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E D D Zapata-Cornejo, D Zarzoso, S D Pinches, S E Sharapov, M Fitzgerald. Segmentation of MHD modes using Fourier transform, wavelets and computer vision algorithms. 2024. hal-04599681v2

**HAL Id: hal-04599681**

**<https://hal.science/hal-04599681v2>**

Preprint submitted on 19 Jul 2024

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# Segmentation of MHD modes using Fourier transform, wavelets and computer vision algorithms

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**Abstract.** MHD activity in fusion devices is typically analyzed by examining time-frequency spectrograms obtained from various diagnostics. MHD modes often co-exist with various types of noise and complex patterns generated by other events like pellet injection or active diagnostics. Traditionally, identifying MHD modes has been a manual task, making it labor-intensive. To overcome this issue, this study proposes the use of computer vision algorithms for noise removal and automatic feature extraction. First, the automatic detection of straight-line patterns is achieved by applying the Hough transform. Then, the discrete wavelet transform is proposed to break down spectrograms into sub-images of different scales, removing broadband noise and pellet injection signatures. The multiscale decomposition is subsequently extended to multiple directions using either 2D Fourier transforms or curvelets, achieving a high signal-to-noise ratio in spectrograms and eliminating undesired frequency sweeps of TAE antenna. Once MHD activity is successfully enhanced, a pipeline of algorithms for ridge detection, thresholding and labeling perform a segmentation of the image, automatically labeling individual modes. This study demonstrates the effectiveness of computer vision algorithms for the identification of MHD modes. The use of such algorithms may potentially help in the analysis process and the creation of large databases of modes.

**Keywords:** MHD activity, spectrograms, computer vision, wavelets, curvelets

## 1. Introduction

Achieving nuclear fusion requires specific plasma properties (confinement time, density and temperature) and a steady operation: free of disruptions, and instabilities. Particularly, the presence of instabilities can cause disruptions and major particle losses that can damage the plasma-facing components of magnetic fusion devices. Therefore, the detection, prevention, or control of plasma instabilities are paramount to increasing plasma performance and avoiding machine damage. Consequently, these problems are very active research topics in fusion physics and engineering.

Magnetohydrodynamic (MHD) activity, like energetic particles (EP) driven Alfvén eigenmodes [1, 2], can be observed with different diagnostic systems: magnetic sensors [3] (Mirnov coils [4]), electron cyclotron emission (ECE) [5, 6], soft X-ray measurements [7], or Far infrared interferometry (FIR) [8]. Frequently, the end product of the diagnostic analysis is a spectrogram: a time-frequency representation of the plasma oscillations.

Given magnetic fluctuations spectrograms, different finite frequency oscillations (modes) can be identified in the image. However, more information is needed to fully characterize these modes: radial amplitude (location), mode numbers, growth rate, and the causing drive (source of free energy). Different diagnostics complement each other to obtain all this information, and additional analysis with theory and simulation needs to be carried out to identify the cause of the observed time-frequency pattern. Nevertheless, for detection purposes, a first identification of the modes need to be done with the spectrograms information.

The identification of modes is often complicated by the presence of noise and other artifacts in the spectrograms. The sources of noise can be variate and the object of study for each diagnostic system and experimental device. Sometimes, the noise can have its origin in the diagnostic system itself, external sources (like active diagnostics or heating systems), or it can be an artifact of the signal processing algorithms. In addition, noise can have different patterns: it can be broadband noise, or located ridges in time-frequency, which are indistinguishable to the actual MHD modes. These sources of noise and time-frequency structures need to be acknowledged to detect true mode patterns.

In the later years, the data-driven culture and the use of artificial intelligence have extended all over business and industry. Since the appearance of these disruptive technologies, a research effort has been carried out to apply these innovations to the detection of plasma instabilities. Several works aimed to detect EP driven Alfvén eigenmodes using manually labeled datasets: in

COMPASS [9], NSTX [10], DIII-D [11–14]. Particularly, deep learning segmentation was investigated in TJ-II [15]. Because the spectrograms of plasma diagnostics are images, the application of computer vision algorithms (CV) or deep learning algorithms (DL) is straightforward.

The classic computer vision approach differs from the deep learning approach in several aspects. In a classic CV, the image features are extracted by designing a workflow of algorithms and mathematical models. For instance, wavelet transforms are part of the CV algorithms (they are a whole field on their own) and they are extensively used for image compression and manipulation.

These algorithms were developed over years of research, nowadays they require very few computational resources, and they do not require a dataset of images. Their effectiveness relies on assumptions about the image properties, so the mathematical manipulation of the image is deterministic and highly interpretable. For instance, the wavelet strength relies on the acknowledgment of multiscale features in signals and images. However, it is necessary to experiment with different algorithms and their parameters for each image.

In contrast, feature extraction is done automatically in DL models. For instance, using convolutional neural networks (CNNs). In this case, the features are learned using inductive bias, so deep neural networks need to be trained using labeled datasets. Roughly speaking, a CNN can be understood as a concatenation of image filters, in which the parameters are learned using statistics of a given dataset to solve a specific problem. Overall, the fundamental difference between classic CV and DL approaches is the following: in classic CV image features are calculated, and in DL the image features are inferred.

If the amount of data is enough, deep learning can outperform classic CV. However, big image datasets are needed to achieve this advantage, and the performance of DL collapses [16] when the patterns to detect are not present in the training dataset. In addition, computational resources often require multiple GPUs, and the datasets need to be carefully curated before they can be used. Moreover, labeling images is still a highly time-consuming task necessary before DL models can be trained. Therefore, CV and signal processing find their utility when data is scarce or computational resources are constrained, CV is still used in preparing data for deep learning algorithms [17] often enhancing DL performance.

The research on the application of classic CV and wavelet for image processing in Fusion applications is limited. To our knowledge, only previous work [13] from DIII-D uses computer vision algorithms, morphological filters specifically, to prepare data for using machine learning. For automatic identification of MHD modes: Ridge detection and multi-wavelet convolutional neural

networks have been explored in two master theses [18, 19] respectively. This gap in knowledge regarding the use of CV to extract information from plasma spectrograms motivated the research presented in this paper.

This paper is organized as follows. In section 2, the algorithms used in the paper are introduced. The removal of broadband noise and vertical lines from spectrograms is discussed in section 3. Then, we introduce Hough transform to detect straight lines patterns in arbitrary directions in section 4. Following the detection of these objects, sections 5 and 6 are devoted to discussing two methods to remove them in, using 2D-FFT and curvelets respectively. Once, we have explored methods for removing noise, we proceed in section 7 with the segmentation of the spectrogram modes. Finally, section 8 is devoted to the conclusions of the reported work and perspectives beyond the present paper.

## 2. Spectral algorithms and computer vision

The goal of the presented work is to design a pipeline of algorithms for the segmentation of spectrogram images, identifying the MHD activity in time and frequency separately from noise and other image features. Given an image, the segmentation problem can be defined as the determination of regions of pixels corresponding to different objects. The algorithms used have two differentiated objectives: feature extraction and object detection.

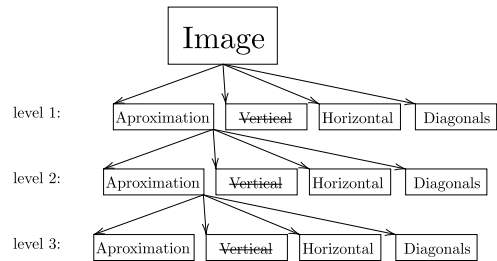
Extracting the features of interest is a previous requisite for the segmentation pipeline to work properly, the steps are: detection of straight lines, removal of straight lines and broadband noise. Once the features are extracted (noise removed), the basic steps for segmentation are ridge detection, automatic thresholding and labeling.

This work uses free and open-source software. We have used the PyWavelets implementation [20] for the discrete wavelet transform DWT. The CV algorithms used are available in the Scikit-Image library [21]. Rather than aiming for the tuning of hyperparameters, we compared different algorithm performances with the default parameters, looking for the ones that best adapt to our data features. In addition, this work uses CurveLab implementation, copyrighted by the authors [22], and it is available for academic use. The Python library Curvelops allows Curvelab integration with the rest of the Python workflow.

First, the spectrograms of diagnostic signals are calculated using the discrete version of the short-time Fourier transform (STFT) given by Scipy implementation, with the following setting: the length of the FFT windows is 2048 samples, the spectral amplitude is given in dB scale, the window function used is the Tukey window, and the colormap used is “turbo”, a rainbow colormap similar to “jet”, which was proposed by Google AI research, enhancing value dissimilarities and perceptual uniformity, the rest of parameters are the default library parameters. The images are then resized to 1024 by 1024 pixels before applying the pipeline.

The discrete wavelet transform is used to remove broadband noise and vertical lines from the spectrograms

(section 3): discrete wavelets can be seen as pyramids of multiscale and multidirectional filters that decompose and image in filtered sub-images, they are extensively used in image processing to remove noise and extract features. By using discrete wavelet transform (DWT), each image can be decomposed in 4 sub-images: an approximation image, vertical details, horizontal details, and diagonal details. The approximation images are used iteratively to continue the decomposition in the next level as shown in Fig.1. An example of spectrogram decomposition is shown in Fig.2. The approximation image is equivalent to applying a low-pass filter to the columns and a low-pass filter to the rows. That is why the approximation is noted as LL in many sources and it is the notation that we follow in the present paper. Similarly, the vertical details image is equivalent to applying a low-pass filter in the rows and a high-pass filter in the columns (hence the LH notation). The horizontal details image (HL) and diagonal details image (HH) complement the decomposition. In this work, we use the Haar wavelet.

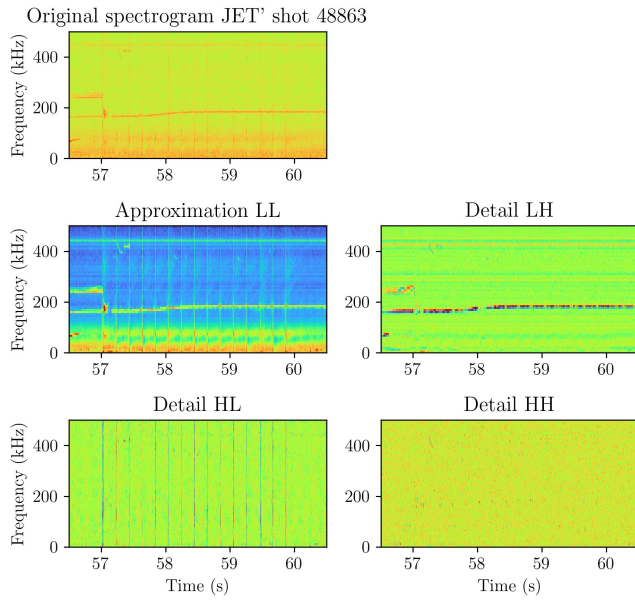


**Figure 1.** Schematic representation of the wavelet cascade of filters at different levels. Each level includes an approximation image together with vertical, horizontal and diagonal details

The utility of DWT is raised from the fact that the MHD instabilities that can be observed in spectrograms have low spatial frequencies, in other words: low repetition rates across the spectrogram image. While signal noise has high spatial frequencies.

In this paper, we used the Hough transform [23, 24] to detect straight lines  $y = mx + b$  in images (section 4). Without entering in all the details: for each pixel point, multiple straight lines represented by  $x \cos(\theta) + y \sin(\theta) = \rho$  are considered. Each one is situated at a distance  $\rho$  from the origin and the perpendicular to each candidate line forms a  $\theta$  angle with x-axis. The image is then transformed into a 2D space (Hough space) in which all straight lines are transformed into sine curves. The accumulation of sinusoids in a point of Hough space indicates the presence of a straight line characterized by  $\rho$  and  $\theta$  (Fig.5). It is important to mention that some edge detection (or ridge detection) is needed before running the Hough transform. Otherwise, accumulation points are not clear and the straight line detection might not be efficient enough. For this reason, the Canny edge detector [25] has been used in this case.

The frequency content of an image can be also studied by extending the definition of the discrete Fourier transform to two dimensions. Many periodic patterns can be detected



**Figure 2.** Example of a JET' spectrogram (top) and its third level wavelet decomposition (bottom) composed of the approximation and the horizontal, vertical and diagonal details.

in the frequency space. The main application of the two-dimensional Fourier transform in computer vision is the manipulation of the image in the frequency space using masks. In this paper, 2D-FFT is employed for filtering spectral components in a desired direction (section 5). The implementation of the 2D Fourier transform can be found in Python's Numpy library.

The discrete wavelet decomposition of images is a powerful tool for denoising and extracting features [26–31]. However, the number of directions might be too coarse in some scenarios. For instance, a vertical and horizontal multiscale pattern could not be enough to describe curved ridges filling the image space. Likewise can happen with MHD activity on spectrograms. The lack of directionality of DWT motivated the development of the curvelet transform [22, 32], which is employed in the present work to extend the results with DWT (section 3) to many directions (section 6)

The fast Curvelet transform [22] is based on partitioning the Fourier space: A tessellation of windows (wedges) applied to the Fourier space creates a multi-scale, multi-directional filter bank. The fast Curvelet transform of an image  $f(x_1, x_2)$  can be defined as

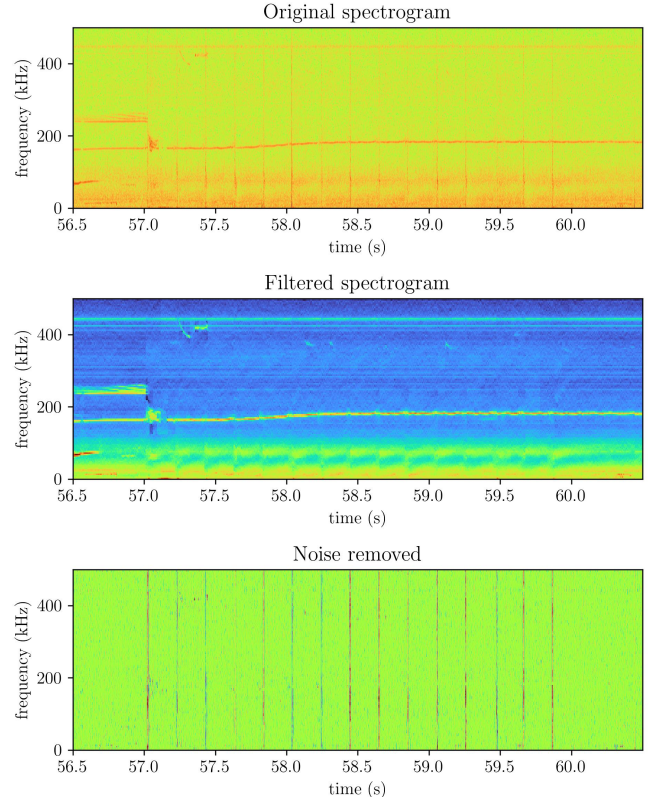
$$\begin{aligned} & \text{Curvelet transform}\{f(x_1, x_2)\} \\ &= \sum_{\text{scales}} \sum_{\text{angles}} \langle f, \phi_{\text{scale}, \text{angle}} \rangle \phi_{\text{scale}, \text{angle}}, \end{aligned} \quad (1)$$

where  $\langle f, \phi_{\text{scale}, \text{angle}} \rangle$  is the weight corresponding to the wedge  $\phi_{\text{scale}, \text{angle}}$  in Fourier space (the rigorous definition can be found in [22]).

Finally, the algorithms used to perform the segmentation (section 7) are: the ridge Sato's filter [33] with scales  $\sigma_{\text{scales}} = [1, 2]$  to detect mode ridges in the spectrograms; the Yen's automatic thresholding algorithm [34] which is

used to separate signal from noise and binarize the spectrogram images. Finally, a pixel connectivity filter [35, 36] is used to label separated elements in the binary images. The algorithm parameters are the Scikit-Image library default ones [21].

### 3. Broadband noise removal using discrete wavelet transforms



**Figure 3.** Example of broadband spectral noise removal on JET's shot 48863. Clips caused by pellet injections are removed from the spectrogram, leaving only MHD activity in the image. TAEs and EAEs are then easily observed.

In JET shot in Fig.3 we can see various toroidal Alfvén eigenmodes (TAE) over 200 kHz and between 56.5 and 57 s approximately. Then 15 periodic pellet injections fuel the plasma (they can be distinguished by the vertical lines in the spectrogram). The pellet injections fundamentally increase plasma density and reduce its temperature. It can be seen in the first pellet injection just after 57.0 s, how they affect the TAE modes. As the density increases abruptly, the TAE frequency  $f_{\text{TAE}} \propto 1/\sqrt{n}$  decreases, and then the TAE disappears soon afterward. A similar effect can be observed on an elliptical Alfvén eigenmode (EAE) at  $\approx 420$  kHz and  $\approx 57.5$  s. More deeply, the effect of pellet injection is a modification of the Alfvén continuum spectrum, which is studied in [37] with shots similar to the one shown in Fig.3.

The time series signals from JET magnetic diagnostics have abundant spikes and discontinuities. It is well known



that the Fourier transform has difficulties in representing non-differentiable or non-stationary time series, producing Gibbs artifacts in the signal's reconstruction and spectral leakage in the frequency space. The classic example is the Fourier transform of a square signal in which ripples are present at the edges of the square reconstruction, the decomposition of sines and cosines used by FFT struggles to recreate this type of signal. A dramatic example is the Fourier transform of a unit impulse (Dirac's delta  $\delta(\tau = 0)$ ), which requires infinite frequencies to reconstruct the pulsed signal. Because these patterns are present in diagnostics signals, JET's time-frequency spectrograms have abundant broadband noise.

The character of spectrograms noise is highly anisotropic, due to the spectral leakage of the STFT on each time window. This broadband noise is located mostly in the vertical details sub-image. Therefore removing the vertical details of the image allows us to clean the spectrograms. When vertical details pixels (all levels of vertical sub-images, as indicated in Fig.1) are set to zero and the inverse DWT is applied, broadband spectral noise is significantly reduced. An example is shown in Fig.3 (including pellet injection events of this particular example). The steps are summarized in the algorithm (1).

Approximation and horizontal details subimages are left unchanged. In addition, some high-frequency noise is present in the diagonal subimages, so they have a soft thresholding (all pixel values in diagonal subimages are multiplied by  $\alpha_D = 0.5$ ).

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**Algorithm 1:** Remove broadband noise, clics and pops from spectrogram

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**Input:** Time series  $\mathbf{s}$

**Parameters:** Levels deep:  $N=8$

Vertical threshold:  $\alpha_V = 0$ ,

diagonal threshold:  $\alpha_D = 0.5$

**Output:** Reassigned spectrogram  $S_{xx(mod)}$

**Steps:**

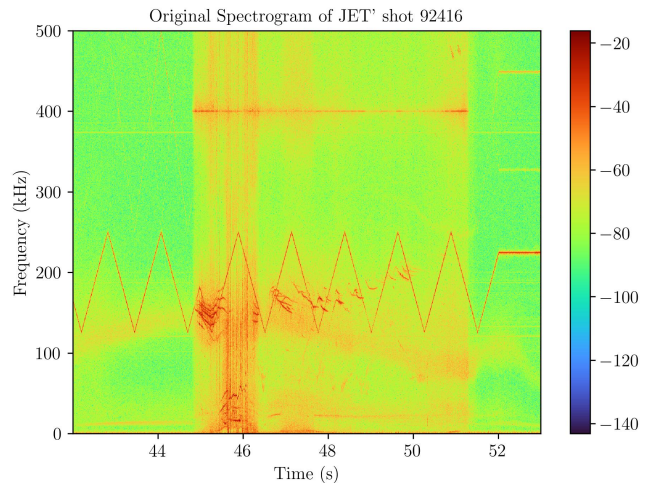
- 1 Obtain spectrogram matrix  $S_{xx}$  using STFT( $\mathbf{s}$ ).
  - 2 Workout DWT tree.
  - 3 Set  $\alpha_V = 0$  in all vertical details images in levels 1:N (hard thresholding).
  - 4 Set  $\alpha_D = 0.5$  in all diagonal details images in level 1:N (soft thresholding).
  - 5 Use inverse DWT to generate a filtered spectrogram.
- 

It is important to remark that we are modeling noise through the choice of one direction and the selection of the model parameters, therefore it is necessary to check these prior assumptions while using this algorithm. So far we have assumed that all the information contained in the vertical direction is noise or undesired artifacts. However, this is not the case for rapid sweeping frequencies of physical origin like fishbones or energetic particle modes. Then, the algorithm removes these type of modes and the information removed cannot be discarded.

Given this case, it is convenient to examine the removed image and evaluate how much information has been removed. Then several approaches are possible: (1) if all vertical modes are removed, it is necessary to continue the analysis on the vertical components, this way vertical and horizontal components can be segmented separately and finally merged together; (2) use soft thresholding ( $\alpha_V = 0.5$  or greater) to adjust the subtracted fraction of the vertical component and proceed with segmentation (these modes are strongly driven and contrast is high enough to segment them directly); (3) use the approximation image of levels 1 or 2 instead, because keeping one of the first approximation sub-images can also result in a spectrogram with an improved signal-to-noise ratio, though omitting details sub-images could produce modes with coarser details.

The maximum number of levels that can be calculated depends on the number of pixels in the image, the more pixels, the more levels can be calculated. Given an optimal time-frequency uncertainty, determined by the window size in the STFT. One way of increasing the number of pixels in the spectrogram is allowing more overlapping of time windows. The maximum number of levels can be determined by the appearance of border effects, and we calculate all levels possible.

#### 4. Straight line pattern detection



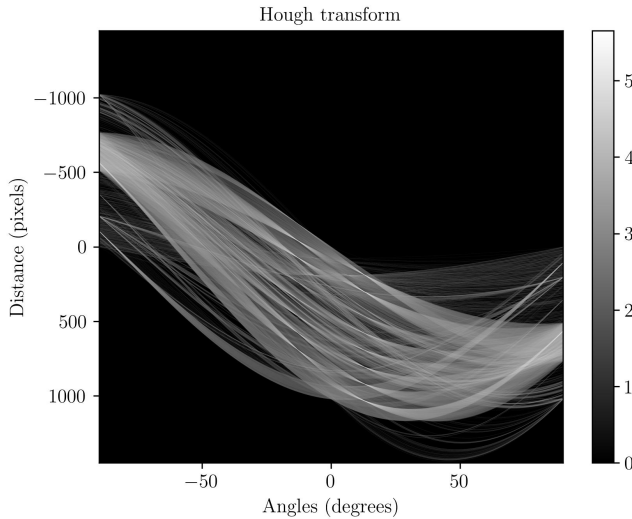
**Figure 4.** Spectrogram of JET shot 92416.

Some signals observed in spectrograms are straight lines with certain orientations. In many cases, these signals are not caused by plasma instabilities. For instance, the TAE antenna creates the frequency sweeping pattern that can be observed in Fig.4. The shot 92416 is an afterglow experiment studied in detail [38]. To remove the straight line patterns shown in this shot, we need to generalize the result obtained with the pellet signals to other directions different than the vertical.

It is to be expected that the pellet's injection times or requested TAE antenna frequencies are available in the

shot database. However, side lobes (harmonics) of the TAE antenna signal can appear.

Before applying the Hough transform, it is necessary to enhance the edges in the spectrogram image. The Canny edge detector is used for this purpose. Then, the Hough transform expresses the image in its own space. The accumulation of overlapping sinusoids over a point creates bright regions in Fig.5, providing evidence of a straight line. Note how some curves converge to points at  $\pm 90$  degrees (horizontal lines in images), and around  $\pm 10$  degrees (antenna sweep).



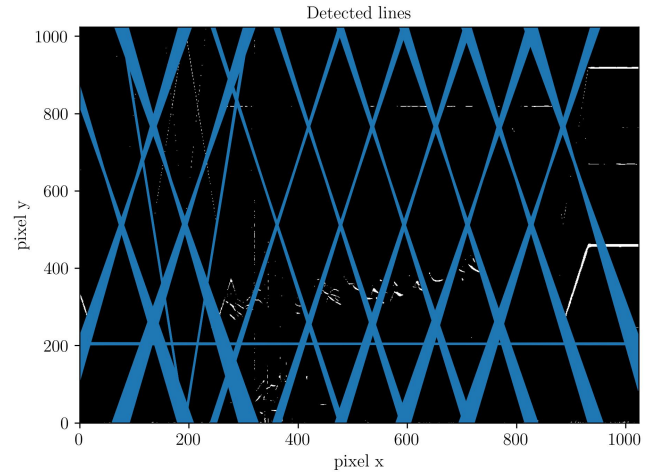
**Figure 5.** Result of Hough transform. The accumulation of sinusoids passing through a point indicates the presence of a straight line in the image space.

The result of the straight-line detection is shown in Fig.6. The angles detected are centered around  $0.39 \pm 1.63$ ,  $77.59 \pm 2.63$ ,  $83.1 \pm 1.63$ ,  $95.97 \pm 2.01$ ,  $103.32 \pm 2.61$ , and  $179.61 \pm 1.65$  (in degrees). In addition, it is worth mentioning that probabilistic Hough transform [24] can be used to add priors like line length, angular orientation, or separation between lines. The result is shown in Fig.7. This extends further applications of the Hough transform.

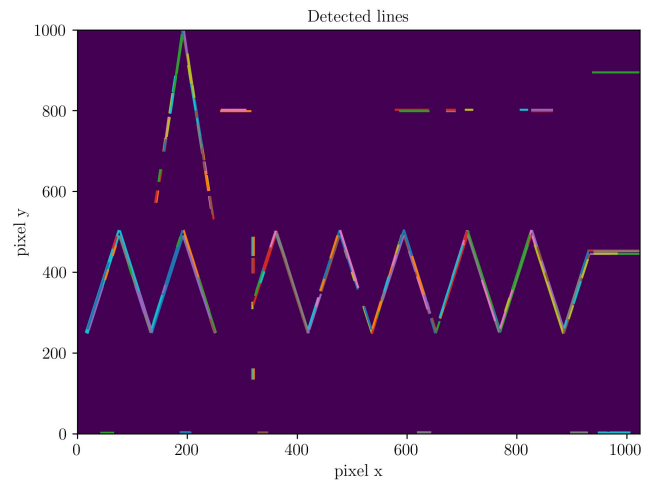
## 5. Removal of oriented patterns using 2D FFT

To proceed with the removal of oriented patterns, we start with the straight lines detected using Hough transform (corresponding to the TAE antenna sweep). Our first approach would be to transform the spectrogram's image  $f(x_1, x_2)$  to the Fourier space  $F(k_1, k_2)$ . The steps are summarized in the algorithm (2).

The Fourier space contains the image information expressed as spatial frequencies along the two image directions. Then a mask over the magnitude spectrum can be designed to remove all frequencies along the desired directions. Note that the FFT2D rotates the straight line angles  $\pi/2$  or  $90^\circ$  detected with the Hough transform, for instance, lines detected at  $77.59^\circ$  generate features at  $77.59^\circ - 90^\circ = 12.4^\circ$  in the Fourier space. The



**Figure 6.** Result of Hough transform analysis showing the straight lines detected.



**Figure 7.** Result of probabilistic Hough transform. Prior length is 12 pixels.

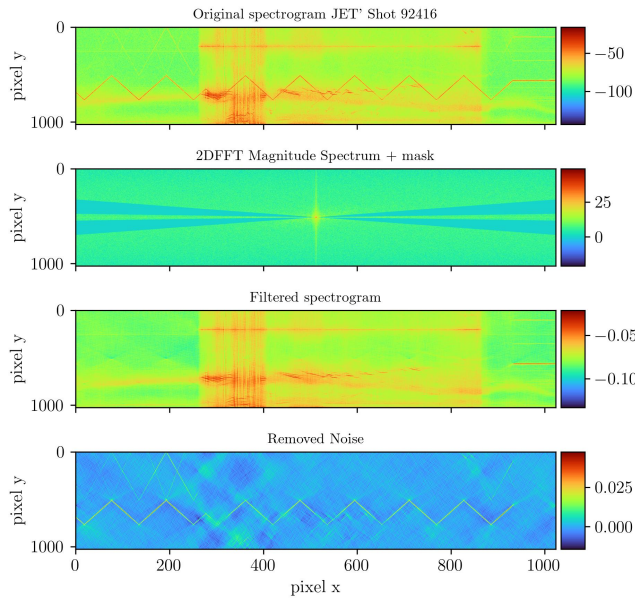
supplementary angles of  $\pm 12^\circ$  are  $12.4^\circ + 180^\circ = 192.4^\circ$  and  $-12.4^\circ + 180^\circ = 167.6^\circ$ .

Therefore, the mask angles used in this example are  $\theta = [\theta_1, \theta_2, \theta_3, \theta_4] = [12.4^\circ, -12.4^\circ, 192.4^\circ, 167.6^\circ]$ . Then, the angular mask widths are set to  $\Delta\theta = [\Delta\theta_1, \Delta\theta_2, \Delta\theta_3, \Delta\theta_4] = [8^\circ, 8^\circ, 8^\circ, 8^\circ]$ . In addition, the radial mask is set so it reaches the end of the Fourier 2D space, so the mask cut-off is  $\delta = [\delta_1, \delta_2, \delta_3, \delta_4] = [1024, 1024, 1024, 1024]$ .

The inverse Fourier transform applied to the masked spectra generates an image free from features along these angles. The result of the inverse 2D FFT is given in a complex number matrix, so the real part (or the absolute value) of this matrix needs to be taken in order to plot the spectrogram. Taking the real part preserves the original dynamic range of the spectrogram (colors) removing the TAE antenna signal as shown in in Fig.8. It is to be noted that the amplitude values are modified (observe the colorbars scale in Fig.8). Taking the absolute value gives

a similar result, but it might return a negative image, therefore changing the color range of Fig.8).

To summarize, Fig.8 shows the original spectra, the 2D FFT magnitude spectrum with a filter mask, the resulting spectrogram, and the features removed from the images: the TAE antenna signal is successfully removed from the spectrogram. It is to be noted that removing these directions keeps most information of the original signal (sawteeth or MHD activity can not be observed in the removed features). However, modes aligned with these directions can be attenuated or disappear. As already mentioned, if there are modes in the vertical direction we can proceed by further processing the vertical image. In the case of FFT2D it is also possible to redesign the mask and create a directional band pass filter.



**Figure 8.** Use of 2D FFT to remove TAE antenna sweeps: Original image, Mask over 2D FFT, Filtered image, and noise removed.

If algorithms (1) and (2) are combined, the resulting image offers an improved contrast highlighting MHD features of the signal. In Fig.9 most of broadband noise and the complete TAE antenna signal are removed. However, this approach is not without limitations. If the MHD activity aligns with the TAE antenna sweeps, we might lose these modes. For instance, two elliptic alfvén eigenmodes (EAE)s disappear, these small modes are situated at 51s and 475 kHz approximately (decreasing in frequency). Moreover, sawteeth signals are still crossing the MHD modes.

Depending of the application, the design of the mask might need some trial and error in selecting the parameters. In the 2D FFT low frequencies are situated in the center. To not cover this region, the mask is a composition of radial circle sectors centered at angles  $\theta$  with respective apertures  $\Delta\theta$ . The mask starts at a radial cut-off  $\delta$  distance from the origin, so low spatial-frequencies are not filtered. In addition, it has been found useful to resize the

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**Algorithm 2:** Remove straight line patten using 2D FFT high pass directional filters

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**Input:** Time series  $\mathbf{s}$

**Parameters:**

Mask angles:  $\theta = [\theta_1, \dots, \theta_N]$ .

Angle width:  $\Delta\theta = [\Delta\theta_1, \dots, \Delta\theta_N]$ .

Mask cut-off:  $\delta = [\delta_1, \dots, \delta_N]$

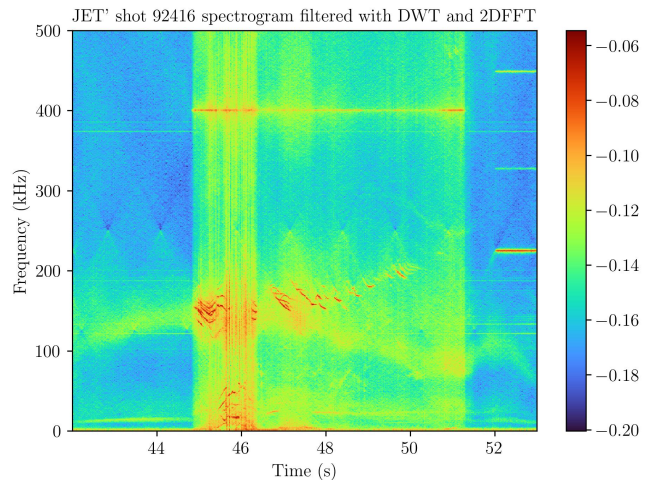
**Output:** Reassigned spectrogram  $S_{xx(mod)}$

**Steps:**

- 1 Obtain spectrogram matrix  $S_{xx}$  using STFT( $\mathbf{s}$ ).
  - 2 Resize image  $S_{xx}$  to have squared size:  $1024 \times 1024$ .
  - 3 Transform resized image to frequency space.
  - 4 Apply Mask to frequency space (truncated circle sectors centered at  $\theta_i$ , width  $\Delta\theta_i$ , and maximum radius  $\delta_i$ ).
  - 5 Inverse transform the masked image to obtain the filtered image  $S_{xx(mod)}$ .
  - 6 Return  $\text{Re}\{S_{xx(mod)}\}$
- 

spectrogram to a square image in advance. This helps to design a symmetric mask (the radial mask apertures  $\Delta\theta$  are centered around the given angles  $\theta$ ).

It has been found that this algorithm is remarkably useful for removing straight lines crossing the whole image, like the ones commonly present in spectrograms from interferometers. Once the mask is designed for this use case ( $\theta = 0$  or  $90$  and  $\Delta\theta = 1$ ) the fine-tuning of parameters is optional.



**Figure 9.** Result of combining Algorithm 1 and 2. On the left the original spectrogram is shown, in the right picture the result of using both algorithms.

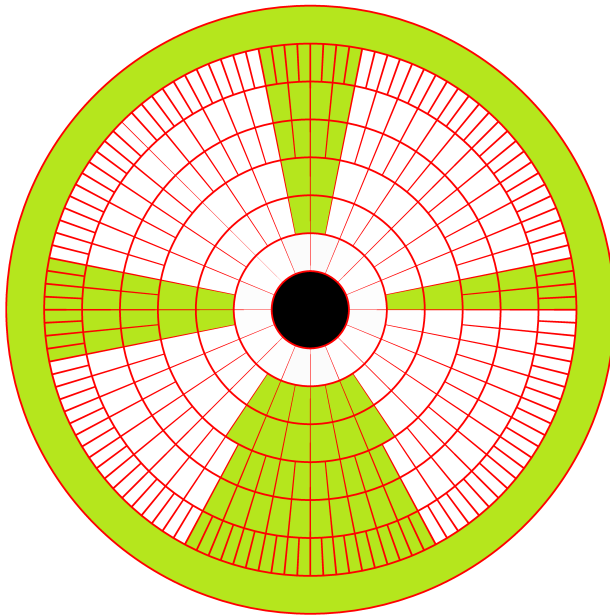
The manipulation of Fourier space is a key concept to understanding curvelet transform as well. Given the success of using discrete wavelets in the algorithm (1) we worked on generalizing this approach by using curvelets.



## 6. Multiscale-multidirection pattern removal using curvelets

The curvelet transform [22] is a multidirectional generalization of the DWT, better suited when images have curvy edges and multiple directional features, like the MHD modes in our spectrograms. For removing noise and undesired components in a selected angular direction, corresponding subimages are set 0 and then the inverse curvelet transform is applied.

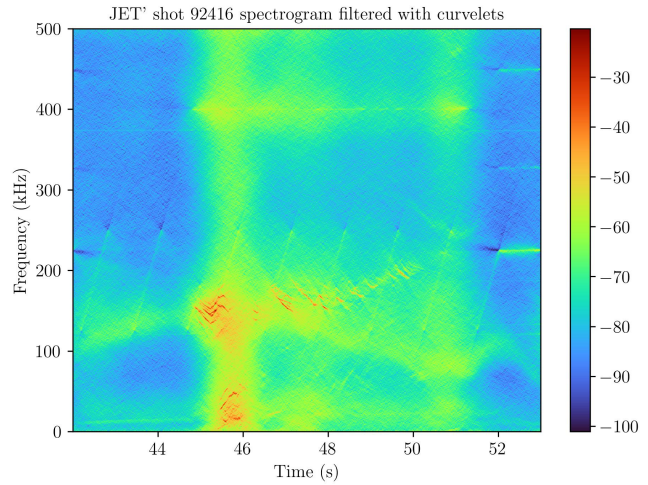
In Fig.10, a polar representation of the 2D Fourier space is shown. The 2D Fourier space is divided in a tessellation of “wedges” [22]. Each wedge has a corresponding subimage with certain scale and directional properties. The wedges closer to the center are subimages with large scale (low-frequency) features. The colored wedges are the ones selected to be removed before the inverse Curvelet transform is applied. These directions are vertical, horizontal, and the corresponding directions of the antenna sweeping. The scales to be removed in these directions are everyone but the corresponding to the two larger scales (lower frequencies represented in the center wedge, and the first concentric wedges).



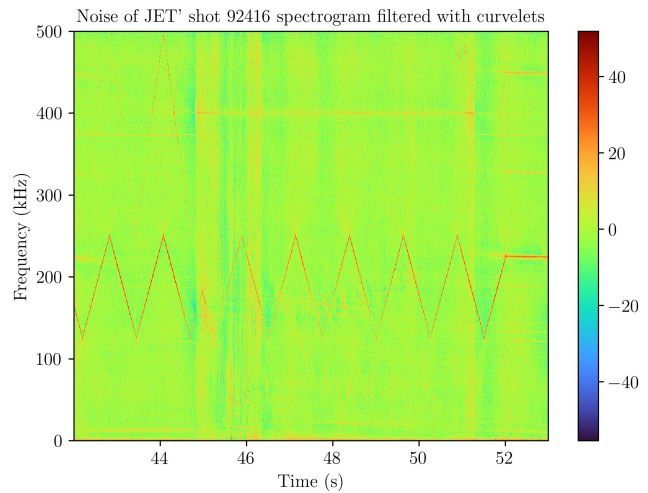
**Figure 10.** Cartoon of curvelet’s wedges in polar coordinates. Colored wedges are set to zero before doing the inverse Curvelet transform

The result of using the algorithm (3) steps 1-3 can be seen in Fig.11, the noise removed is plotted in Fig.12. Curvelets are able to remove anisotropic noise and improve spectrogram contrast. Moreover, the TAE antenna signal and the ICRH subharmonics are successfully removed from the spectrogram, sawteeth are eliminated as well. The wedge tessellation is configured by selecting the number of scales and wedges corresponding to the angles detected with the Hough transform. The interested reader can find more details about the curvelet transform in Ma’s review paper

[32].



**Figure 11.** Result of applying curvelet transform algorithm to remove TAE antenna: Algorithm (3), steps: 1-3.



**Figure 12.** Noise extracted using curvelets

It is worth mentioning that although all examples in this paper originate from magnetic sensor signals, these noise removal algorithms could be useful with interferometers or LIDAR diagnostic signals as well, which particularly can suffer from straight line artifacts caused by phase jumps.

## 7. Automatic segmentation of MHD modes

After improving contrast and having removed other undesired signal components, classic CV algorithms can perform optimally labeling the MHD activity, using all the steps indicated in the algorithm (3).

Given the result of Fig.11: Sato’s ridge operator can be applied to detect the mode pixels. It is worth mentioning that the Meijering’s ridge filter [39] can perform as well or

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**Algorithm 3:** Complete pipeline for automatic labeling of MHD activity

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**Input:** Time series  $\mathbf{s}$

**Parameters:**  $\sigma = 1$ ,  $\sigma_{\text{scales}} = [1, 2]$ ,  
 $\theta = [\theta_1, \dots, \theta_N]$ ,  $\varsigma = 9$  (optional)

**Output:** Reassigned spectrogram  $S_{xx(\text{mod})}$

**Steps:**

- 1 Calculate the spectrogram STFT( $\mathbf{s}$ );
  - 2 Detect straight line patterns or specify angles manually.
  - 3 Apply curvelet transform (or use Algorithm 2 and skip steps 4 and 5).
  - 4 Set to 0 (hard thresholding) wedges corresponding to directions  $\theta$
  - 5 Apply inverse curvelet transform, take the absolute value and invert the image.
  - 6 Apply Sato's ridge operator with  $\sigma_{\text{scales}} = [1, 2]$ . (Or Meijering's)
  - 7 Smoothing: Gaussian( $\sigma=1$ ).
  - 8 Yen's automatic thresholding (binarize the image).
  - 9 Mark up pixel-connected areas (for labeling MHD activity), using a full-connectivity filter
  - 10 Removed noisy labels: modes with less than  $\varsigma=9$  pixels. (Optional)
- 

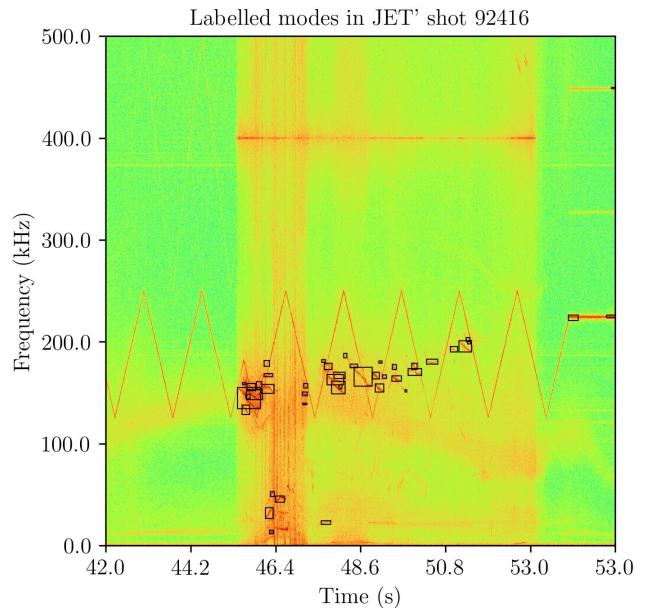
better than Sato's. Afterwards, a Gaussian smoothing of 1 pixel width is applied to remove some background smearing texture left by the Ridge operator. Finally, Yen's automatic thresholding is used to binarize the image: the pixel values are 0 or 1.

Then, it is easy to detect connected areas by using a connectivity filter. When two pixels are next to each other and have the same value, they are linked. In a 2-connectivity filter (full), diagonal linking is allowed, whereas in a 1-connectivity filter, only vertical and horizontal-vertical linking is permitted. To give some examples, in a  $3 \times 3$  image, among all combinations, 5 connected pixels variation on a binarized image can be

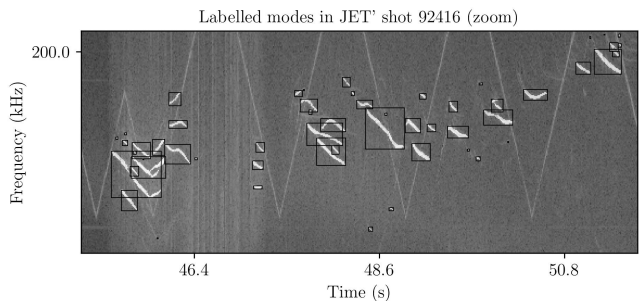
$$\begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}.$$

Next step is optional (remove noisy labels). We can considered noisy modes: those with less than 9 pixels connected. In other words, a labelled mode is noisy if a mode is a pixel not fully linked with surroundings. This criteria can vary depending on the number of pixels in the spectrogram and the size of the modes.

Algorithm (3) result in Fig.13. We conclude that individual modes are successfully labeled with minor errors like a few modes missed and only three false positives out of 45 regions of pixels detected. In addition, some modes of very low signal-to-noise ratio and mostly aligned with the removed directions are missed.



**Figure 13.** Result of automatic labeling over original spectrogram. In total, 43 modes are segmented correctly. After 53 s, part of the TAE antenna signal produces 3 false positives.



**Figure 14.** Detail of the result of automatic labeling

It is worth mentioning the intrinsic limitations that every segmentation algorithm exhibits, including the ones presented in this work: missing modes (false negatives), identifying noise as modes (false positives), merging crossing structures or fragmentizing (separating) continuous structures (because of fluctuations in pixel intensity). In addition, when using ridge detectors, we are assuming that the mode signal has this structure. With this assumption, details like extended shadows (or big blobs) can be eliminated. In our case, there is no ground truth so the presented algorithms are unsupervised learning algorithms. Consequently, the result has to be interpreted and if it is good enough it can serve as a ground truth for other algorithms.

It is important to remark that identifying the instability name for each time-frequency structure is an ill-posed problem as the spectrogram alone does not contain enough information. However, the methods introduced in this work can be enhanced by combining information from other diagnostics or using robust theory-based results from

physics. For instance, it is easy to add phase information from other magnetic sensors via mode number analysis or coherence of the signal, this would help to separate crossing modes and labeling some instabilities. Moreover, physical theory or simulations can complete the analysis. For example, the Alfvén spectra can be calculated, therefore it can add information on frequencies corresponding to different instabilities. Further MHD numerical calculation can identify time-frequency properties of the plasma, inferring equilibrium information or kinetic effects.

In addition, it is to be noted that an application with a graphical user interface could be used to discard these minor labeling errors. For instance, a tool called *Wavystar* with a GUI has been implemented, available under request in JET. This application implements algorithms discussed in this work, and other analysis capabilities of transitory signals not treated in this paper.

We conclude by mentioning that the computational resources needed to run these algorithms are very low. A common laptop (11th Gen Intel(R) Core(TM) i7-1185G7, 3.00GHz) can run these algorithms in a few seconds without special memory requirements (16-32 GB RAM). Also, the presented algorithms have few hyper-parameters. Moreover, the data pipelines presented in this work offer high flexibility: image filters, ridge detectors, and thresholding algorithms can be modified, interchanged, or skipped to be adapted to new use cases and data from different machines. These facts make them suitable for mining big databases.

## 8. Conclusion and future work

The main innovation introduced in this work is the use of wavelets and curvelets along with simple CV algorithms to filter (reassign) the spectrograms of magnetic sensors. The complete pipeline successfully removes noise and undesired patterns in a fully interpretable way, in other words the addition of removed noise and filtered spectrogram returns the original signal.

The main concepts that allowed these results are two: (1) noise present in spectrograms is highly anisotropic, and (2) the plasma phenomena observed in spectrograms are multi-scale. Therefore, removing features in a certain scale and direction maintains a high fraction of the original information containing the MHD modes.

Nowadays, the state of the art in computer vision algorithms is the use of deep CNNs and other neural network architectures. However, they require huge amounts of curated data. The application of classic computer vision algorithms has not been extensively researched in Fusion applications, which constitutes a gap of knowledge that this work aims to fill. The application of these classic algorithms is a necessary step for creating curated datasets, improving the performance of future deep learning algorithms.

Data contained in spectrograms, like frequencies, duration, and amplitudes of the MHD modes, can be extracted, stored and further studied. The possibility of completing the results of the introduced methods with established physics of the MHD activity can further develop the potential application of this work. Therefore, a

straightforward application of the algorithms introduced in this paper is the creation and curation of a database of modes. Finally, the database obtained can be used to train DL networks for real-time mode prediction.

## Acknowledgments

All **CurveLab** commercial rights are reserved to [22] authors, though it is freely available for academic use. The algorithms presented here only call CurveLab functions through the open-sourced Python library **curvelets**.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200-EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

This work has received financial support from the AIM4EP project (ANR-21-CE30-0018), funded by the French National Research Agency (ANR) and from the Aix-Marseille University Initiative of Excellence - A\*Midex, Investissements d’Avenir programme AMX-19-IET-013.

This work has received funding under the Implementing Agreement No. 2 to the Agreement on Academic and Scientific Cooperation (REF. : AMUDRVCP09052019-1 / 4300002670) between the ITER International Fusion Energy Organization and Aix-Marseille University. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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