“TP” Practical Work : Fluctuation observation in magnetized plasmas by a high speed camera

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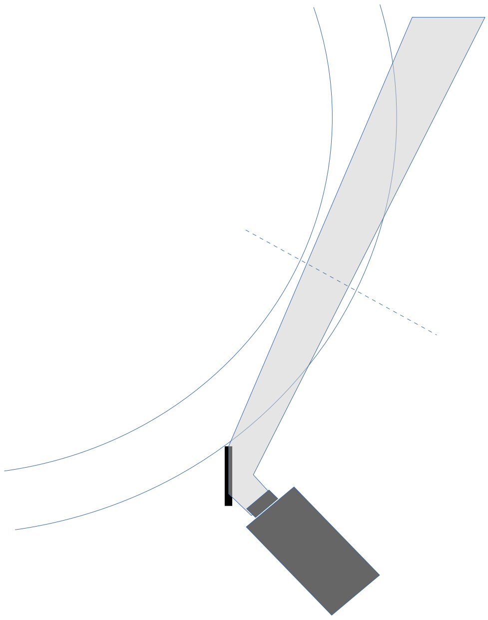
Camera geometry

A fast speed camera observes the plasma in front of a Torix quartz window.

A mirror is placed right behind the window to give a tangential view to the camera. The focal position is $90\,cm$ in front of the camera lens. This corresponds to the position where the observation direction is tangential to the magnetized plasma.



Abel Inversion

The camera measures the light emitted by the plasma.

The plasma is considered to be a transparent 3D object. Each camera pixel integrates the emitted light all along the observation direction. The Abel inversion is used to deduce the light emitted in the poloidal plane perpendicular to the view direction from this measurement.

Conditions

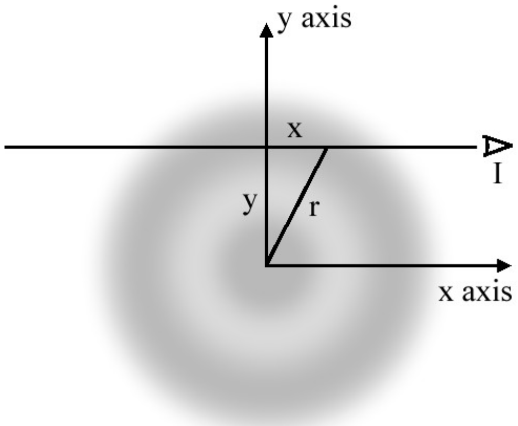
We assume

- the plasma is transparent and the light received by one pixel is the emitted light integrated along the observation direction ;
- all observation directions are parallel to each other ;
- the emitted light is axis-symmetric along the magnetic field lines at least along the distance the camera view angle crosses the plasma.

Abel integration and inversion

The Abel inversion is applied in each horizontal toroidal plane.

$F(y)$ is the integrated light along a chord. It is a function of y the distance between the chord and the symmetry center $(0,0)$ (the tore axis).



f_2 is the local emitted light for each position in the plasma (x, y) in a horizontal plane. F is deduced from f_2 by integration:

$$F(y)=\int_{-\infty}^{+\infty} f_2(x, y)dx$$

f_2 has a circular symmetry in this plane. This function can be expressed as a large radius function $f(R)$ corresponding to the local emitted light as a function of the tore large radius $R=\sqrt{x^2+y^2}$:

$$f_2(x, y)=f(\sqrt{x^2+y^2})$$

The chord integration $F(y)$ can be expressed as a function of the radius function $f(R)$:

$$F(y)=2\int_{y}^{+\infty} \frac{Rf(R)}{\sqrt{R^2-y^2}} dR$$

The Abel inversion is the reciprocal formula:

$$f(R)=-\frac{1}{\pi}\int_{R}^{+\infty} \frac{1}{\sqrt{y^2-R^2}} \frac{dF(y)}{dy} dy$$

This integration is only valid for profiles that are regular enough. $f(R)$ have to drop to zero more quickly than $1/R$.

The Abel inversion formula allows to deduce the emitted light in the plane perpendicular to the position where the camera view direction is tangential to the plasma from the chord integrated light.

Inversion geometry

The camera image pixel X-axis has to be calibrated to the tore large radius.

For this you need:

- a pixel length calibration,
- a common reference position between the camera image and the probe position.

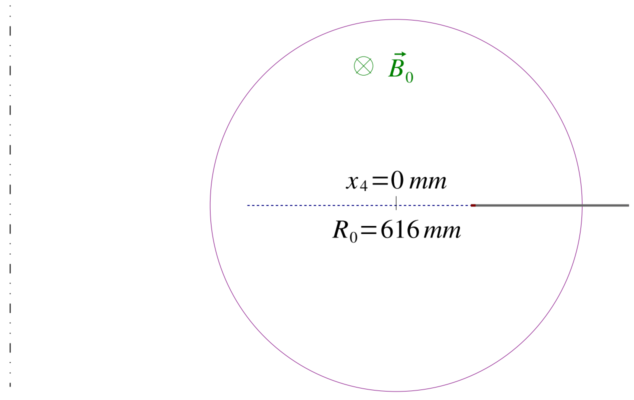
Length calibration

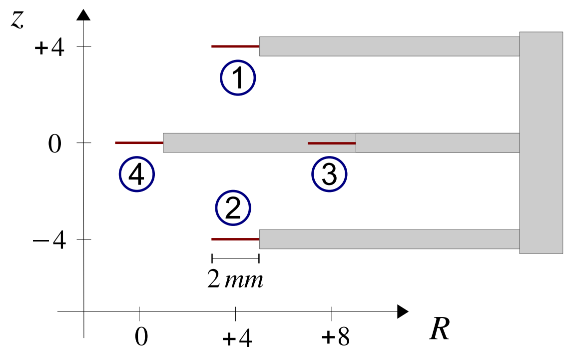
A calibration measurement done with a test pattern placed where the camera observation direction is tangential to the plasma : this gives the pixel step length calibration.

Reference position

In order to associate the camera x-axis with the large radius, we associate the electron density maximum radial position measured by the probe to the maximum emitted light x-axis position for the image y position corresponding to the probe.

The reference position 0 for the probe 4 corresponds to the tore large radius $R_0=616\,mm$.





Abel Inversion Methods

The Abel inversion is an improper integral because of the denominator: the integration is not a simple trapezoid summation.

There are different methods to implement the Abel inversion integration. We use the 3 point algorithm: it is less sensitive to measurement noise.

Practical work

The object of the practical work is to try to characterize the spatial properties of the drift wave.

Probe and Camera measurements

The operating parameters are as follows:

Toroidal magnetic field: $B_{\phi 0}=0{,}3\,T$

Neutral Argon Pressure: $P_n=3{,}5\ 10^{-4}\,Torr$

Discharge (filament polarization) voltage: $U_d=-90\,V$

Discharge current: $I_d=0{,}25\,A$

Vertical magnetic field: $B_v=0\,;12\,;16\,G$.

We measure the fluctuating signals on the 4 probes using the generator frequency $50\,kHz$. The measurements are made radially from the position $R_{4\,min}=-64\,mm$ to position $R_{4\,max}=52\,mm$ by step $4\,mm$ ($R_{4\,max}=0$ corresponds to $R_0=616\,mm$).

$5\,000$ camera images are measured at $100\,kF/s$ for 2 different probe positions: $R_{4\,max}=-36\,mm$ and $R_{4\,max}=52\,mm$.

Data analysis

You can get this document from the web. Once connected to the linux session:

```
[vosges ~]$ firefox
# To get the pdf file for this document: www.lpp.fr → "pages personnelles" → "C. Honoré"
https://www.lpp.polytechnique.fr/-Cyrille-Honore-
# To view the pdf
[vosges ~]$ evince honore2025pw_camera.pdf &
```

Data collection

Get the data tar file from the cloud:

```
# TP #1 : TorixCamera_240304_Bz12_tp1.tar.bz2
https://filesender.renater.fr/?s=download&token=4f2b4c38-3482-480b-abc4-69edff888176
# TP #2 : TorixCamera_240304_Bz16_tp2.tar.bz2
https://filesender.renater.fr/?s=download&token=6af1852d-2ee3-4486-9476-49128753182a
# TP #3 : TorixCamera_240306_Bz12pgauss_tp3.tar.bz2
https://filesender.renater.fr/?s=download&token=8727e00f-c333-4867-b93c-dad3da1f5d1b
# TP #4 : TorixCamera_240306_Bz16pgauss_tp4.tar.bz2
https://filesender.renater.fr/?s=download&token=e323d84d-2166-4e4c-b134-6b77fa48be69
# TP #5 : TorixCamera_250303_TPcamera12G_tp5.tar.bz2
https://filesender.renater.fr/?s=download&token=e00ef4b9-4bad-4595-bdab-ad6f26ba3afc
# TP #6 : TorixCamera_250303_TPcamera16G_tp6.tar.bz2
https://filesender.renater.fr/?s=download&token=ef0c89d9-5d00-46b7-bad1-f77aa614c8eb
```

Once it is downloaded, you can uncompress the data (within a few minutes...) :

```
[vosges ~]$ tar jxvf TorixCamera_240304_12G_tp1.tar.bz2
```

This creates a file (startup.m) and a folder (matlab).

To check them once the uncompression is ended, you can launch the file manager:

```
[vosges ~]$ nautilus &
```

Then you can launch Matlab:

[vosges ~]$ matlab &

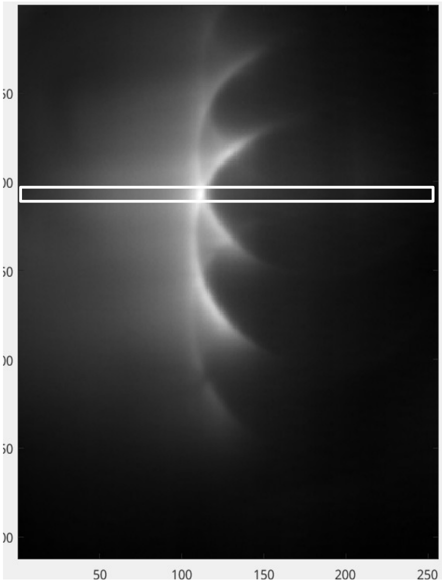
Matlab should find folders to add to its path ("data..." "main...") in order to access the data and programs.

Camera radial position calibration

In order to apply the Abel inversion we have to calibrate the pixel x-axis with the Tore large radius.

First we need the pixel step calibration $mmpx$: we use the test pattern image. The test pattern was placed in the plane perpendicular to the position where the camera view direction is perpendicular to tore radius.

```
imcal = imread('240117_calib_9.6mm.tif'); % load calibration image for 240304 and 240306
imcal = imread('250121__calib_9.6mm.tif'); % load calibration image for 250303
figure, imagescn(imcal); % plot image
export_fig(gcf,'-dpng','-r300','-nocrop',''fig_calib.png); % export figure as PNG file
```



We also need a reference position. We assume the position for which the light is maximum corresponds to the position for which the electron density is maximum.

We must first identify on the camera image the pixel height corresponding to the probe measurement iy_{pr} . For this purpose we compare the time averaged images for different probe radial positions to observe the effect of the probe shadow along the magnetic field on the image.

```
im12am = litpfvimag('240304_Bz12G_-36mm_50kHz','m'); % load time average image
```

Then we can compare the light radial profile for this height to the probe electron density profile.

We need to extract the maximum position for the light ix_{max}

```
R0 = 616 ; % R_0 : probe large radius at x=0 ; iypr: probe height [pixel]
figure, plot(1:size(im12am,2),im12am(iypr,:)); xlabel('ix [px]'); ylabel('light [a.u.]');
```

And we need to extract the electron density maximum position R_{max} .

```
B_T = 0.3; Fgen = 50e3; % magnetic field [T] ; probe gene freq. [Hz]
[x,~,ne,~,Vp] = probe_profiles('240304_Bz12G',B_T,Fgen,4) % computes probe radial profiles
load('240304_Bz12G_50kHz_p4_profiles'); % load profiles ; variables: x B_T TeV ne ni Vp
```

```
plot(x,ne); xlabel('[mm]'); ylabel('[m^{-3}]'); % graph of ne(x [mm])
```

Abel inversion

Once the calibration is done, the Abel inversion can be performed for measurements with and without the vertical magnetic field.

```
prpos = -36; rotation = 0; % acquisition probe position ; image rotation angle
% To compute and save Abel inversion :
implread('240304_Bz12G',prpos,Fgen,inf,rotation,1,[mmpx,Rxp,ixm],1);
% mmpx : mm/pixel ; Rxp : density max R position ; ixm : light max x-axis pixel
```

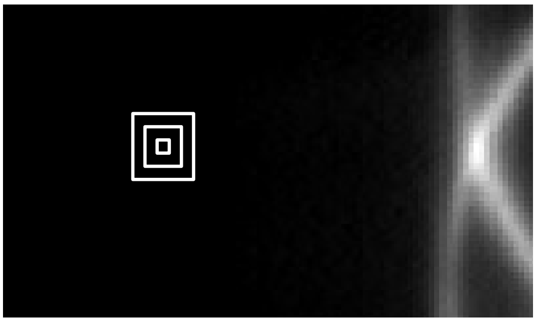
Compare the time averaged image before and after the Abel inversion.

```
% load the time averaged Abel reversed image:
im12abm = implreadabel('240304_Bz12G_-36mm_50kHz_abel','m');
```

Compare the light radial profile before and after the Abel inversion for the probe height iy_{pr} , and with the probe electron density radial profile.

```
plot(x+R0,ne/max(ne),mmpx*((1:size(im12am,2))-ixm)+Rxp,im12am(iypr,:));
% load the 3D Abel inversed image matrix (y,x,t):
[im12ab,dt] = implreadabel('240304_Bz12G_-36mm_50kHz_abel',inf);
```

Pixel averaging and noise



We apply the frequency auto-spectrum analysis to a pixel time signal corresponding to the high field side (HFS) gradient zone (for the measurements with the vertical magnetic field).

We consider the height iy_{pr} corresponding to the probe height, and the radial position ix_g , 3 mm in front of the filament in the HFS gradient zone.

We try to enhance the spectrum analysis by doing some pixel averaging using the neighboring pixels.

```
pxt = pxmean(im12ab,iy,ix,npx);
% pxt: 1D time signal for pixel (iy,ix) averaged with +/-npx along x and y axis (5x5 pixels)
```

Test the auto-spectrum analysis for the same center pixel and different pixel width (from 1 to 6 neighboring pixels).

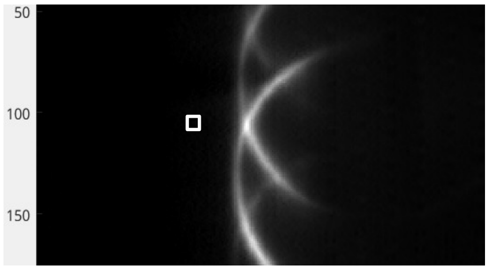
```
% Time signal frequency auto-spectrum :
nfft = 200; % data number for each spectrum or correlation
[sp4,f] = ispect(pxmean(im12ab,iy,ix,4),[ ],nfft,dt); % sp: auto-spectrum ; f: frequency vector
semilogy(f,sp1,f,sp2); legend('sp1','sp2'); % auto-spectrum graph in logarithmic y-scale
```

Why are the frequency spectrum peaks more visible for larger pixel spatial averaging?

What is the spatial resolution loss for these pixel averaging ?

For the following pixel time signal analyses, we always use the 4 neighbors width averaging.

Camera Pixel and probe electron density cross-correlation



Compute the probe electron density signal for the probe 4 at $x=-36\,mm$ position for the case with the vertical magnetic field.

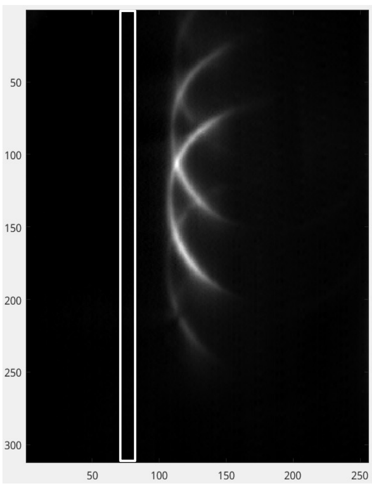
```
[~,net,~,~,~,~,~,dtp] = probe_caract_dyn('240304_Bz12G_-36mm_50kHz',B_T,4,inf,'dyn');
% 1D vector net is the density time series ; scalar dtp is the time step between 2 data.
```

Compute the frequency cross-correlation between the probe electron density signal and a camera pixel that is close to the probe (linked with the magnetic field).

```
% 2 time signal frequency cross-spectrum :
[ispne12,f] = ispect(net,pxmean(im12ab,iy,ix,4),nfft,dtp);
% ispne12: cross-spectrum ; f : frequency [Hz]
[~,~,icorne12,tc,maxic,tmaxic] = ispect(net,pxmean(im12ab,iy,ix,4),nfft,dtp,'n');
% icorne12: cross-correlation on normalized data;
% tc: correlation time vector; maxic, tmaxic: correlation maximum and max time
semilogy(f,abs(ispne12))  % cross-spectrum modulus graph
plot(f,angle(ispne12))  % cross-spectrum argument graph [in radian]
plot(tc,icorne12)   % cross-correlation graph
% If the 2nd parameter (pxmean(im12ab,iy,ix,4)) lags behind the 1st parameter (net) :
%  -> the cross-spectrum argument is negative for f>0
%  -> the maximum correlation is reached for tc>0
```

Why is the cross-correlation quite large ? Which signal physical differences explain the cross-correlation is not 100% ?

Mode dispersion relation k_y, ω



The pixel image allows to do a more complete analysis using all pixels in the vertical direction to obtain a k_y, ω dispersion relation for the HFS gradient zone for a radial position. We choose the same pixel radial position in the HFS gradient zone ix_g .

We apply this analysis with and without the vertical magnetic field.

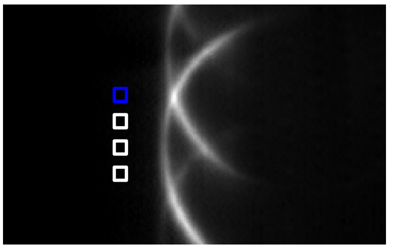
```
[spzzt12,ky,f] = spectzt(im12ab,ixg,8,nfft,dt,mmpx); % 2D y-axis and time autospectrum
% im12ab: 3D matrix ; ixg: x position ; 8: +/-8 pixels averaged along x ; nfft: data nb per fft
% dt: time step [s] ; mmpx: pixel step [mm/px] ; spzzt12: 2D spectrum ; ky [m^-1] ; f [Hz]
% a peak at ky>0 and f>0 corresponds to a propagation along increasing y-pixel.
[ky2,f2] = meshgrid(ky,f);
figure, surf(ky2,f2/1e3,log10(spzzt12)')
set(gca,'xlim',[-3e3,3e3]), view(90,90), xlabel('k [m^{-1}]'); ylabel('f [kHz]');
```

What are the dispersion relation differences between with and without the vertical magnetic field ?

Can we locate the drift mode in this dispersion relation ?

For the dispersion relation **with** the vertical magnetic field : what is the value of k_y we observe for low frequencies (and even $f=0$) ? To which vertical step this k_y correspond to ?

Vertical dynamics analyzed with vertical aligned pixels

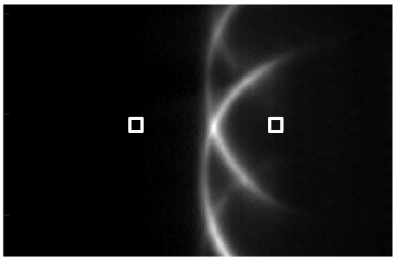


It is possible to analyze the vertical wave propagation the same way it is done with the probe by selecting 2 pixels vertically separated by several millimeters.

We can here test this cross-correlation and spectrum for different pixel vertical distances, from 0 to 100 pixels by steps of 10 pixels with the vertical magnetic field.

How does the cross-correlation maximum vary with the pixel distance ? What information does it give about the mode spatial properties ?

Plasma rotation around the filament



Compute the cross-correlation between 2 pixels radially spaced on each side of the filament at the probe height with and without the vertical magnetic field. Each pixel will be 8 mm away from the filament.

Why is the cross-correlation maximum different with and without the vertical magnetic field?