applied in [5] to 226751 ELMs of more than 1200 JET discharges, thereby providing results of high statistical relevance.

This article describes an automatic technique to analyse the JET electron temperature profiles in H-mode plasmas in order to quantify the edge temperature gradient degradation during ELMs.

This paper is structured as follows: Section 2 includes a brief introduction to Support Vector Regression, Universal Multi-Event Locator and the automatic location of ELMs in JET. Section 3 describes how to quantify the degradation of the ETG between two times. Section 4 is intended to explain the analysis of the temporal evolution of the ETG during ELMs. Finally, Section 5 includes the results obtained analysing 748 pulses from JET campaigns from C15a to C26.

2. AUTOMATIC LOCATION OF ELMS IN JET

The application introduced in this paper requires a method to automatically locate ELMs in discharges. Ref. [5] introduces the application of a Universal Multi-Event Locator (UMEL) [6] to the location of ELMs in JET pulses.

UMEL is a technique based on Support Vector Regression (SVR) to locate events in waveforms and images. SVR [7] is the adaptation of Support Vector Machines (SVM) to regression. Using SVR and given a set of S training samples $(\mathbf{x}_1, y_1),...,(\mathbf{x}_S, y_S)$, $(\mathbf{x}_i \in \mathbb{R}''$ and $\mathbf{y}_i = f(\mathbf{x}_i)$ where: $f:\mathbb{R}'' \rightarrow \mathbb{R})$, the regression function is given by [8]:

$$f^*(x) = \sum_{k=1}^{S} \gamma_k^* H(x_k, x) \tag{2.1}$$

The parameters $\gamma_k{}^*$ are determined using the solution of a quadratic optimization problem:

$$\gamma_k^* = \alpha_k - \beta_k^*,\ k = 1,...,S \tag{2.2}$$

where the parameters are chosen by maximizing the function:

$$Q(\alpha, \beta) = -e\sum_{k=1}^{S}(\alpha_k + \beta_k) + \sum_{k=1}^{S}(\alpha_k - \beta_k) - \frac{1}{2}\sum_{k,l=1}^{S}(\alpha_k - \beta_k)(\alpha_l - \beta_l)\, H(x_k, x_l) \tag{2.3}$$

subject to the constraints:

$$\sum_{k=1}^{S}\alpha_k = \sum_{k=1}^{S}\beta_k,\ 0 \leq \alpha_k \leq \frac{C}{S},\ 0 \leq \beta_k \frac{C}{S},\ \ 1,...,S \tag{2.4}$$

where H is an inner product kernel, e is the width of the e-insensitive zone (large values of e correspond to very smooth regressions) and C is a regularization parameter.

Only a subset of the parameters γ^* in equation (2.1) is nonzero. The data points x associated with the nonzero γ^* are called Support Vectors (SV). Then, eq. (2.1) can be written as:

$$f^*(x) = \sum_{k=1}^{SV} \gamma_k^* H(x_k, x) \tag{2.5}$$

UMEL distinguishes between two different SVs: the Internal Support Vectors (ISVs) and the External Support Vectors (ESVs). The ISVs lie inside the e-insensitive zone of the regression loss function (also called e-tube) while the ESVs lie outside the e-tube:

$$\text{External Support Vector} \equiv ESV \subset SV, \forall i \in ESV, |y_i - f(x_i) > e \tag{2.6}$$

$$\text{Internal Support Vector} \equiv ISV \subset SV, \forall i \in ISV, |y_i - f(x_i) \leq e \tag{2.7}$$

On the one hand, ISVs are necessary samples for the regression estimation and, on the other hand, ESVs are also necessary samples but with a higher degree of relevance (they are the most difficult samples to regress). Figure 2 includes an example of ISVs and ESVs on a step function. The samples around the step are the most difficult to regress and therefore ESVs appear in these points. Some ISVs appear in both sides of the signal. The solid line represents the SVR fit and the space between the dashed lines is the e-tube.

Using the location capabilities of UMEL, it is possible to locate ELMs in plasma signals. In [5], the location of ELMs in a JET pulse is carried out in two steps:

1. **H-mode location:** using UMEL, the H mode interval of JET pulses is located (Figure 3(a)). The D_α signal is fitted using SVR and the ESVs appear in the signal peaks corresponding to the ELMs. Since ELMs only appear in H-mode plasma, it is possible to determine the beginning and the end of the H-mode using the ESV times.
2. **ELM location:** features of the D_α emission and the diamagnetic energy are compared. Firstly, UMEL is used to locate peaks in the H-mode time interval of the D_α signal. Then, the diamagnetic energy is sliced into small pieces (35ms) around the peaks times and UMEL is used again to locate drops within the slices. An ELM is detected when a D_α peak and a diamagnetic energy drop take place within a window of 5ms (Figure 3(b) and 3(c)).

This method is automatic and does not require human intervention (the same set of UMEL parameters can be used for a wide range of JET pulses). The method returns the list of ELM times for a given list of JET pulses.

3. ANALYSIS OF THE EDGE TEMPERATURE GRADIENT

As it was mentioned previously, the H-mode is characterized (among other things) by the existence of an ETB. As shown in Fig.1, the ETB can be located in the electron temperature profiles of H-mode plasmas as a high steep gradient close to the plasma edge. Since the ETG is defined as the difference of the electron temperature (ET) between two consecutive radial points at the ETB, a new parameter that estimates this difference is introduced. It is called Steep Gradient Temperature (SGT). As the ET profile decreases from the plasma centre to the edge, the SGT oscillates around a mean value and peaks at the ETB. The value around which the SGT oscillates has been called Steep Gradient Baseline (SGB) and it is determined as the mean value of the SGT between the plasma core and the ETB.

Figure 4 contains two examples of ET profiles, the SGT and the SGB for two instants of JET Pulse No: 78072. On one hand, Figure 4 (a) shows the ET profile, the SGT and the SGB at 7.8s, when the plasma is still in L-mode. The ET profile decreases from the centre to the edge without high gradients and therefore the SGT is almost constant but for a few points near the major radius 3.8m. On the other hand, Figure 4(b) plots an H-mode time instant of JET Pulse No: 78072. In contrast to Figure 4(a), a high steep gradient appears in the ET profile and, therefore, the SGT shows a clear peak close to the major radius 3.8m. The units of the ET are plotted on the left side hand of the figure while the units of the SGT and the SGB are plotted on the right side.

For every time in H-mode, it is possible to quantify the ETG amplitude using the SGB as a reference of the temperature gradient. The value of the SGT at the ETB (SGTETB) is estimated as the highest point of the SGT close to the plasma edge. In Figure 4(b), this point has been emphasized with a circle. The ETG coefficient is determined as:

$$ETG_{coef} = \frac{SGT_{ETB}}{SGB} \tag{3.1}$$

The ETG_{coef} is equal to 1 if $SGT_{ETB} = SGB$. It implies that the temperature gradient mean value at the plasma core is the same than the gradient at the plasma edge (there is not ETB). The larger the difference between the SGT_{ETB} and the SGB, the higher the value of ETGcoef is. In the example of Figure 4(b), the SGT at the *ETB* is SGT_{ETB} = 227.4eV, the SGB is SGB = 47.62eV and thus, the *ETG* coefficient is ETG_{coef} = 227.4 / 47.62 = 4.775.

3.1 MEASURING THE DEGRATION OF THE ETG BETWEEN TWO INSTANTS

The ETG_{coef} quantifies the ETG at a certain time. Since the plasma evolves in time, the electron temperature does also and therefore the ETG varies. As a result, it is worth obtaining a numeric value for the ETG degradation to study the plasma evolution. Here, the degradation of the ETG between two times is computed using the values of the ETGcoef at these times ($ETG_{coef,1}$ and $ETG_{coef,2}$):

$$degradation\,(ETG_{coef,\,1}, ETG_{coef,\,2}) = 1 - \frac{ETG_{coef,\,2} - 1}{ETG_{coef,\,1} - 1}\ ,\ ETG_{coef,\,2} \leq ETG_{coef,\,1} \tag{3.2}$$

The coefficient $ETG_{coef,1}$ can be interpreted as a reference value of the ETG. The ETG degradation is equal to 1 (100%) if the ETG_2 is equal to 1 (the gradient at the plasma edge is the same than at the plasma core and, therefore, there is not ETB). In contrast the ETG degradation is equal to 0 (0%) if $ETG_1 = ETG_2$ (the gradients at both times are similar).

4. DEGRADATION OF THE ETG DURING ELMS ON JET

ELMs are MHD instabilities at the edge of the plasma. At each ELM burst, the ETB is reduced and the plasma confinement degrades [4]. ELMs lead to a fast loss of energy and particles from the plasma edge. The energy loss due to ELMs causes a reduction in the global energy confinement time [9,10].

The temporal evolution of the electron temperature during an ELM can be seen in Figure 5. Before the ELM, the temperature profile shows a high ETG at the ETB close to the plasma edge. When the ELM occurs, the ETG is reduced and the gradient degrades. After the ELM, the ETG is recovered.

Since ELMs are instabilities at the plasma edge, the gradient of the electron temperature in the plasma core is not affected. Thus, the SGB is not altered and it is possible to consider that $SGB_1 \approx SGB_2$. Using this simplification and substituting the value of the ETG from Eq. (3.1) into Eq. (3.2) we obtain:

$$degradation\ (ETG_{coef,\ 1}, ETG_{coef,\ 2}) = \frac{\frac{SGT_{ETB,1}}{SGB} - \frac{SGT_{ETB,2}}{SGB}}{\frac{SGT_{ETB\ 1}}{SGB} - 1} = \frac{SGT_{ETB,1} - SGT_{ETB,2}}{SGT_{ETB,1} - SGT} \quad (4.1)$$

The SGT at the ETB 2 ms before an ELM ($SGT_{ETB,ELM-2}$) is used as a reference value to quantify the degradation of the ETG 2 ms after the ELM time. 2ms before the ELM, the electron temperature profile is still not affected by the incoming ELM (Figure 6(a)). The SGT is measured again at the ETB 2 ms after the ELM time ($SGT_{ETB,ELM+2}$, Figure 6(b)). These values are used to compute the degradation of the ETG using Eq. (4.1):

$$degradation\ (ETG_{coef\,ELM-1}, ETG_{coef\,+\,2}) = \frac{SGT_{ETB,ELM-2} - SGT_{ETB,ELM+2}}{SGT_{ETB,ELM-2} - SGB} \quad (4.2)$$

The value of the SGB is computed 2ms before the ELM using the values of the SGT between the plasma core and the ETB (Figure 6(a)).

The technique to quantify the degradation of the ETG explained above has been applied to the analysis of the ETG during ELMs in JET. Firstly, the methodology to ELMs location explained in Section 2 has been applied to located ELMs in a wide range of JET pulses. More than 700 pulses from JET campaigns from C15a to C26 have been analysed and more than 46000 ELMs have been located.

After an ELM, the ETG is recovered within a few milliseconds. In the case of the analysed ELMs, 11350 (24.574%) ones recovered the initial ETG two milliseconds after them. Table 2 shows the results obtained for each JET campaign. 2ms after the ELMs, the ETG degradation mean value is 23.948%. Figure 7 shows the distribution of the ETG degradation obtained (the ELMs where the ETG is recovered 2ms after them have been omitted). The maximum number of ELMs is located between the 10% and the 20% of EPG degradation.

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Campaign	Pulses	ELMs	ELMs with ETG recovered	EPG degradation mean value (non-recovered ETG cases)
15a	8	846	455 (53.786 %)	22.710 %
15b	23	1136	463 (40.757 %)	27.235 %
16-17	138	8893	3088 (34.724 %)	22.263 %
18	19	863	283 (32.797 %)	20.363 %
19	5	74	14 (18.919 %)	37.958 %
20	67	3762	509 (13.530 %)	30.761 %
21	39	2425	635 (26.186 %)	28.668 %
22	49	2594	408 (15.729 %)	24.791 %
23	108	6293	1233 (19.593 %)	21.642 %
24	10	436	48 (11.009 %)	33.772 %
25	60	2586	527 (20.379 %)	26.126 %
26	222	16279	3687 (22.649 %)	22.376 %
Total	748	46187	11350 (24.574 %)	23.948 %

Table 1: Degradation results at ELM time + 2ms

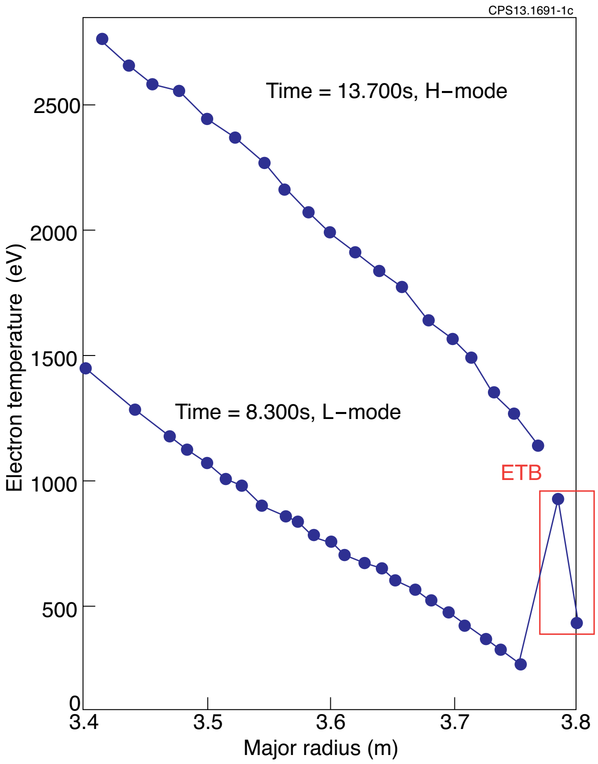

Figure 1: L-mode and H-mode temperature profiles in JET Pulse No: 73569.

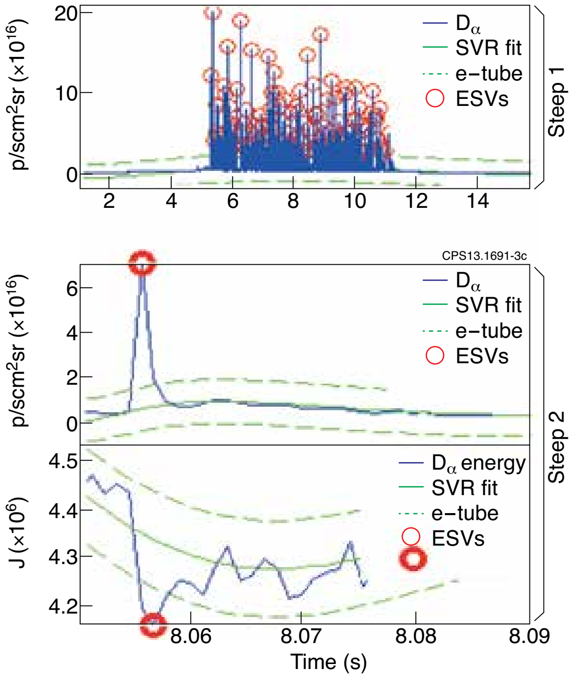

Figure 2: UMEL example.

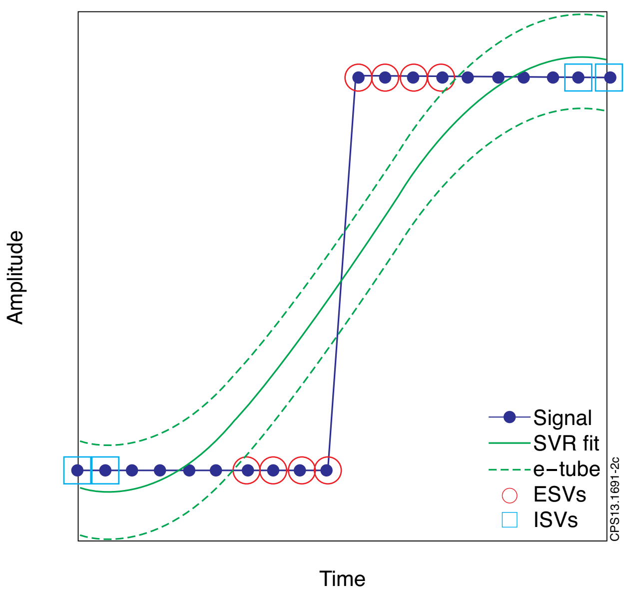

Figure 3: ELMs location using UMEL in JET Pulse No: 73569.

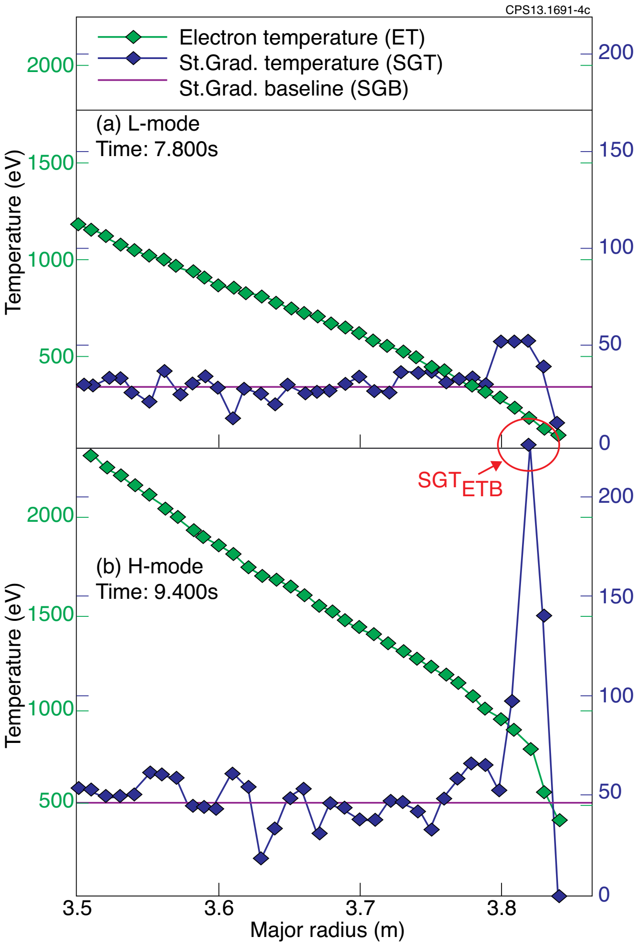

Figure 4: ET, SGT and SGB at an L-mode instant (a) and an H-mode instant (b) in JET Pulse No: 78072.

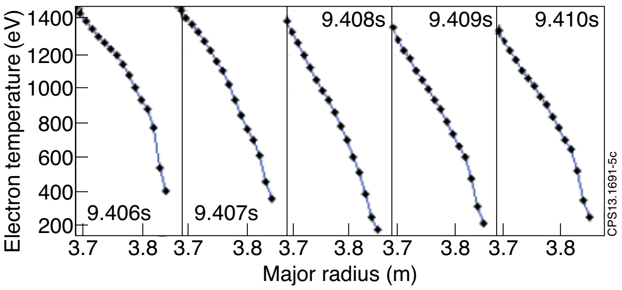

Figure 5: Temporal evolution of the electron temperature profile in JET Pulse No: 78072 during an ELM at 9.407s.

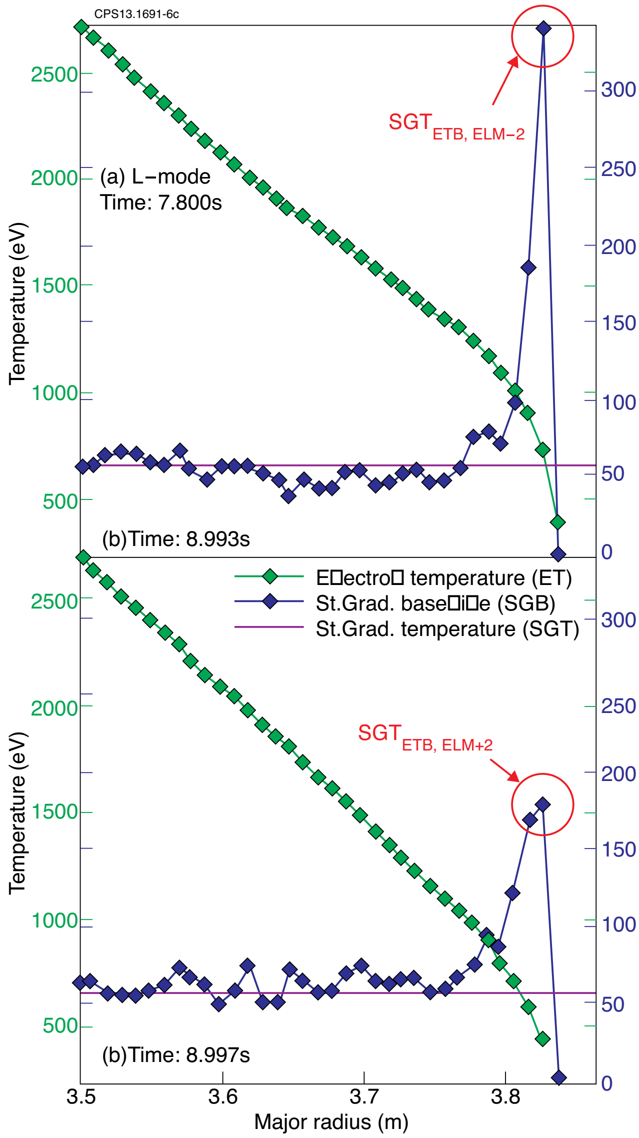

Figure 6: ET, SGT and SGB 2ms before (a) and 2ms after an ELM (b) in JET Pulse No: 78072.

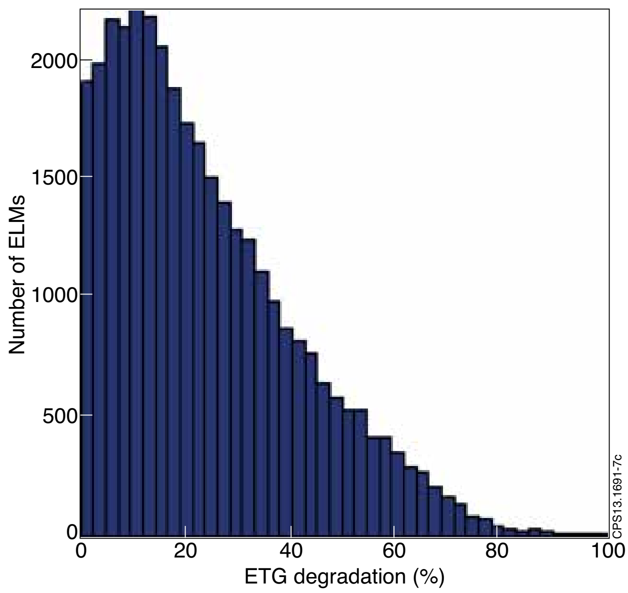

Figure 7: Distribution of the ETG degradation results.