Quasi Neutralità – Debye Shielding

Per definizione…

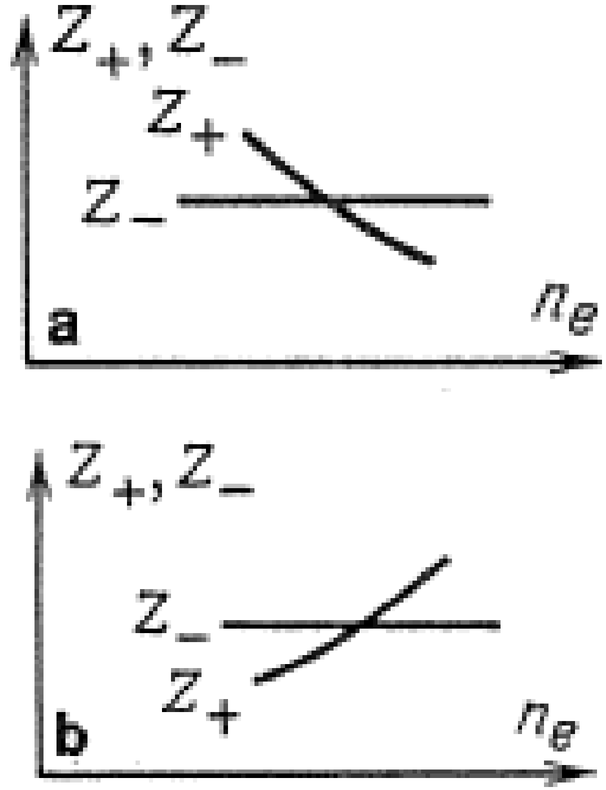
…un plasma è un gas ionizzato globalmente neutro…

Descrizione fluida: ne/ni/ng, Te/Ti/Tg, E

$$\frac{dn_e}{dt} = Z_+ - Z_- \,.$$

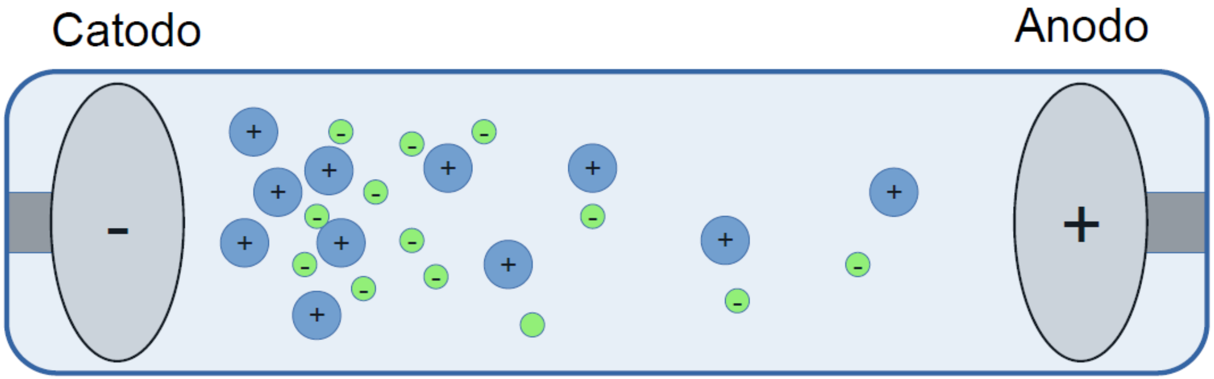
$$Z_+ \sim K_{ion}(\mathrm{Te})\ \mathrm{ne\ ng}$$

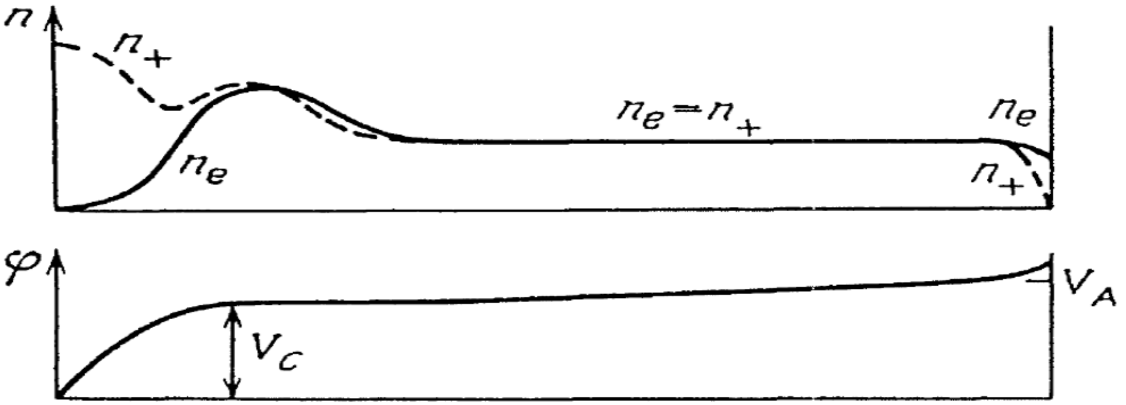
$$Z_- \sim v_{diff}\ \mathrm{ne} \ /\ K_{rec}\ \mathrm{ne}^2$$



(a) stabile/(b) instabile

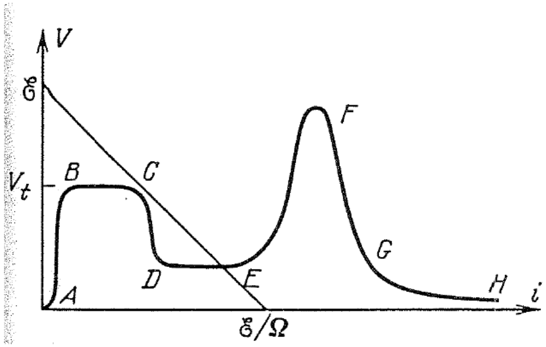
Scariche elettriche nei gas
Glow discharge





Scariche elettriche nei gas
Glow discharge

Te/ng ≈ cost => Z+ ≈ ne, Z- ≈ ne/ne^2 => stable



Ω_{EXT} ≈ cost => J↗, V=(ξ-ΩI)↘, Kion↘

$$Z_+ \sim ne^a (a < 0),\ Z_- \sim ne^a (a \approx 0)$$

Gas heating => Tg↗, ng↘, E/N ↗, Kion↗ $Z_+ \sim ne^a\ (a > 0)$

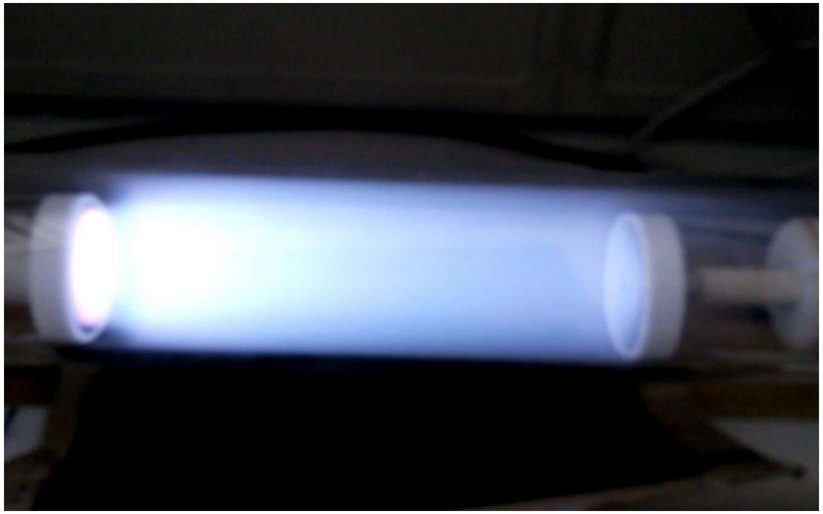
Step-wise ionization => nx↗, Kion↗ $Z_+ \sim n \cdot n_X\ (\approx n^2)$

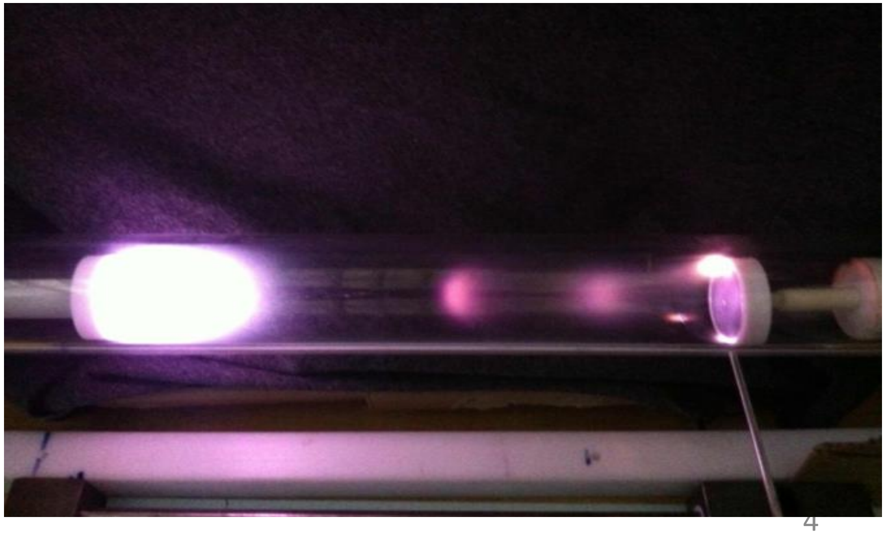
(Maxwellization/At-Detachment)

Scariche elettriche nei gas
Glow discharge

Homogeneous plasma => inhomogeneous

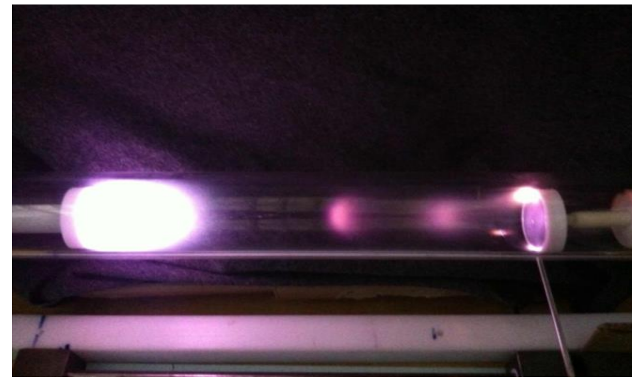
Striation (longitudinal)
Contraction (transverse)



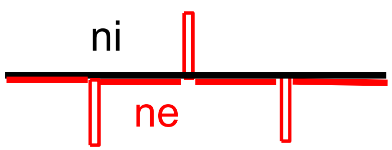


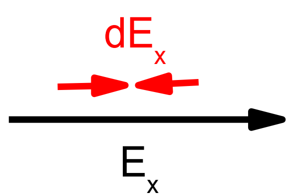
Scariche elettriche nei gas
Glow discharge

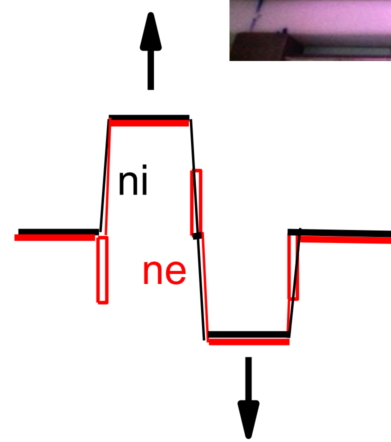
Striation



Step-wise ionization =>
ne ↗, nx↗, Kion↗





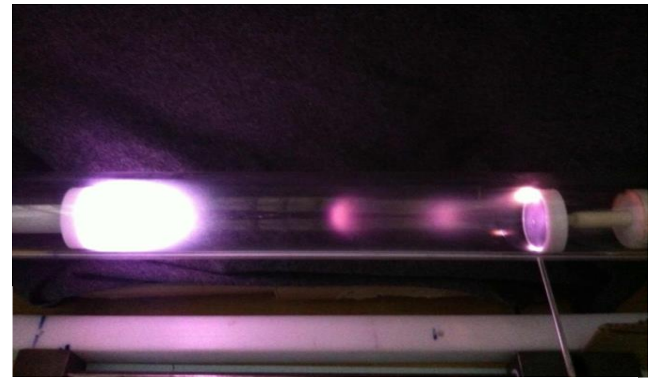


Longitudinal: $|E| \sim E_x \pm dE_x$

Transverse inefficient: $|E| \sim \sqrt{E_x^2 + dE_y^2} \sim E_x + \frac{1}{2} dE_y^2 / E_x$

Scariche elettriche nei gas
Glow discharge

Striation



Step-wise ionization => nx↗, Kion↗

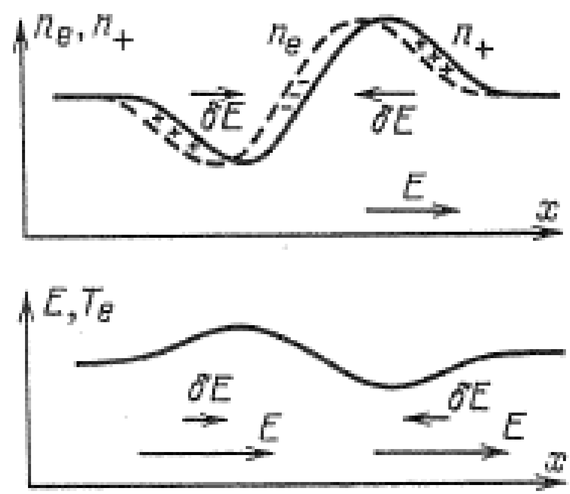
$$dn_e/dt = k_i N n_e + k_i^* N^* n_e - \nu_{da} n_e \ , \quad k_i = k_i(T_e) \ ,$$

$$dn^*/dt = k^* N n_e - k_2 N^* n_e - \nu_d^* N^* \ , \quad k^* = k^*(T_e) \ .$$

$$N^* \approx N^*[n_e(t)] \approx k^* N n_e / (k_2 n_e + \nu_d^*) \ .$$

$$n_e \propto \exp(\Omega t)$$

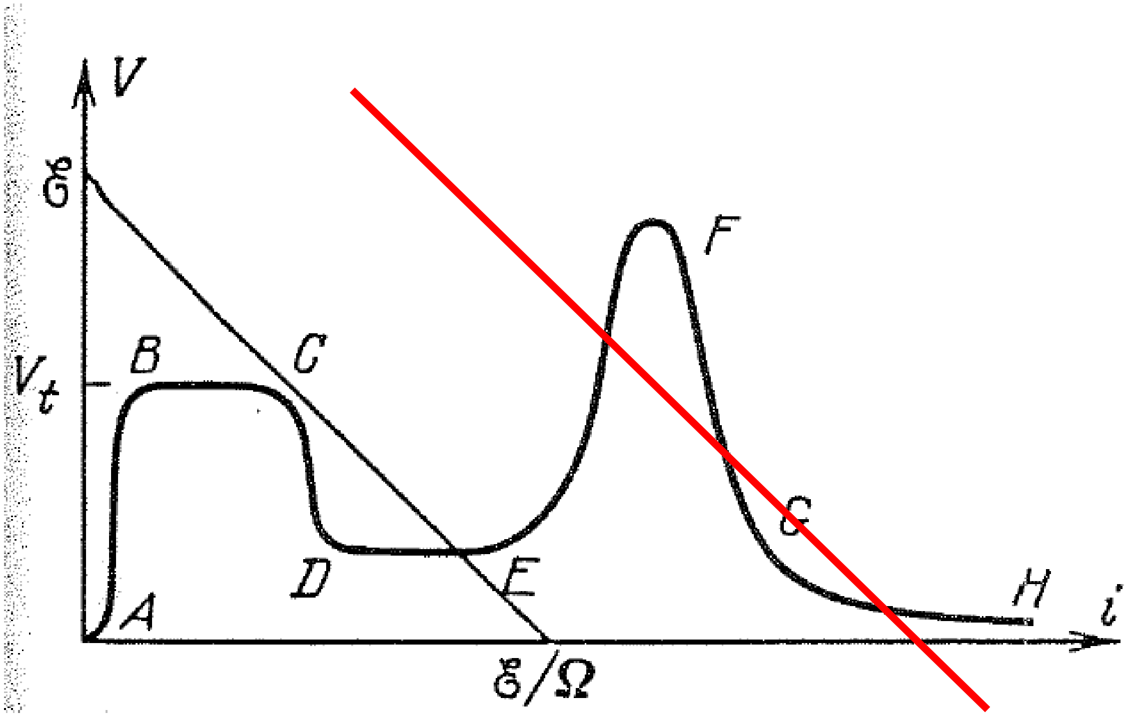
$$\Omega = \frac{\nu_d^* k_i^* N^{*2}}{\nu^* n_e} + \frac{\delta \ln T_e}{\delta \ln n_e} \left(\hat{\nu}_i \nu_i + \hat{\nu}^* k_i^* N^* \right)$$



J ~ cost => ne = a + b sin (kz) Longitudinal profile => propagates

Scariche elettriche nei gas
Glow discharge

Contraction



Positive Column => Current Filament

Glow Discharge => Arc (Voltaic)

Scariche elettriche nei gas
Glow discharge

Contraction due to Thermal Instability

$$\delta n_e \uparrow \rightarrow \delta(jE) \uparrow \rightarrow \delta T \uparrow \rightarrow \delta N \downarrow \rightarrow \delta(E/N) \uparrow \rightarrow \delta T_e \uparrow \rightarrow \delta n_e \uparrow \ .$$

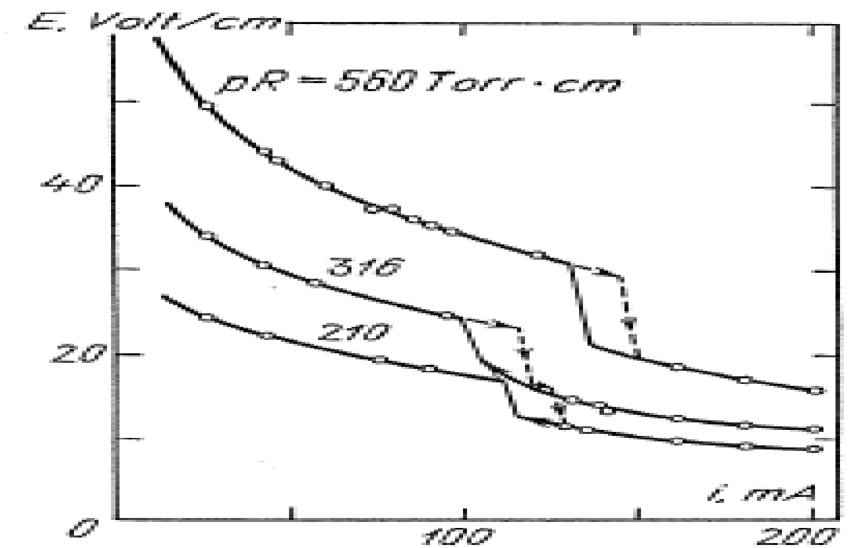
$$\Omega = \nu_T^0 \frac{\delta \ln n_e}{\delta \ln T} - \nu_{T,F} \ , \quad \nu_T^0 = \frac{\sigma E^2}{N c_{p1} T} = \frac{\gamma - 1}{\gamma} \frac{\sigma E^2}{p} \qquad jE > N c_{p1} T \nu_{T,F} / \hat{\nu}_1$$

Transverse: $Z_{-} \sim \frac{D}{R^2} ne + K_{rec} ne^2$ $\quad \mathrm{R}_{eff} \sim \sqrt{D / K_{rec} ne}$

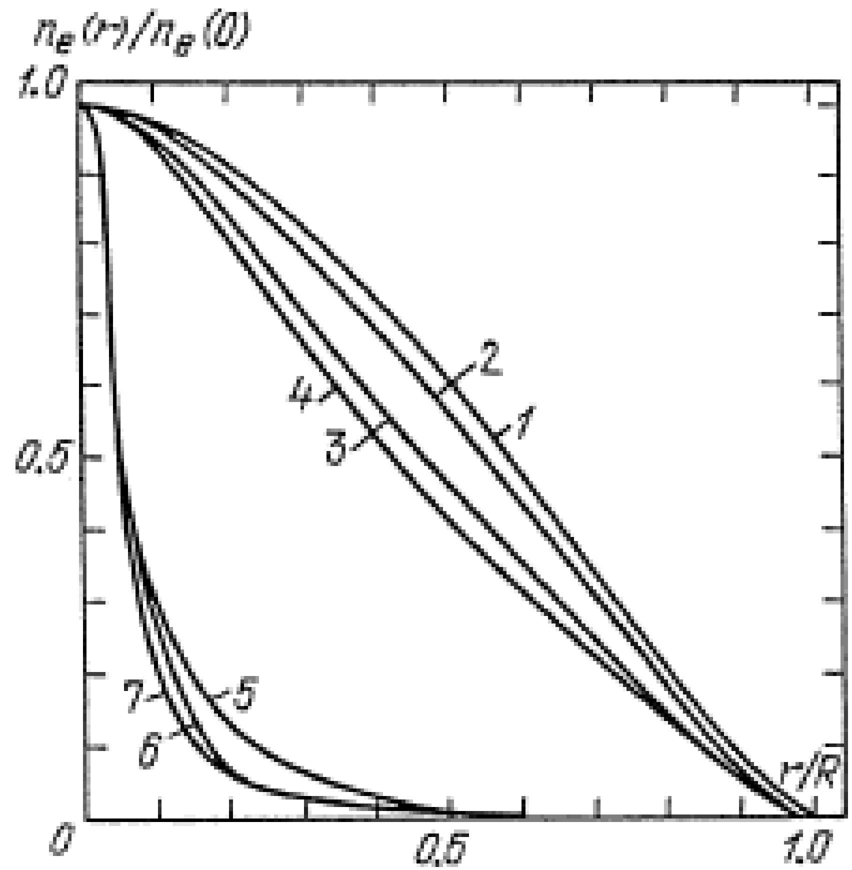
Longitudinal inefficient: I ≈ cost => ne(x) ≈ cost

Scariche elettriche nei gas
Glow discharge

Contraction due to Thermal Instability



i, mA	$T_e(0)$, eV	$T(0)$, K	$n_e(0)$, 10^{11} cm^{-3}
13.5	3.0	440	0.12
43	3.3	650	0.39
75	3.6	840	0.93
96	3.7	930	1.2
120	3.0	1200	54
160	2.6	1300	72
200	2.5	1400	93



Moto di una carica in un plasma magnetizzato

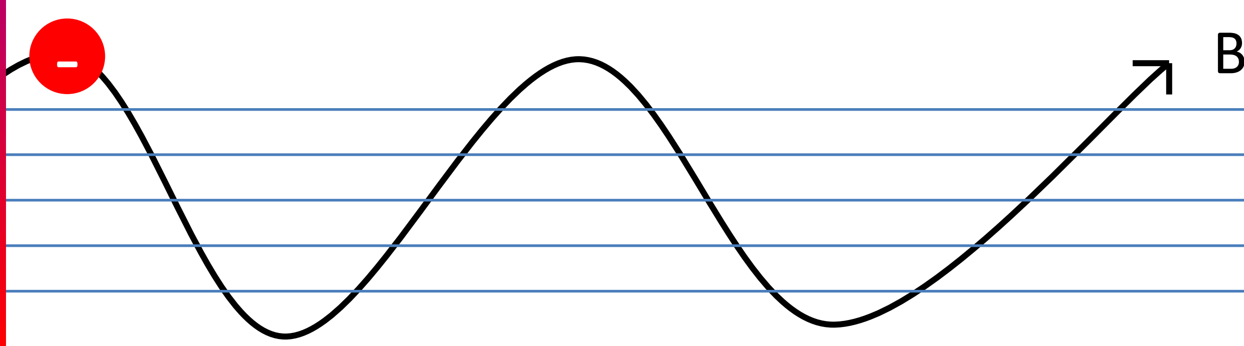
In un campo magnetico uniforme in una direzione:

$$
\begin{cases}
m\frac{dv_{\parallel}}{dt} = q(v_{\parallel} \wedge B_{\parallel}) = 0 \\
m\frac{dv_{1\perp}}{dt} = q v_{2\perp} B \\
m\frac{dv_{2\perp}}{dt} = -q v_{1\perp} B
\end{cases}
$$

Frequenza di ciclotrone (o di girazione):

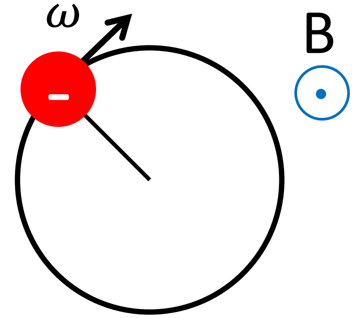
$$\omega_c = \frac{qB}{m}$$

$$
\begin{aligned}
v_{\parallel} &= const \\
v_{1\perp} &= v_{\perp}\cos(\omega_c t) \\
v_{2\perp} &= v_{\perp} sin(\omega_c t)
\end{aligned}
$$



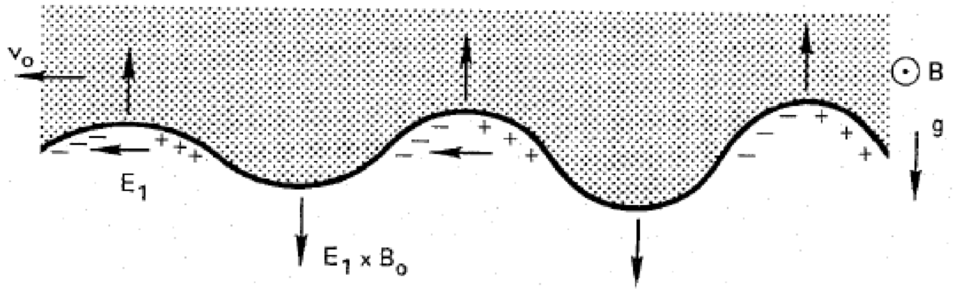
Raggio di larmor

$$r_L = \frac{|v_{\perp}|}{\omega}$$

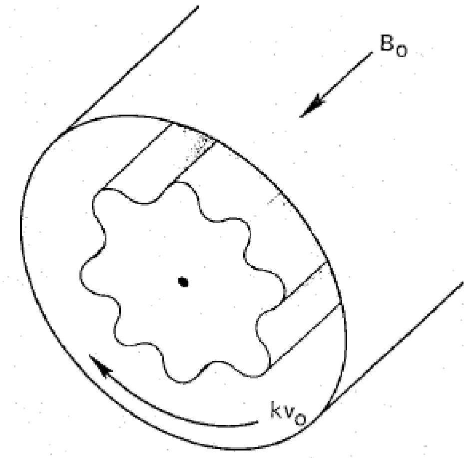


Instabilità di un plasma magnetizzato

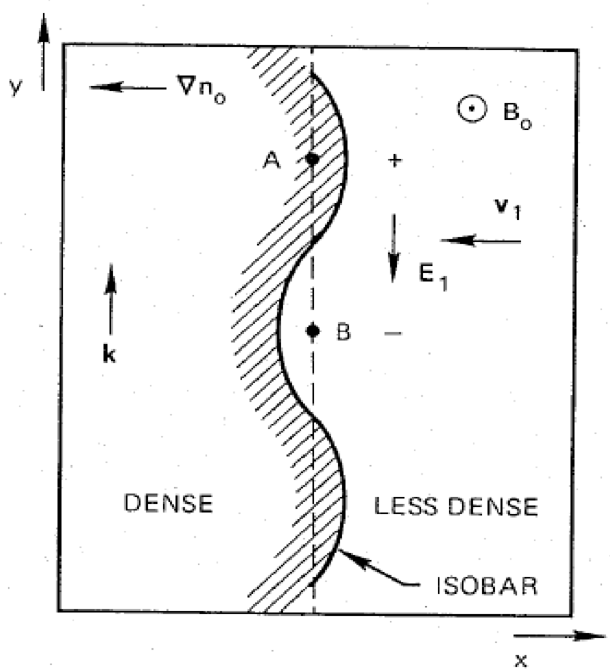
Rayleigh-Taylor (gravitational)



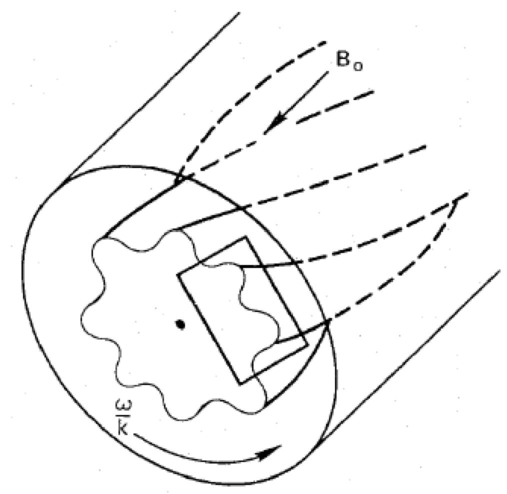
Flute structure



Drift wave instability

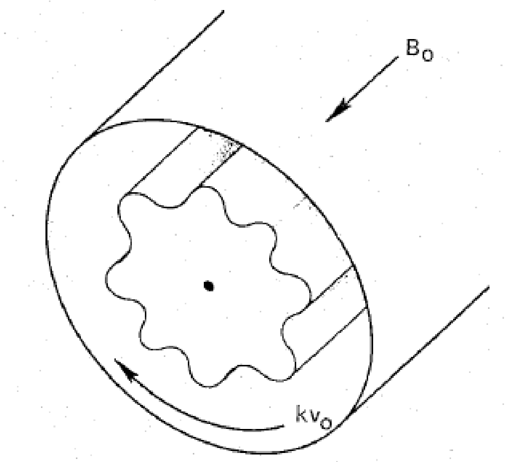


Drift structure



Instabilità di un plasma magnetizzato

Flute structure

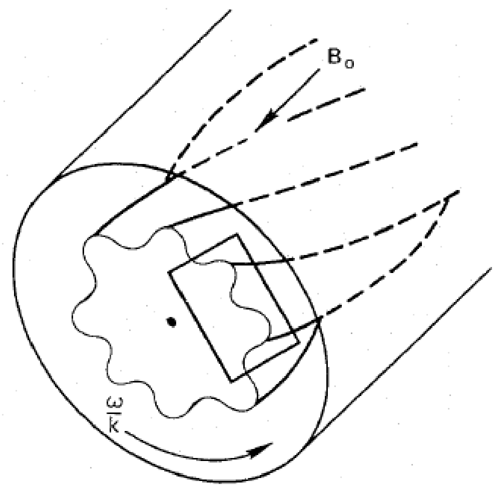


K// = 0

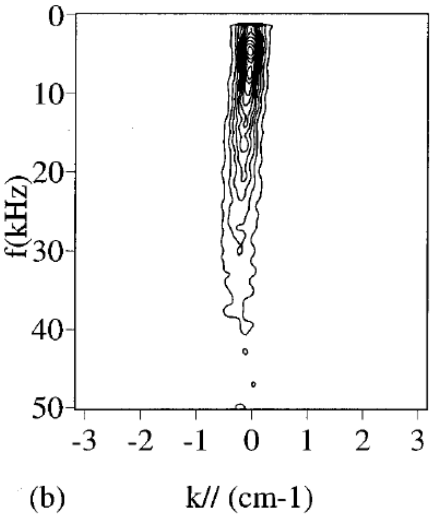
$$\frac{\tilde{n}}{\langle n \rangle} \ll \frac{e\tilde{\Phi}}{\langle kT_e \rangle},$$

$$\Phi(\overline{n},\overline{E}) \approx 0$$

Drift structure



K// ≠ 0



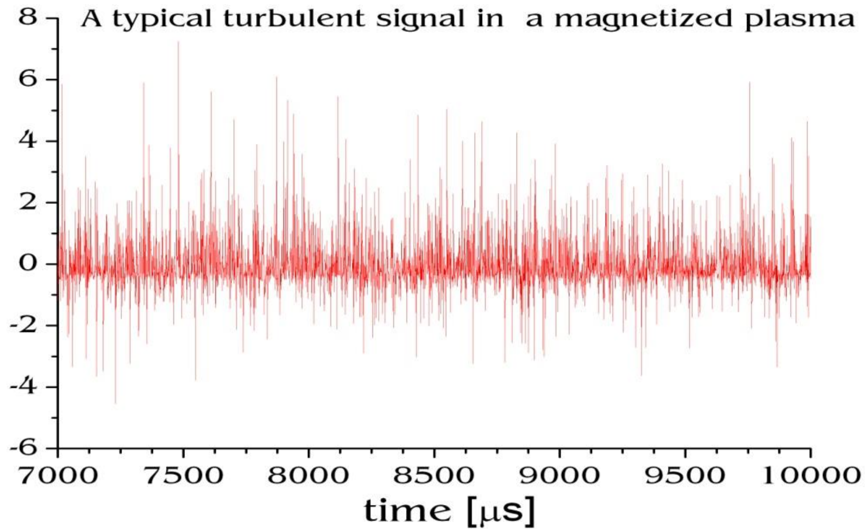
$$\frac{\tilde{n}}{\langle n \rangle} \approx \frac{e\tilde{\Phi}}{\langle kT_e \rangle},$$

$$\Phi(\overline{n},\overline{E}) \approx \pi / 2$$

Turbolenza

Hydrodynamics:
- Non-linear differential equations
- Scale difference between energy dissipation and energy input.

=> MHD turbulence



Fluctuations: $$X = \langle X \rangle + \overline{X}$$

Deterministic: $X_n : \sigma_X \longrightarrow 0, \; n \longrightarrow \infty$

Turbulence: $\sigma \rightarrow \alpha \neq 0$

Turbolenza

Approccio analitico alle fluttuazioni

FFT, power spectrum, Beall analysis

$$S(k,\omega) = \frac{1}{M} \sum_{i=1}^{M} I_{0,\Delta k}[k - k^i(\omega)] S^i(\omega),$$

$$k^i(\omega) = \frac{1}{\Delta x} \arg[\Phi_2^i(\omega) \Phi_1^{i*}(\omega)],$$

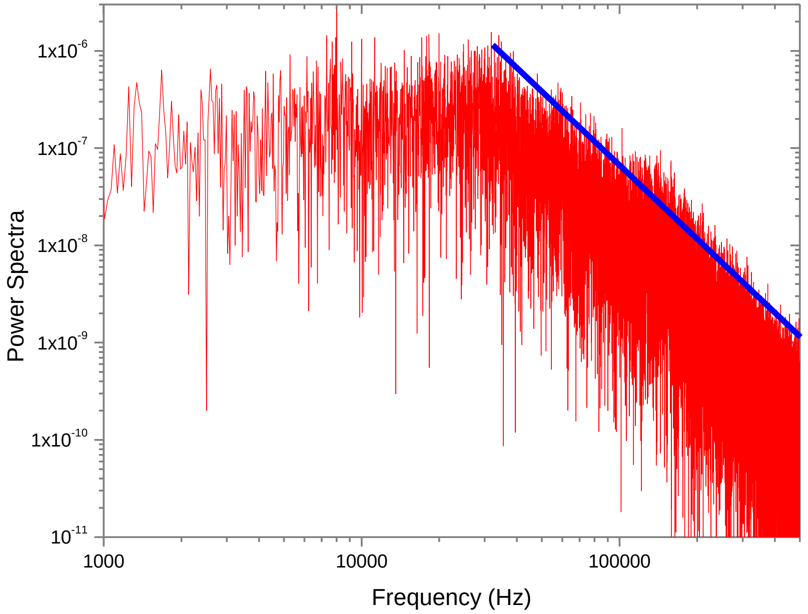
$$S^i(\omega) = \frac{1}{2} [|\Phi_1^i(\omega)|^2 + |\Phi_2^i(\omega)|^2],$$

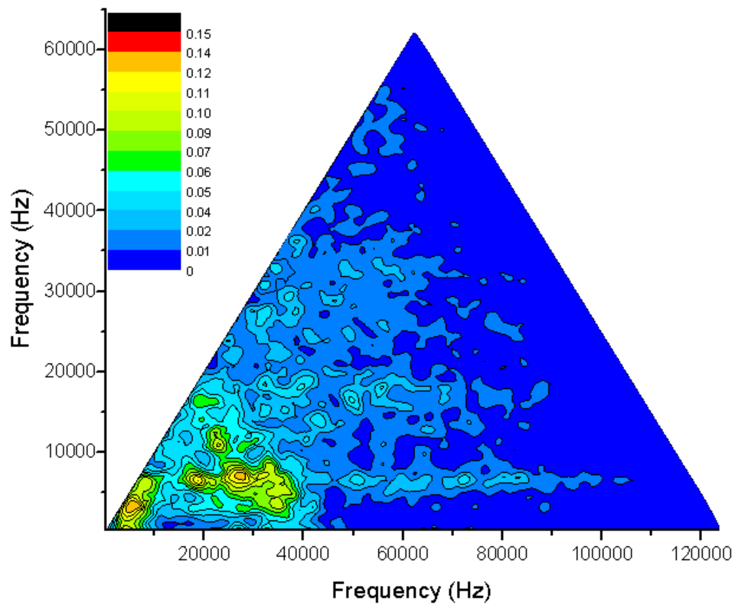
Wave-wave interactions, bicoherence

$$B = b^2(\omega_1,\omega_2,\omega_1+\omega_2) = | \langle f(\omega_1)f(\omega_2)f(\omega_1+\omega_2)^* \rangle |^2 / \langle |f(\omega_1)f(\omega_2)|^2 \rangle | \langle |f(\omega_1+\omega_2)|^2 \rangle$$

Cascade and inverse cascade

$$\partial P_k / \partial t \approx \gamma_k P_k + \sum_{\substack{k_1,k_2 \\ k=k_1+k_2}} T_k(k_1,k_2),$$





Turbolenza

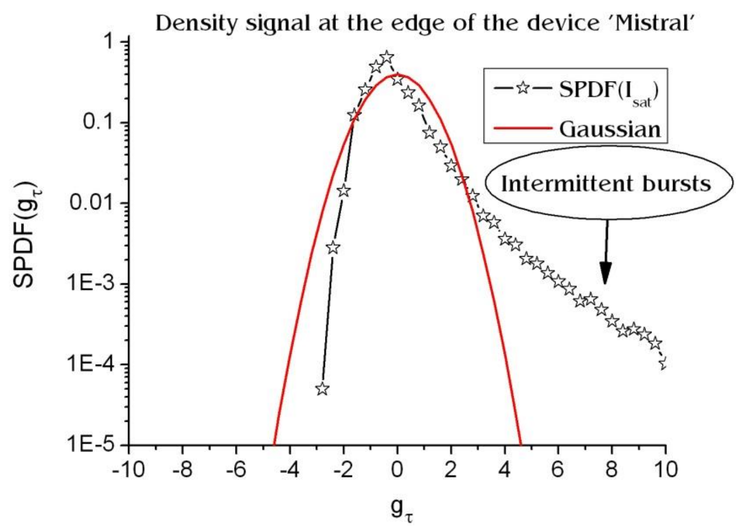
Approccio statistico alle fluttuazioni

$$\{ f(t_n) \}, t_n = nT \quad => \quad \{ f_n \}$$

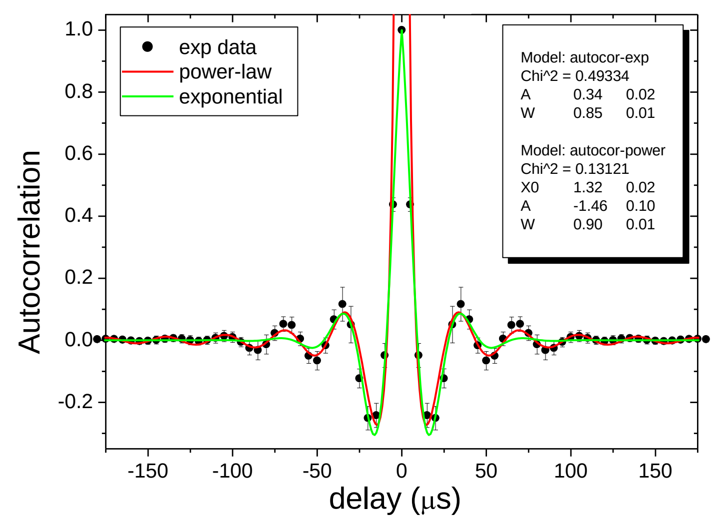
$$frequency => PDF(f)$$

$$m_k = \int f^k PDF(f) df$$

PDF, Non Gaussianity



Time correlations, Memory,
Structure Functions (intermittenza)



$$a(T) = \int f(t) f(t+T) dt$$

$$PDF\left[\left| f(t) - f(t+T) \right|^k \right]$$

$$PDF(T_{wait}), T_{wait} :$$

f(t)>a, f(t+T)>a, f(t+T-1)<a

Turbolenza

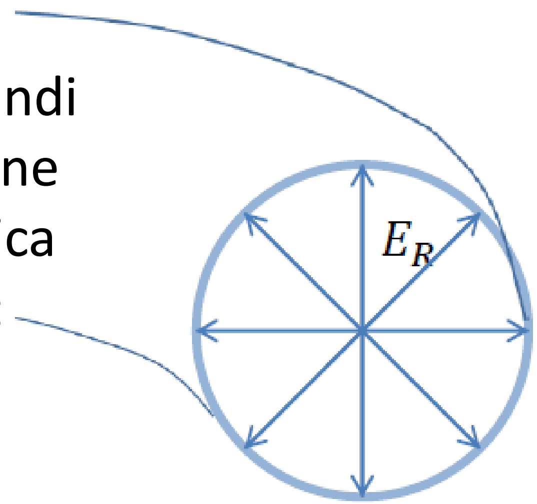
Strutture spazio-temporali (coerenti) delle fluttuazioni

Trasporto convettivo delle fluttuazioni

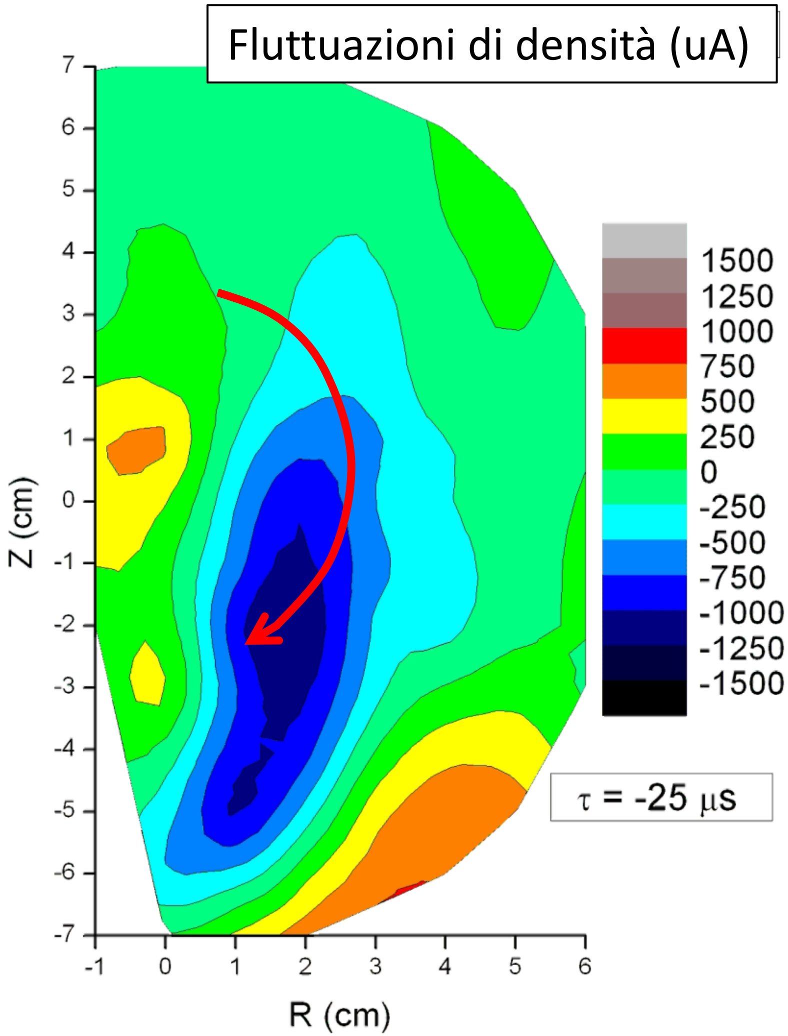
Un campo elettrico E in un plasma magnetizzato a confinamento toroidale

Gli elettroni primari vengono emessi da un filamento al centro della camera e accelerati verso le pareti da un campo elettrico radiale.

Esisterà quindi una rotazione macroscopica del plasma:



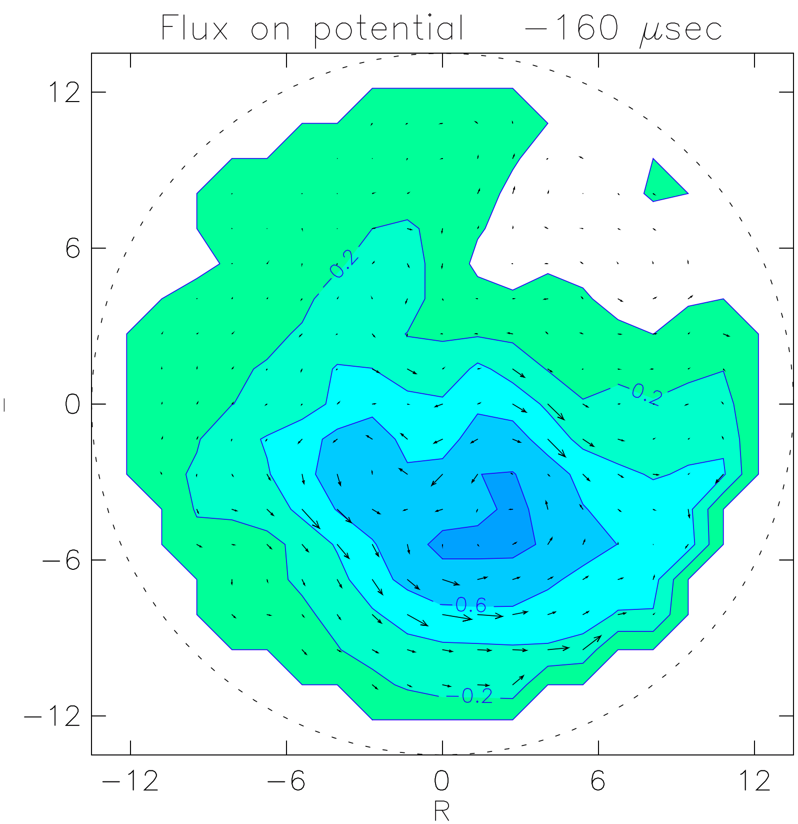
$$v_\theta = \frac{E_R \times B_\varphi}{B^2}$$

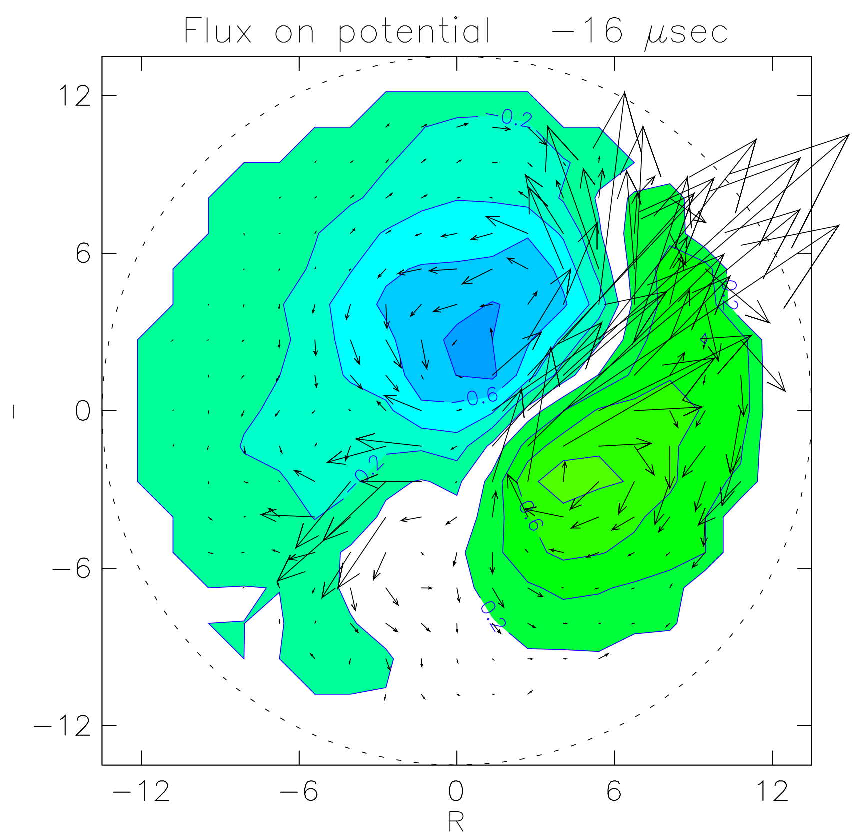


Turbolenza

Vortex structures

Un campo elettrico E fluttuante in un plasma magnetizzato a confinamento toroidale, produce un campo di velocità le cui linee di flusso coincidono con le linee equipotenziali del campo elettrico

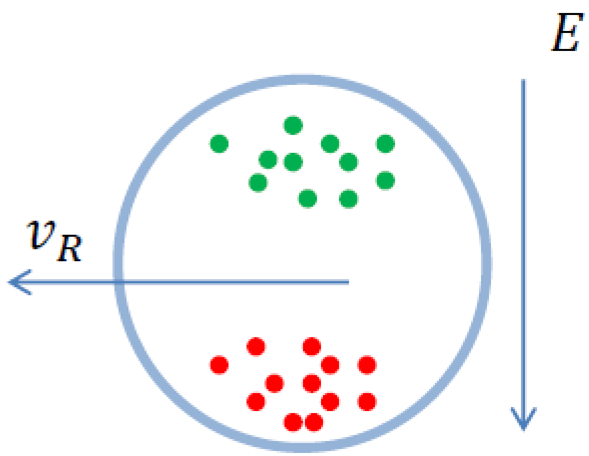




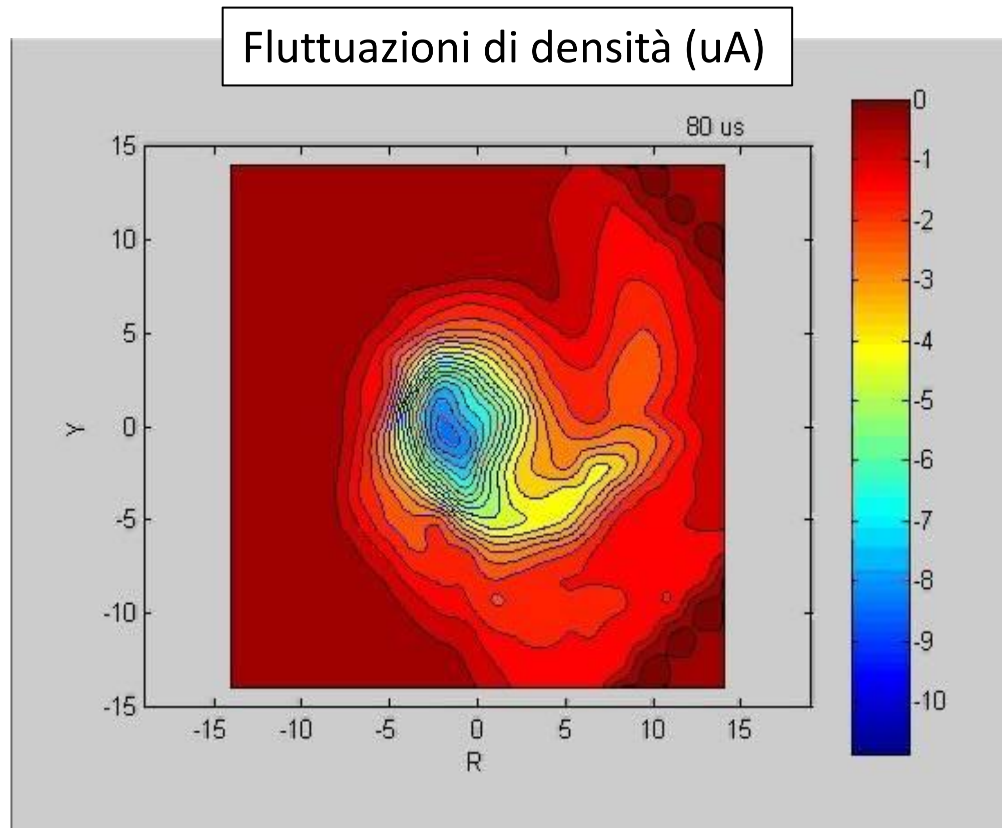
Turbolenza

Trasporto anomalo

Una separazione di carica in un plasma magnetizzato a confinamento toroidale produce una deriva globale ExB verso l'esterno
(magnetic [grad(B)], centrifugal, diamagnetic [grad(P)], neutral drag)

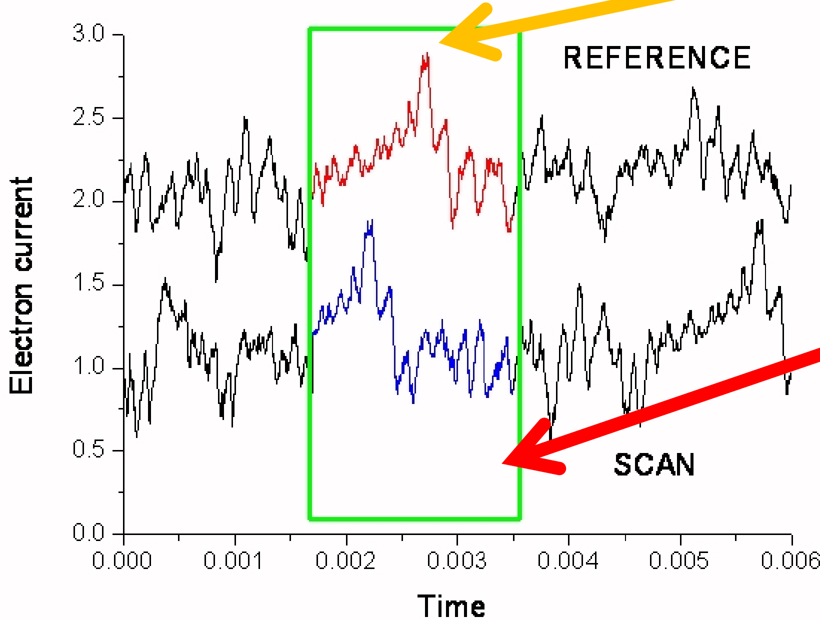


Exp Mistral - Marseille



Conditional sampling (analisi condizionale)

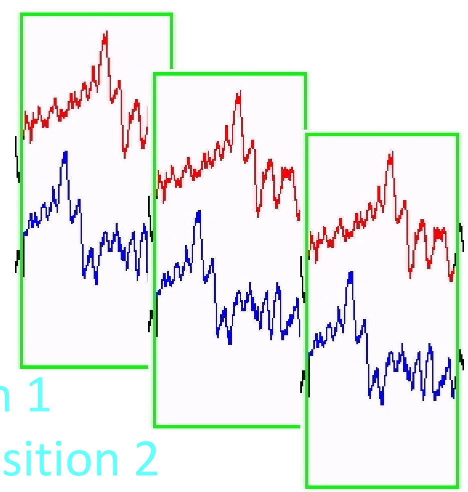
Reconstruction of the spatial and temporal correlations



Identification
of a trigger event
in the reference fixed series

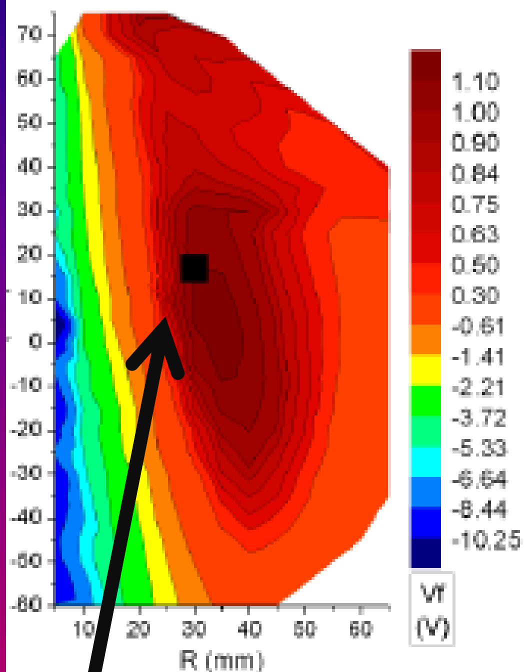
Extraction of
time windows
for each scan position

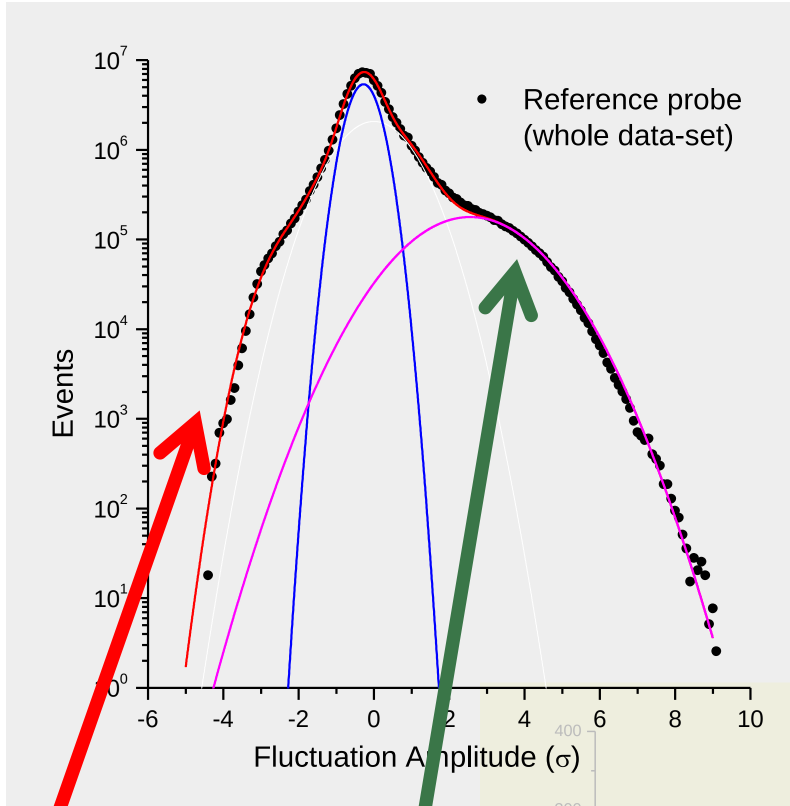
Acquisition of two
simultaneous time series:
one at a fixed location (reference)
the other scanning the whole 2D section



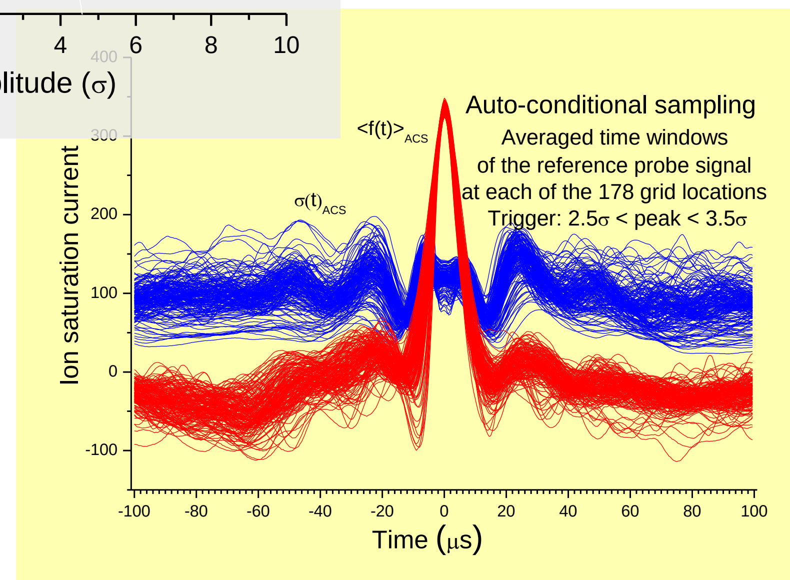
position 1
position 2
position 3

Conditional sampling: trigger events





Reference
time windows:
- Selection of events
- Cancellation of non-coherent fluctuations
- Time Stability



Reference probe

Density blobs

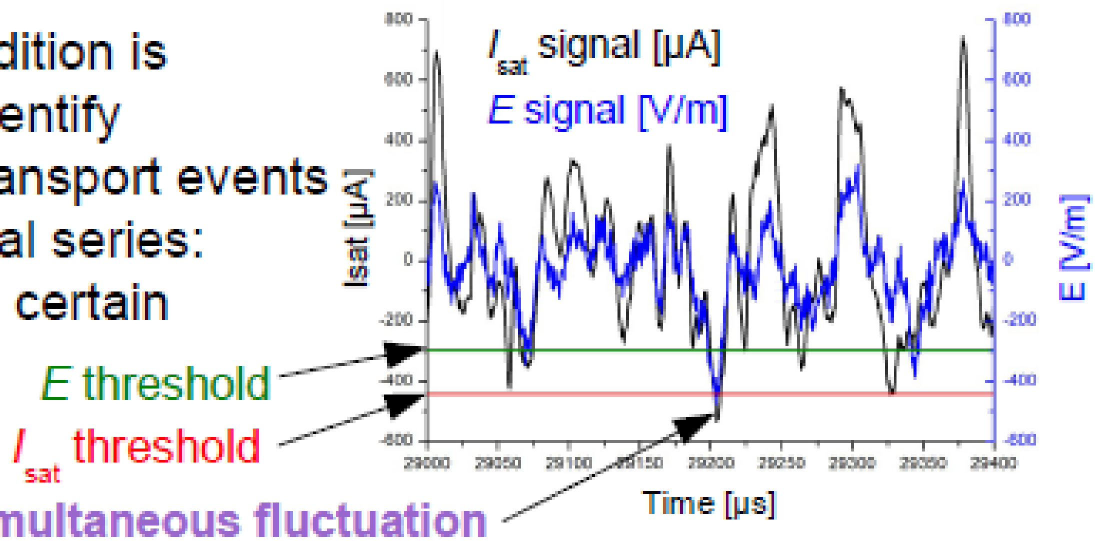
Negative density events: Voids

Esempio: eventi di flusso anomalo

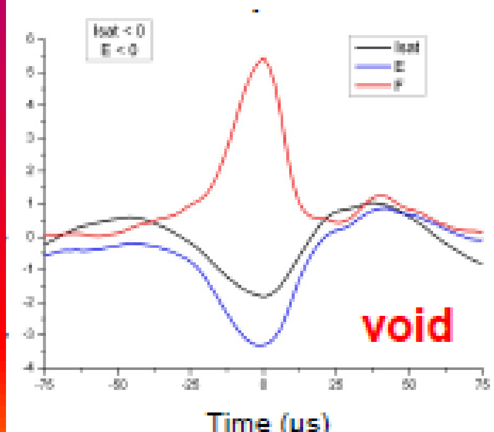
Use a three-pin reference probe: I/V/V => (Isat, Epol)

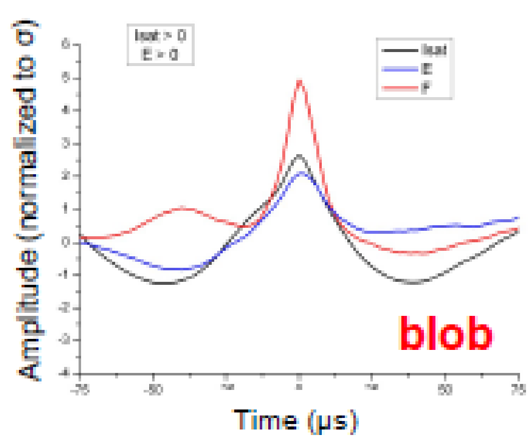
A certain condition is imposed to identify anomalous transport events within temporal series:

- excess of a certain threshold



It correspond to a negative density fluctuation (void) associated with a radial inward ExB velocity





Two kind of anomalous transport events