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# Turbulence in a toroidal magnetized plasma investigated by collective light scattering: plasma form factor and plasma diffusion

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## Abstract

On the toroidal magnetized plasma discharge ToriX, a collective light scattering device has been set to investigate plasma turbulence and transport. The light scattering intensity provides a measurement of the static form factor, at the scale of the scattering wave number  $k$ . The form factor is found to be very large, five to nine orders of magnitude above the equilibrium level. As a function of the  $k$  wave number, an exponential decay is found instead of a scaling law. This implies long range spatial correlation. When a vertical field is added to the horizontal toroidal B field, a significant decay of the form factor intensity is observed.

The scattered light time correlation is investigated as a function of  $k$ . It is interpreted with the help of a model of brownian type of turbulent motion (the Ornstein correlation). According to this model, the signal auto-correlation function is expected to be:

$$C(\tau) = A \exp\{-k^2 l_c^2 [1 - \tau/\tau_c - \exp(-\tau/\tau_c)]\},$$

where  $\tau_c$  and  $l_c$  are the turbulent motion correlation time and length resp. . A best fit of the experimental data with this model correlation provides  $\tau_c$  and  $l_c$  (and possibly  $D = l_c^2 / \tau_c$ , a turbulent diffusion coefficient). Detailed investigations show this method provides a good measurement of the turbulent velocity ( $u = l_c / \tau_c$ ), and some of the non-gaussian properties of the plasma turbulent motion.

## Introduction

Turbulence and transport phenomena can be remotely investigated in plasma devices by collective light scattering. This is true in tokamaks<sup>2,3</sup> as well as in space<sup>4,5</sup> plasmas. The scattered (electric field) signal amplitude and time correlation are expected to be<sup>6</sup>

$$\langle s(t) \cdot s^*(t+\tau) \rangle \cong S(k) \cdot \langle e^{ik\delta(\tau)} \rangle \quad \text{Eq.1}$$

If  $n(k)$  is the electron density spatial Fourier transform at wave vector  $k$ ,  $S(k)$  is the form factor at observed wave vector  $k$ ,

$$S(k) = \langle |n(k)|^2 \rangle / (n_0 V) \quad \text{Eq.2}$$

where  $n_0 V$  is the total number of observed electrons,

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<sup>2</sup> R.E.Slucher and C.M.Surko, Phys. Fluids **23**, 472 (1980);

<sup>3</sup> A. Truc, A. Quémeneur, P. Hennequin, D. Grésillon, F. Gervais, C. Laviron, J. Olivain, S.K. Saha, and P. Devynck, "ALTAIR: An infrared laser scattering diagnostic on the TORE SUPRA tokamak", Rev. Sci. Instrum. **63**, pp. 3716-3724 (1992)

<sup>4</sup> C. Hanuise, J.P. Villain, D. Grésillon, B. Cabrit, R.A. Greenwald and K.B. Baker, Annales Geophysicae **11**, p. 29 (1993)

<sup>5</sup> J.P. Villain, R. André, C. Hanuise and D. Grésillon, Journal of Atmospheric and Terrestrial Physics, Vol. 58, Nos 8/9 pp. 943-958, 1996

<sup>6</sup> D. Grésillon, B. Cabrit, J.P. Villain, C. Hanuise, A. Truc, C. Laviron, P. Hennequin, F. Gervais, A. Quémeneur, X. Garbet, J. Payan, and P. Devynck, "Collective Scattering of Electromagnetic Wave and Cross-B Plasma Diffusion"; Plasma Physics and Controlled Fusion **34**, pp. 1985-1991 (1992).

$\delta(\tau)$  is the displacement of a given fluid element in a time  $\tau$  ,  
 $\langle e^{ik\delta(\tau)} \rangle$  is the statistical characteristic function, i.e. the Fourier transform of the random displacement  $\delta(\tau)$  probability distribution at time  $\tau$ ,  $P(\delta | \tau)$

$$\langle e^{ik\delta(\tau)} \rangle = \int e^{ik\delta} P(\delta | \tau) d\delta \quad \text{Eq.3}$$

Both the form factor and this plasma turbulent motion statistic should be retrieved from the signal of a single scattering diagnostics. Implementing such a method, the plasma form factor and turbulent motion statistics are investigated in a laboratory magnetized plasma.

### The Torix and Fremir devices

The experiment is conducted in "Torix", a toroidal magnetized discharge plasma, of 0.6m (large) and 0.1m (small) radius. The toroidal B-field intensity is 0.17 to 0.36 Tesla, the Argon plasma density is  $10^{17} \text{ m}^{-3}$  and the electron temperature is 2 eV. The plasma configuration is not a stable one, the density fluctuates at a large rate in the kHz range of frequency<sup>7</sup>. An additional uniform B-field component of about one mT along the main (vertical) torus axis, can be applied.

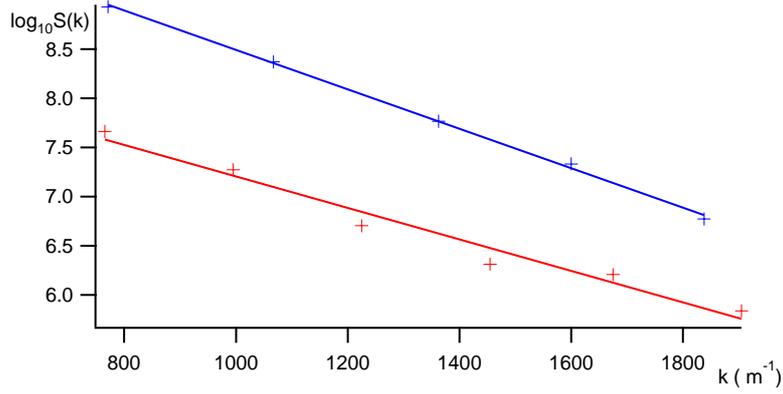
This plasma is observed by the infrared collective scattering device "Fremir", using a 2 Watts DC, CO<sub>2</sub> laser ( $\lambda=10.6\mu$ ) with an 11 mm waist. The primary beam crosses the plasma device equatorial axis along a vertical cord. The scattered light, emitted at an angle of 1.3 to 3.3 mrad with respect to the primary beam axis, is collected, together with an L.O. beam, on a nitrogen cooled photodiode. The scattering analyzing wave vector  $\mathbf{k}$  is along the main radius (across the toroidal B field), and its wave number ranges from 770 to 2000 rad/m. From a quadrature heterodyne detection circuit output, the amplitude and phase of the scattered E-field are recorded as time series.

### Form factor and turbulence amplitude

By calibrating the detection chain, the scattered signal intensity provides a measurement of the "Form factor",  $S(k)$ . For uniform plasma, the form factor is unity whatever is  $k$ . This is not the case in a turbulent plasma. This is illustrated in Fig.1, where the form factor (blue line) is plotted against the scattering wave number  $k$  (semi-log scale). The form factor intensity is large (from  $10^9$  down to  $10^7$ ); it decays exponentially as  $k$  increases from 800 to 1800 rad/m, with a characteristic decay length  $l_p$ . This range of scales is comparable to or slightly larger than the ion Larmor radius  $\rho_{ci}$  at room temperature ( $\rho_{ci} \approx 0.4$  to 0.3 mm), i.e.  $k\rho_{ci} \leq 1$ . The decay characteristic length  $l_p$  is 4.6mm, about ten times  $\rho_{ci}$ .

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<sup>7</sup> S.V.Ratynskaia, V.I.Demidov, K.Rypdal "Measurements of anomalous particle and energy fluxes in a magnetized plasma", Phys. Rev. E 65 (6) : Art.No. 066403 Part 2 (june 2002).



*Figure 1*

*Form factor as a function of wave number (semi-log scale). Top: form factor in a purely toroidal B-field ( $B=0.28T$ ); it is seen as an exponential function of  $k$ . Bottom: form factor for the same plasma parameters except for the addition of a weak vertical field  $B_v=1.8mT$ ; the form factor is decreased by a factor of 13.*

If a small vertical B-field (1.8 mT) is added, the form factor decreases by one to two orders of magnitude. This is shown as the red line in Fig.1. This decay is a consequence of a possible electron helicoidal vertical motion, whereby the  $\nabla B$  vertical charge separation can be compensated, thus attenuating the plasma outward relaxation.

#### Dynamical form factor and turbulent motion

- The scattered E-field time correlation is the statistical "characteristic function" of the random displacement  $\delta(\tau)$  of any fluid element in a time  $\tau$ ,

$$C(\tau) = \langle e^{ik\delta(\tau)} \rangle \quad \text{Eq.4}$$

The Ornstein model correlation is obtained when  $\delta(\tau)$  is a random variable with gaussian probability distribution<sup>8</sup>,

$$\langle e^{ik\delta(\tau)} \rangle = \exp[-k^2 \langle |\delta(\tau)|^2 \rangle / 2] \quad \text{Eq.5}$$

where  $\delta(\tau)$  can be obtained from the correlation length  $l_c$  and the correlation time  $\tau_c$  of the Lagrangian velocity,

$$\langle |\delta(\tau)|^2 \rangle = l_c^2 [1 - \tau/\tau_c - e^{-(\tau/\tau_c)}] \quad \text{Eq.6}$$

For long time ( $\tau > \tau_c$ ), the rms displacement increases linearly at the usual diffusive rate  $\langle |\delta(\tau)|^2 \rangle \approx (l_c^2/\tau_c) \tau$ , and the signal time correlation function is exponential. At short time instead ( $\tau < \tau_c$ ),  $\langle |\delta(\tau)|^2 \rangle$  increases at the rate of the turbulent velocity  $u_t$  ( $u_t = l_c/\tau_c$ ), and the time correlation is gaussian.

- A series of scattered signal time sequences have been recorded in the same plasma ( $B_T=0.336T$ ,  $B_v=1.8mT$ ) with different scattering k-vectors. A frequency spectrum is calculated from the complex signal; from it the no-plasma signal spectrum is subtracted.

<sup>8</sup> B.P.Tomchuk & D.Grésillon, " Ion cross-B collisional diffusion and electromagnetic wave scattering " *Voprosi Atomnoi Nauki i Techniki*, 2000, N°1, National Scientific Center, Kharkhov, Ukraine, pp.205-208.

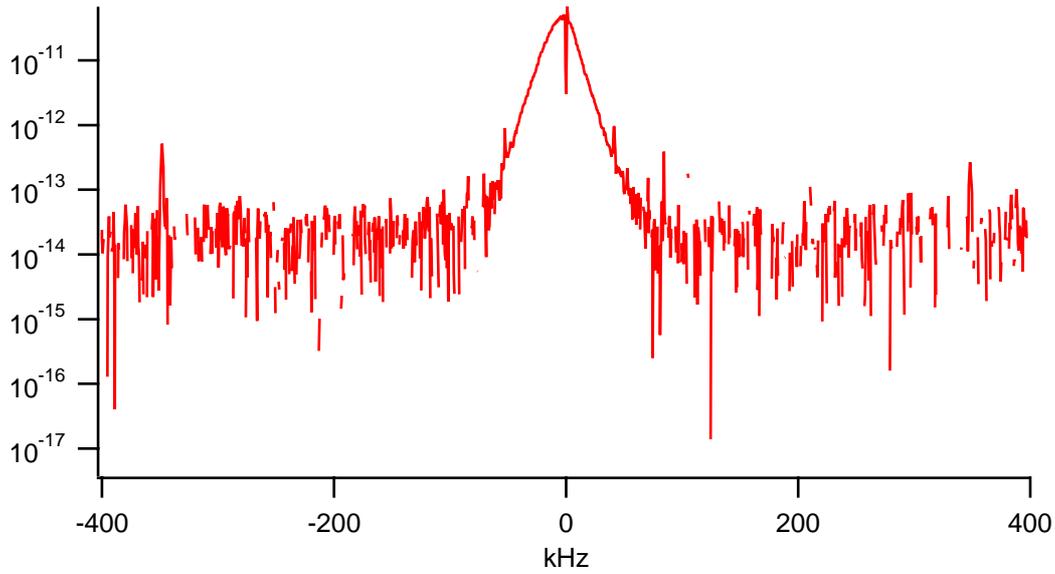


Figure 2

Scattered signal frequency spectrum from a magnetized plasma. The wave vector is  $k=1240$  rad/mm; the toroidal B-field is 0.28T, with an additional vertical B-field of 1.8 mT. The spectrum is symmetrical and the signal dynamics reaches 40db.

The time correlation can be obtained as the spectrum Fourier transform. Before this transformation, a short scale smoothing is effected to erase the low frequency band-reject filter hole near the zero frequency. Six such experimental correlation functions are shown in Fig.2 (black dots), for increasing values of  $k$  from 770 to 1970 rad/mm. Each of them is further fit with the Ornstein correlation function (Eq. 5 and 6), where the correlation time and length are optimized. The best fits are shown as the red lines. An excellent agreement is found.

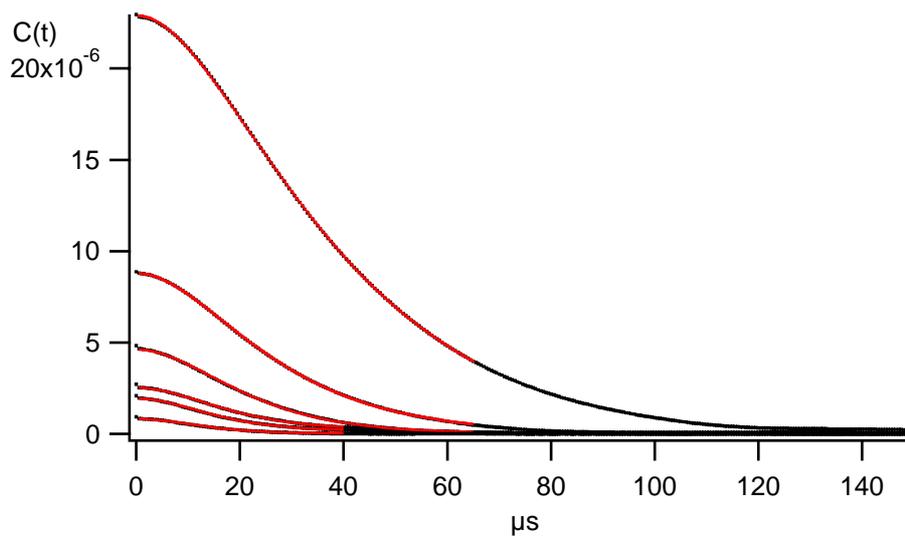
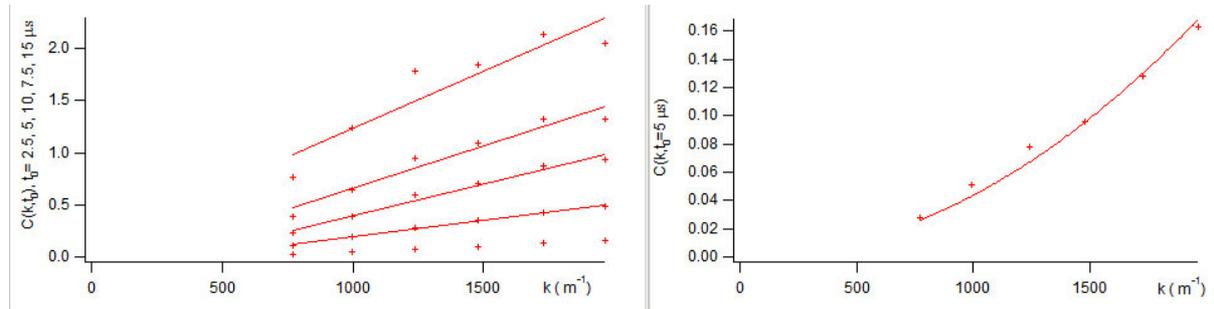


Figure 3

Signal time correlation function, for different wavevector. Black dots: experimental values; red line: the Ornstein model equation best fit. Plasma toroidal  $B=0.336$ T, vertical  $B=1.8$ mT; the wave number is (from top to bottom)  $k=770, 995, 1240, 1480, 1730, 1965$  rad/mm.

From such a fit as in Fig.3, the two parameters  $u_t$  (turbulent velocity) and  $l_c$  (lagrangian correlation length) are extracted. The velocity  $u_t$  is found to be the same ( $58\text{m/s} \pm 3\%$ ) whichever is  $k$ , as expected. But the correlation length  $l_c$  is found to change with  $k$  in such a way that  $kl_c$  is almost constant, and near to one ( $kl_c = 0.9 \pm 20\%$ ). If in addition one is willing to extract a diffusion coefficient ( $D = u_t l_c$ ), it is found to decrease as function of  $k$ . A similar analysis can be made on the signal frequency spectrum, where the fit is done on the Fourier transform of Eq.5; this analysis provides close values for the fit parameters<sup>9</sup>.

These observation contradict the gaussian displacement probability hypothesis and its consequences (Eq.5 and 6). To check this in more details, we plotted the log of the signal correlation as a function of  $k$ , for different times (Fig. 4a and 4b). Eq.5 predicts this log to be proportional to  $k^2$  at any time. This behavior is indeed observed at short time ( $\tau = 2.5\mu\text{s}$ , Fig.3b), but not at longer time where instead the log function is found to be proportional to  $k$  (Fig.3a).



**Figure 4**

*The opposite of the signal correlation logarithm as a function of  $k$ , for fixed times ( $t_0 = 2.5, 5, 10, 7.5$  and  $15 \mu\text{s}$ ). It is seen as increasing linearly with  $k$ , except at short time ( $t_0 = 2.5 \mu\text{s}$ , figure on the right at an enlarged scale) where  $\text{Log}C(k)$  increases as  $k^2$ .*

If the displacement probability is not gaussian, it remains that the signal time correlation is the Fourier transform (with argument  $k$ ) of the displacement probability distribution  $P(\delta | \tau)$  (Eq.3) : from the signal correlation it is possible to extract information on  $P(\delta | \tau)$ . As shown in Fig.4a, the probability FT is an exponential of  $k$  with a negative argument. The displacement probability distribution is provided by an inverse Fourier transform. Performed on such an exponential function of  $k$ , this transform provides  $P(\delta | \tau)$  as a Lorentzian function of the distance  $\delta$ . This is a very long range extending space correlation. In addition, since the slopes in Fig.4b are proportional to  $\tau$ , the Lorentzian characteristic width of the displacement probability increases linearly with time; the rate of increase is near the turbulent velocity  $u_t$ .

<sup>9</sup> Thanks to P.Hennequin, A.Truc and C.Honoré

## Conclusions

Different findings are worth noting from this experiment

- A calibrated measurement of the plasma form factor is possible. In this experiment it is found to be of the order of  $10^7/10^9$ , well above thermal equilibrium where  $S(k)=1$ .
- The form factor spectrum  $S(\mathbf{k})$  does not fit a scale law ( $S \propto k^{-a}$ ) but rather an exponential one ( $S \propto e^{-k l_p}$ ).
- The addition of a weak vertical  $B$  to the main toroidal  $B$ -field decreases the form factor intensity by one and a half order of magnitude.
- A time correlation function model, based on particle random motion concepts, can fit nicely the experimental data for given scattering  $k$ .
- When this model is fit to the experimental data, the plasma turbulent mean square velocity is coherently found.
- But, in contradiction with the particle random motion correlation model, the extracted correlation length  $l_c$ , depends on the observation scale  $k$ . It depends in such a way as  $k l_c \sim 1$ .
- The (fluid element) lagrangian displacement probability distribution can be measured. It is found to be a gaussian function of the distance only for short times, but to be a lorentzian function for times of the order of the correlation time.