Edge plasma diagnostics in tokamaks

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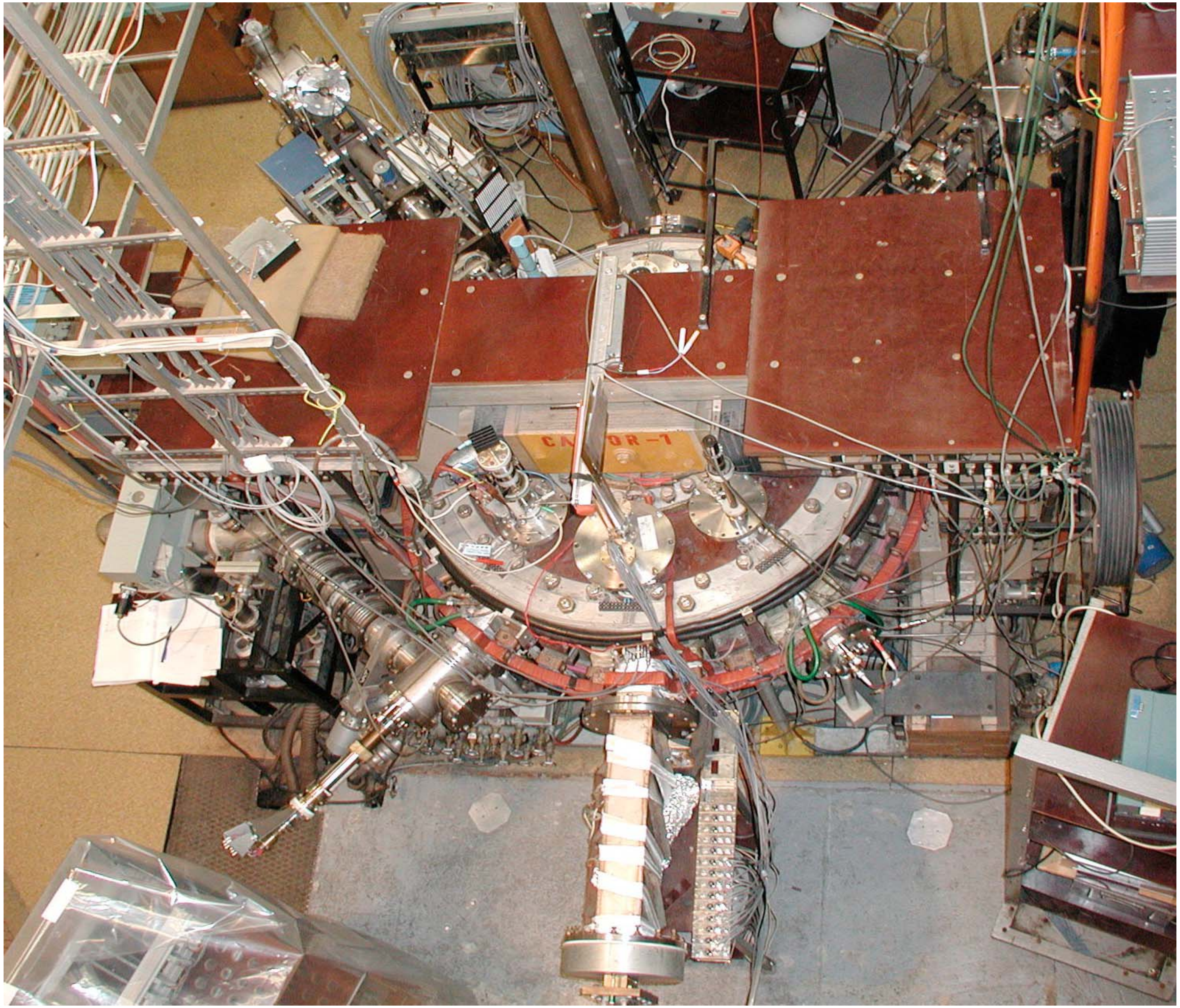
Outline

- Decisive role of the edge plasma in global plasma confinement in tokamaks

- Fluctuation and flow measurements by electric probes

- International cooperation & Education of students



Built in Kurchatov Inst. Moscow
1958
Operational in IPP Prague since
1977
Reconstructed (new vessel)
1985
Associated to EURATOM
1999

CASTOR -Czech Academy of Sciences TORus

COMPARISON OF LARGE AND SMALL SCALE TOKAMAK

	CASTOR	JET
Major radius	0.4 m	3.5 m
Minor radius	0.1 m	1.0 m
Toroidal magnetic field	~1 T	3.5 T
Plasma current	0.01 MA	5.0 MA
Pulse length	0.05 s	30 s
Electron temperature	0.20 keV	~10 keV
Ion temperature	0.05 keV	~10 keV
Plasma density	$\sim 1 \cdot 10^{19}$ m^{-3}	$\sim 1 \cdot 10^{20}$ m^{-3}
Energy confinement time	< 0.001 s	~ 1 s
Budget per year	0.5 MEuro	50 MEuro
Manpower	~15 My	~300 My
Edge plasma density	$\sim 2 \cdot 10^{18}$ m^{-3}	$\sim 4 \cdot 10^{18}$ m^{-3}
Edge plasma temperature	10-40 eV	10-40 eV

Characteristic Features of the CASTOR tokamak

- **Flexible experiment** (vacuum vessel opening & re-staring in one day)
- **Good access to plasma** (ports available at top, bottom & midplane)
- **Shots are reproducible** (~ 100 shots a day)
- **External tools to manipulate plasma** (LHCD, edge polarization)
- **Good edge plasma diagnostics** (+ fast multichannel data acquisition)
- **Experienced staff + educated students**

Principal question

Can small and rather old machine compete with fusion-relevant and big experiments like JET, ASDEX Upgrade, TORE Supra with multi-million budget?

Answer: YES, BUT

Necessary conditions

- **Fusion - relevant program in physics (new ideas)**
- **Good background (appropriate funding & technical support, good data acquisition, sophisticated software,…..)**
- **Strong international collaboration**
- **Motivated students**

Global Confinement in tokamaks

Basic balance equations

$$\boxed{\frac{\mathrm{dW}}{\mathrm{dt}} = \mathrm{P} - \frac{\mathrm{W}}{\tau_{\mathrm{E}}}}$$

← For energy   For particles →

$$\boxed{\frac{dN}{dt} = \Gamma - \frac{N}{\tau_p}}$$

$W=3/2\ nTV$ - Total kinetic energy of plasma

P - Heating power

$N=2\pi^2Ra^2n$ - Total number of particles in the torus

Γ - Particle source (influx of neutrals)

T, n, V - Temperature, Density, Volume

$\tau_E \sim a^2/\chi$ - Energy Confinement Time   **$\tau_p \sim a^2/D$ - Particle Confinement Time**

However!!!!

- **Diffusion D and heat conductivity χ coefficients are 100-1000 x larger the expected at the beginning of tokamak research**
- **Particles and heat are transported across magnetic field lines not by collisions, but due to the plasma turbulence!**

Plasma turbulence is an inherent feature of any tokamak!!!

Plasma turbulence in tokamaks

- Its role was recognized ~ 30 years ago
- However, the nature of the plasma turbulence is still not fully understood!!

Study of turbulence at the plasma edge is relevant to small experiments, because the edge plasma in big and small machines appears to be very similar!!!

What does it mean the edge turbulence

result of fluid modelling at the plasma edge

Poloidal cross-section of the CASTOR tokamak

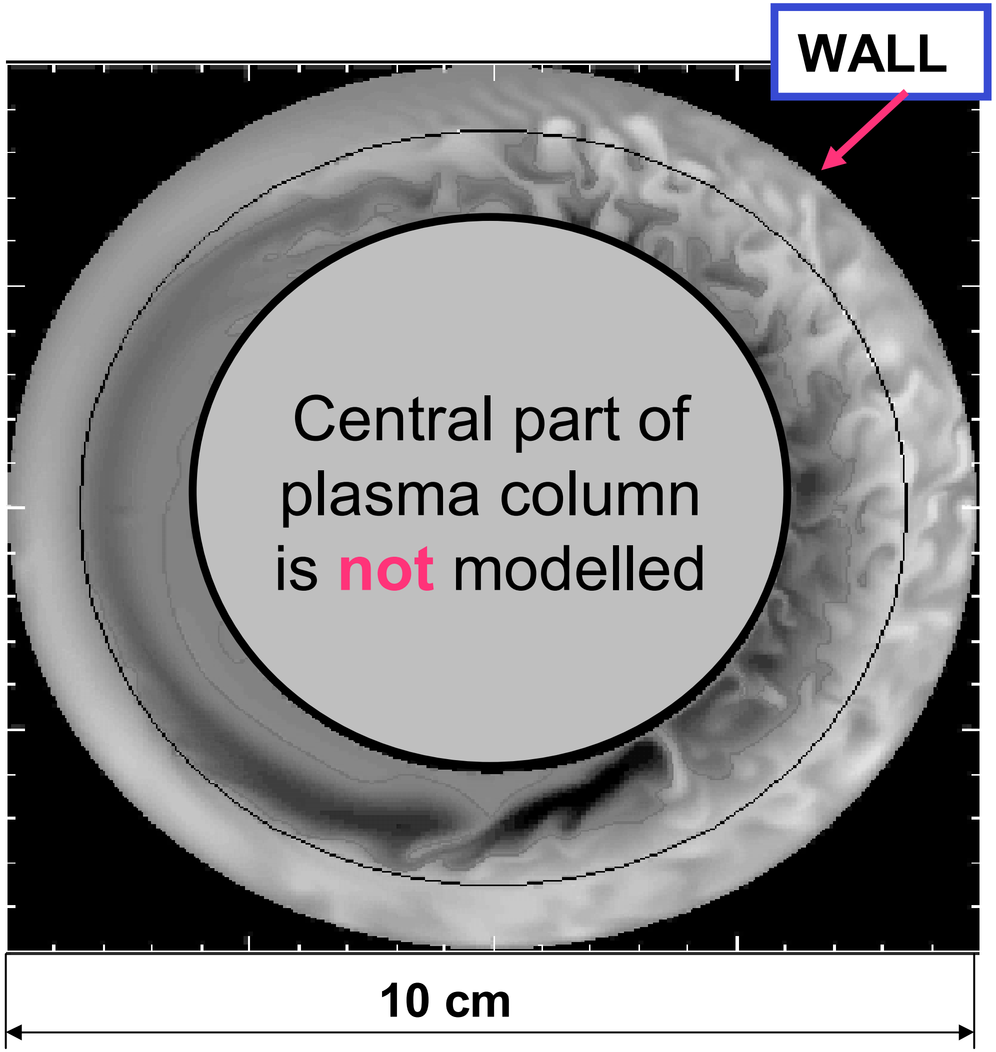
r=10 cm

BRIGHT COLORS

Density is higher than the average value

DARK COLORS

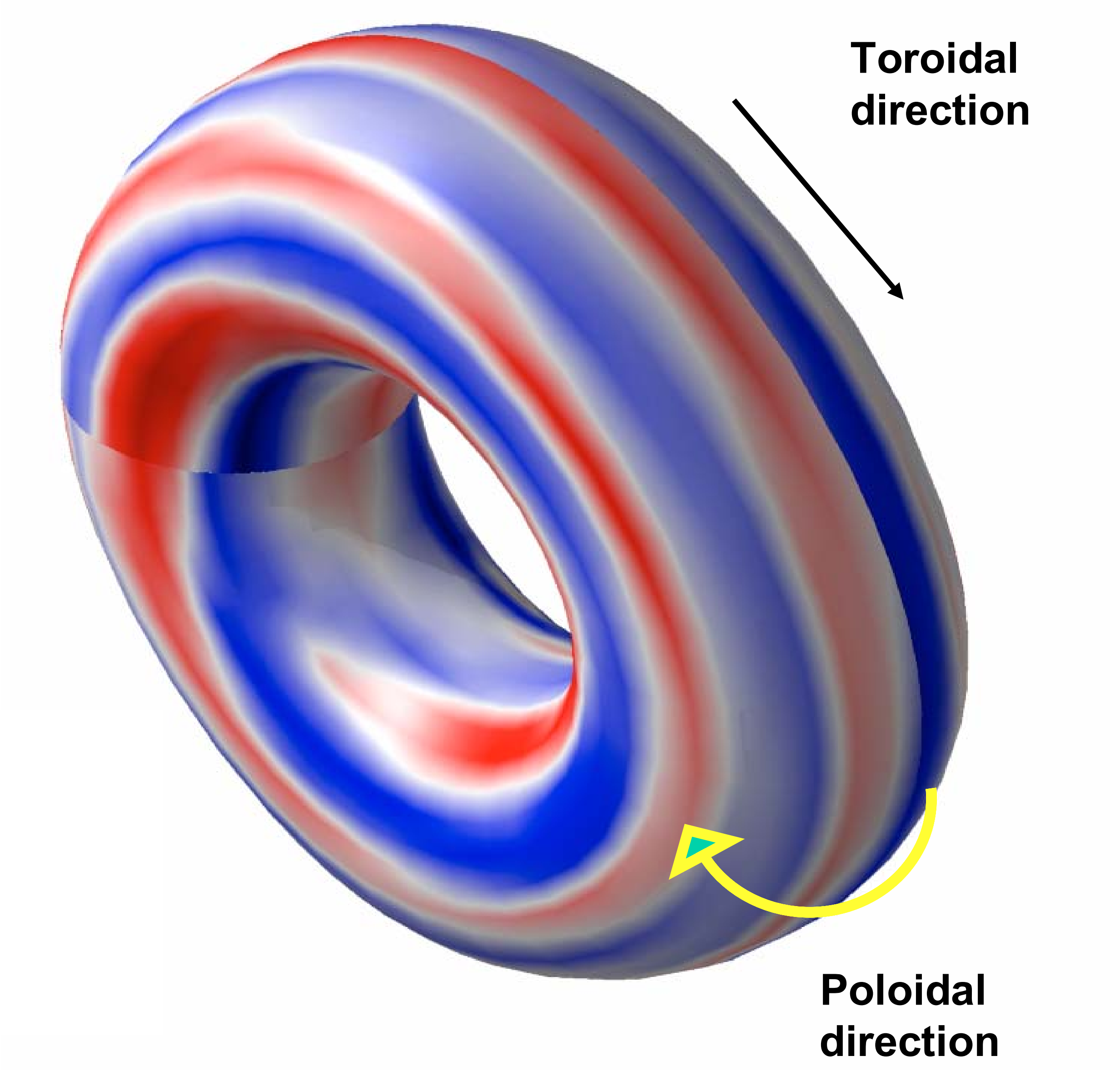
Density is lower than the average value



Central part of plasma column is **not** modelled

Electrostatic Turbulence

at the edge of plasma column



3D character

Flute-like structure(s)
(density or potential)

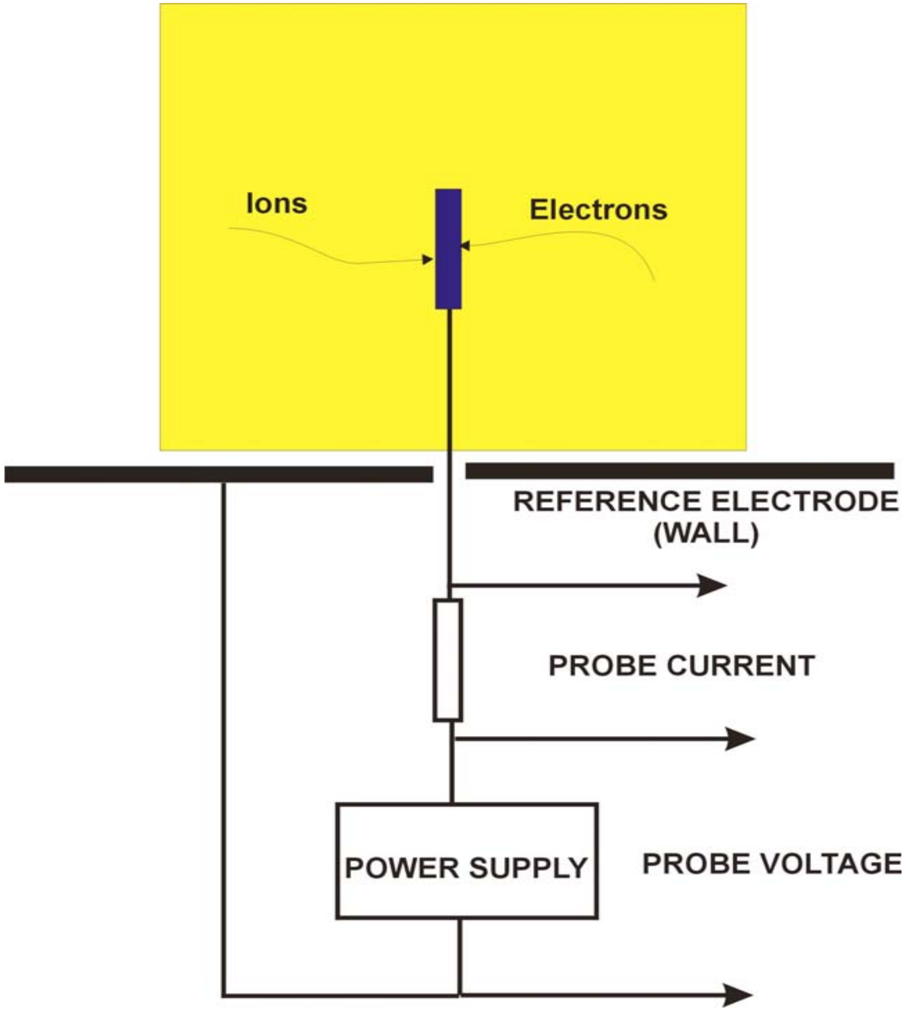
- Form along the magnetic field lines
- Propagate in poloidal direction

It is evident that understanding of physics of the plasma turbulence requires a diagnostic with a good spatial and temporal resolution

The only solution for small scale experiments (in practise) is using of

Langmuir probes

Single Langmuir probe



$$I_{probe} = I_{ion} + I_{electron}$$

Probe voltage >> Plasma potential
Only electron are collected

$$I_{probe} = I_{electron}^{sat}$$

(electron saturation)

Probe voltage << Plasma potential
Only ions are collected

$$I_{probe} = I_{ion}^{sat}$$

(ion saturation ~ density)

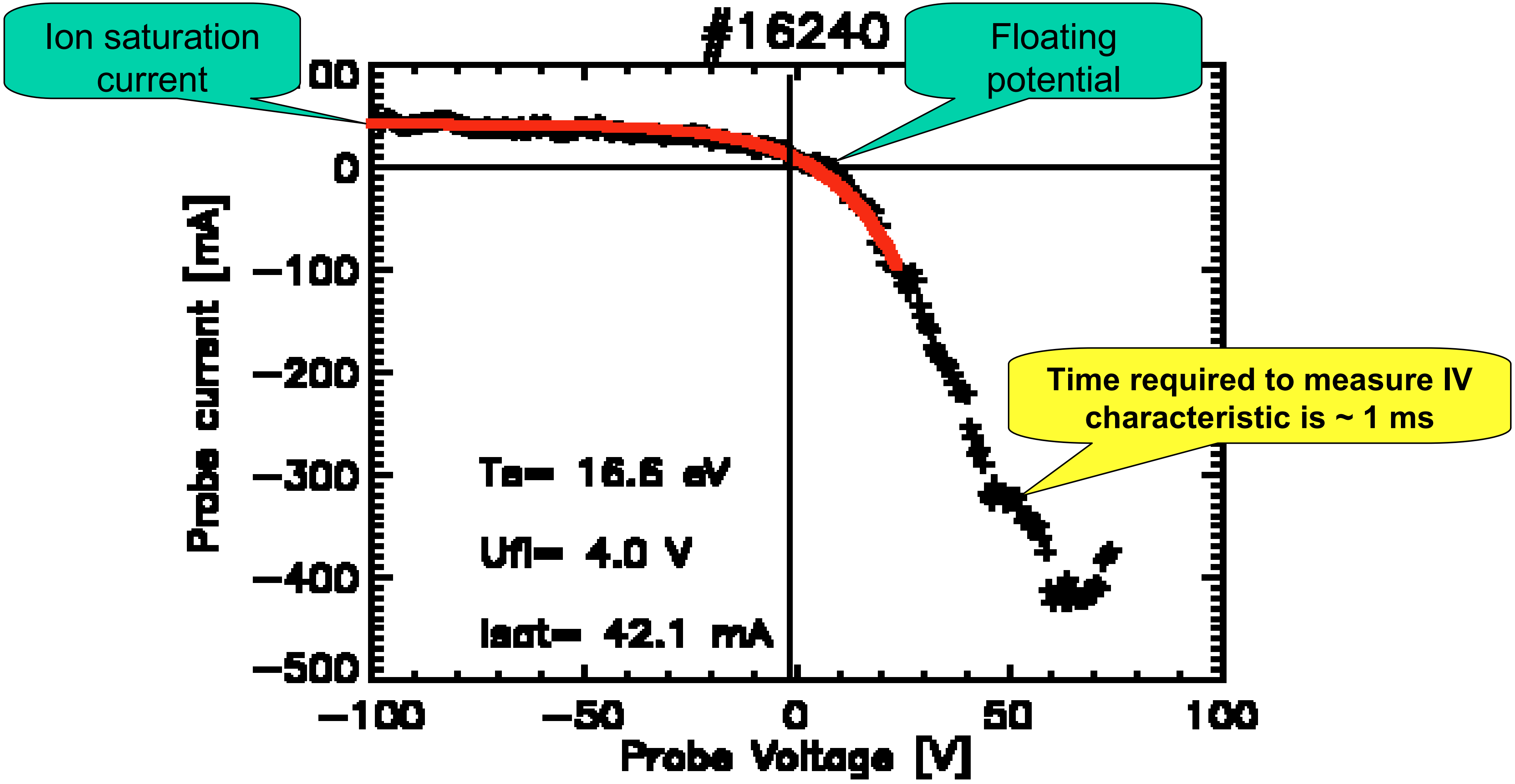
Probe current = 0,

$$I_{ion} = I_{electron}$$

(probe is biased to floating potential)

I-V Characteristic of the single Langmuir probe

$$I_{probe} = I_{ion}^{sat} \{1 - \exp[- e(V_{float} - V_{probe})/kT_e]\}$$



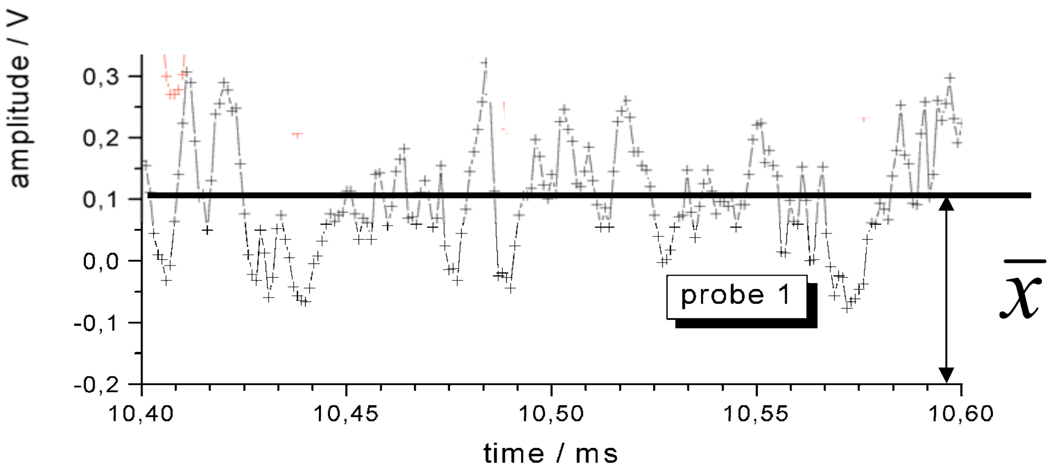
Ion saturation current

Floating potential

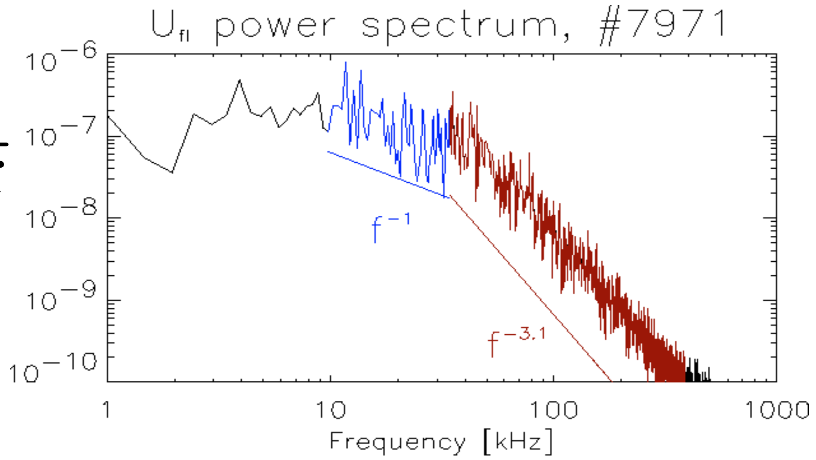
Time required to measure IV characteristic is ~ 1 ms

Single **Langmuir probe** for fluctuation measurement

- **Mean value of the signal** $\langle x(t)\rangle = \bar{x} + \langle \delta x\rangle = \bar{x}$
- **Absolute level of fluctuations** $\tilde{x} = \sqrt{\langle \delta x \delta x\rangle}$
- **Relative level of fluctuations** $\tilde{x} / \bar{x}$
- **Frequency spectrum or Auto-correlation function** $C_{auto}(\tau) = 1/T \int_0^T \delta x(t)\delta x(t+\tau)dt$

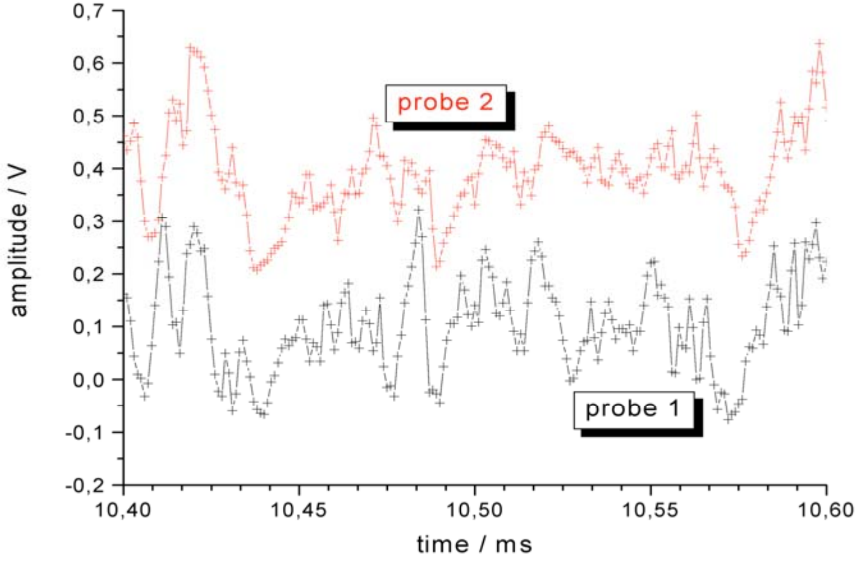


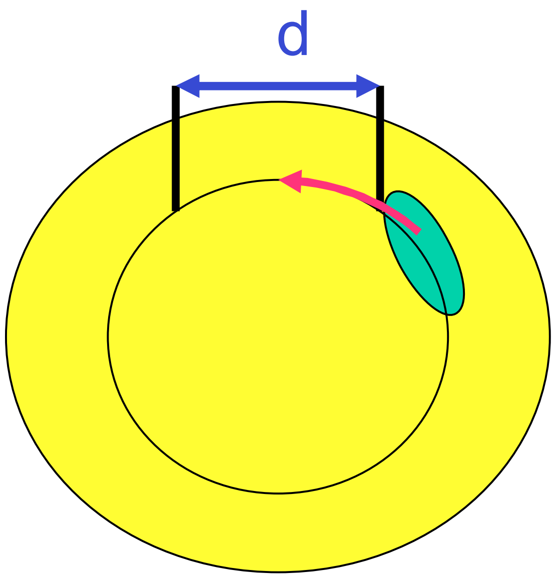
Typical power spectrum

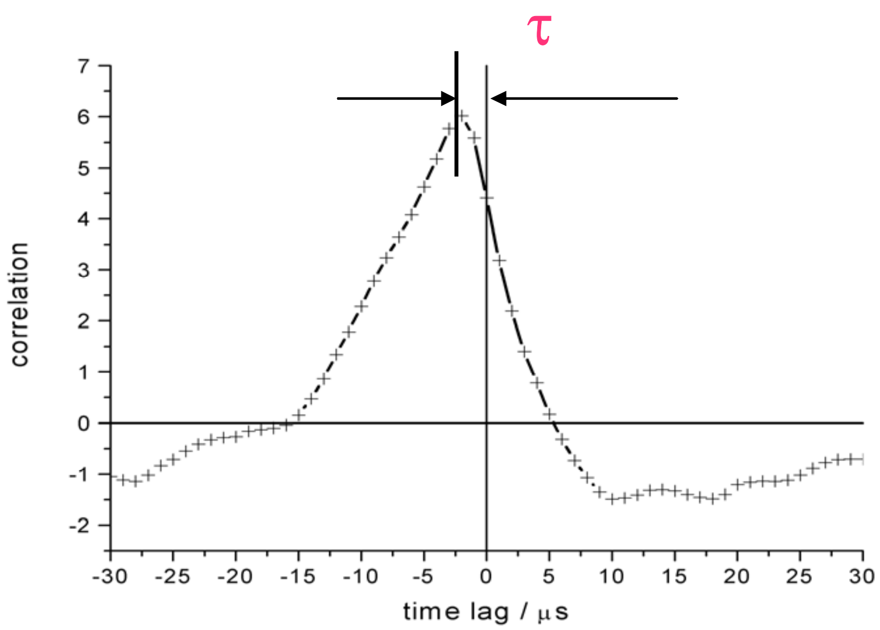


$$x(t) = \bar{x} + \delta x(t)$$

Double Langmuir probe for fluctuation measurement







- **Cross-correlation function**

propagation velocity v = d/ τ

Floating potential V_{float} versus Plasma potential φ

$$\boxed{V_{float} = \varphi - T_e \ln\left(I_{electron}^{sat} / I_{ion}^{sat}\right) \sim \varphi - 2.5T_e}$$

Electron temperature and its fluctuations must be known for correct interpretation of floating potential data

Possible solution: Emissive probe

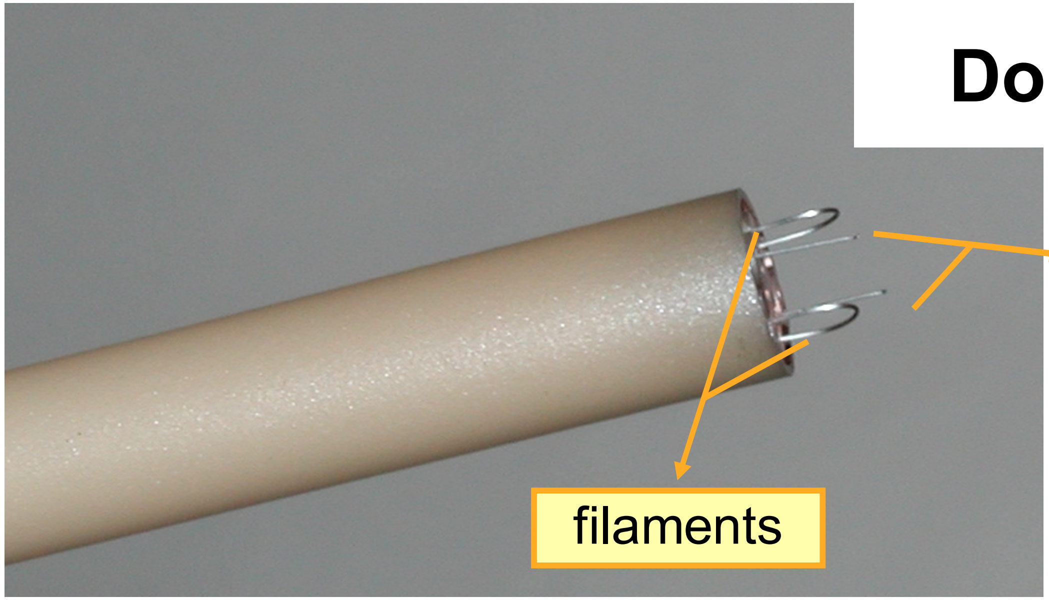
A heated probe emits electron current I_{em}, which is as high as the electron saturation current so that the argument of the logarithm = 1

$$\frac{I_{electron}^{sat}}{I_{ion}^{sat} + I_{em}} = 1 \qquad \Rightarrow V_{float} = \varphi$$

Emissive Probes for Space Potential Measurements

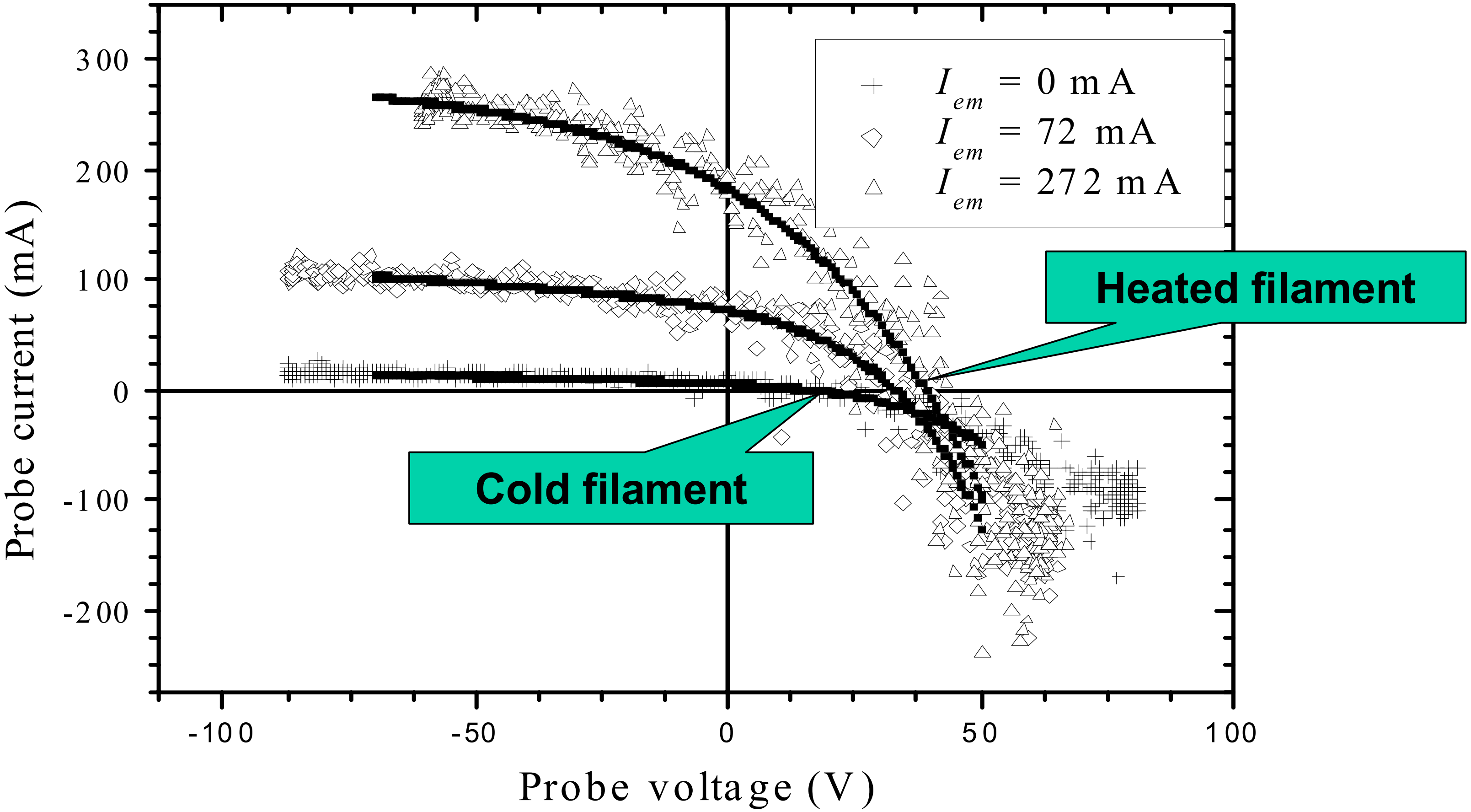
- Loop of Tungsten Wire (0.2 mm)
- Directly heated up > 2800 K
- Spatial resolution 3 mm

Double Emissive Probe

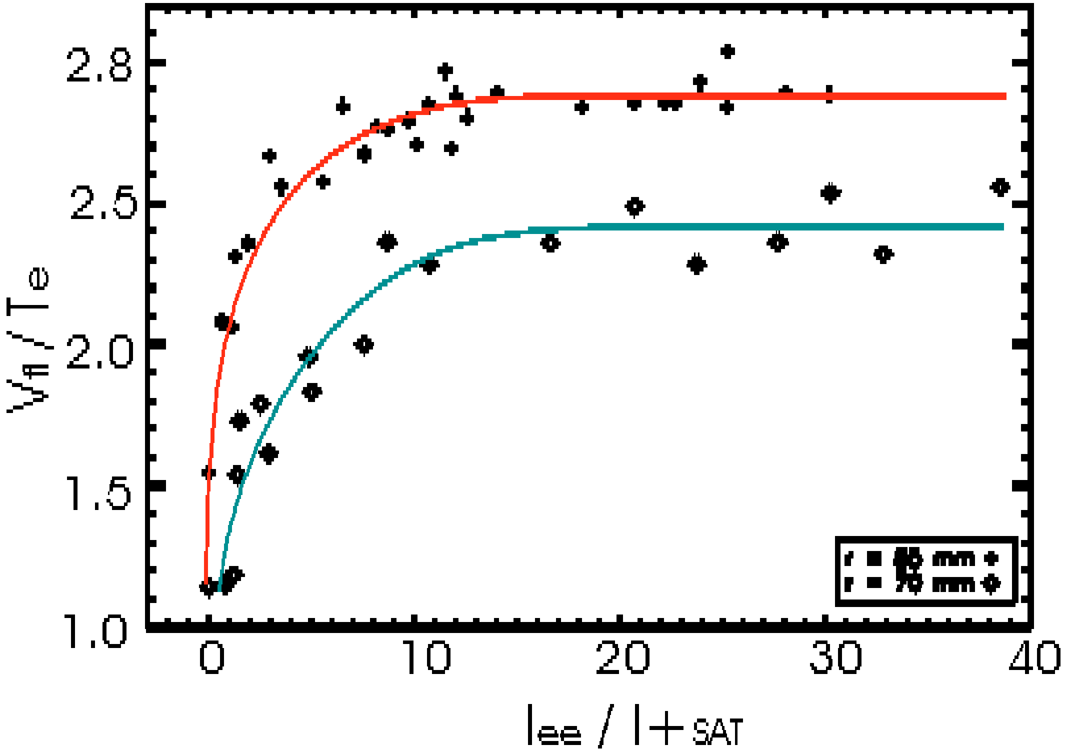


With Innsbruck Uni

Floating potential of the emissive probe



Potential of floating probe versus electron emission current



$$\frac{V_{fl}}{T_e} = f\left(\frac{I_{ee}}{I_{+SAT}}\right)$$

For two radial positions of the probe
In the SOL r=85 mm
In the edge r=70 m

Let us forgot fluctuations of the electron temperature For a moment (see latter).

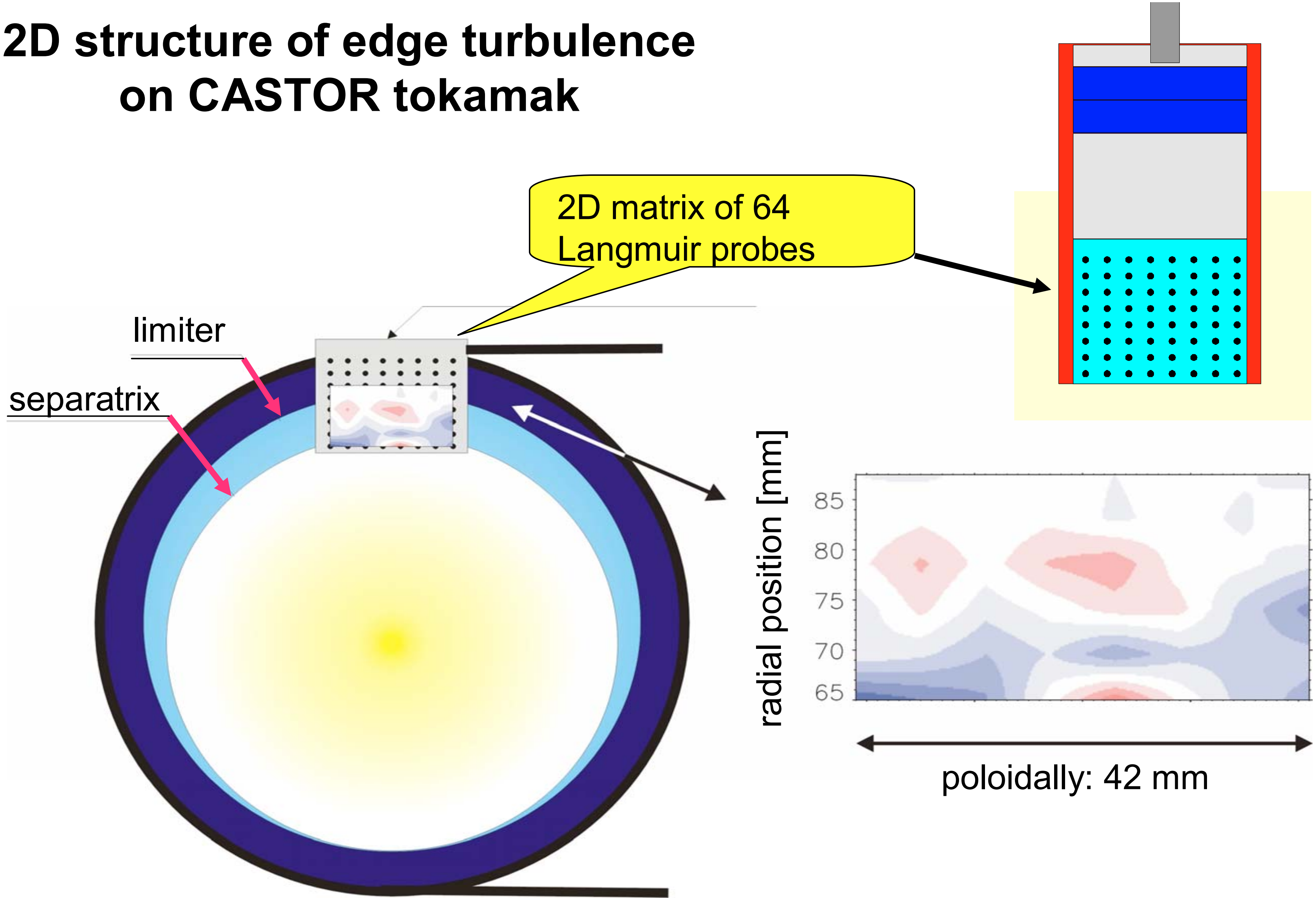
Let us focus on analysis of plasma fluctuations using the spatially resolved data.

For that purpose:

Arrays of the Langmuir probes must be used!

As a first example: 2D matrix of Langmuir probes

2D structure of edge turbulence on CASTOR tokamak

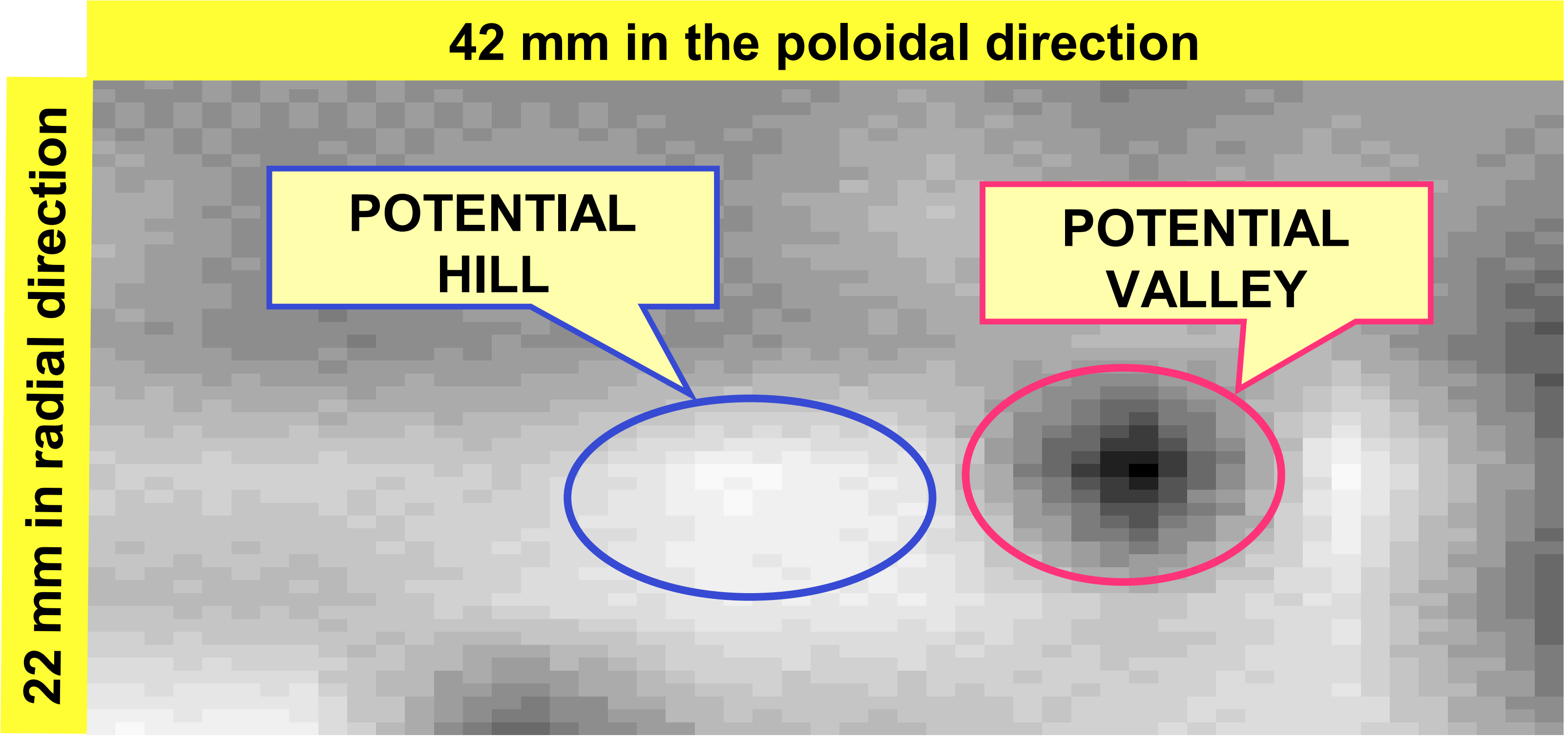


2D matrix of 64 Langmuir probes

Snapshot of potential structures

2D Structure of Edge Turbulence

as measured by a matrix of Langmuir probes

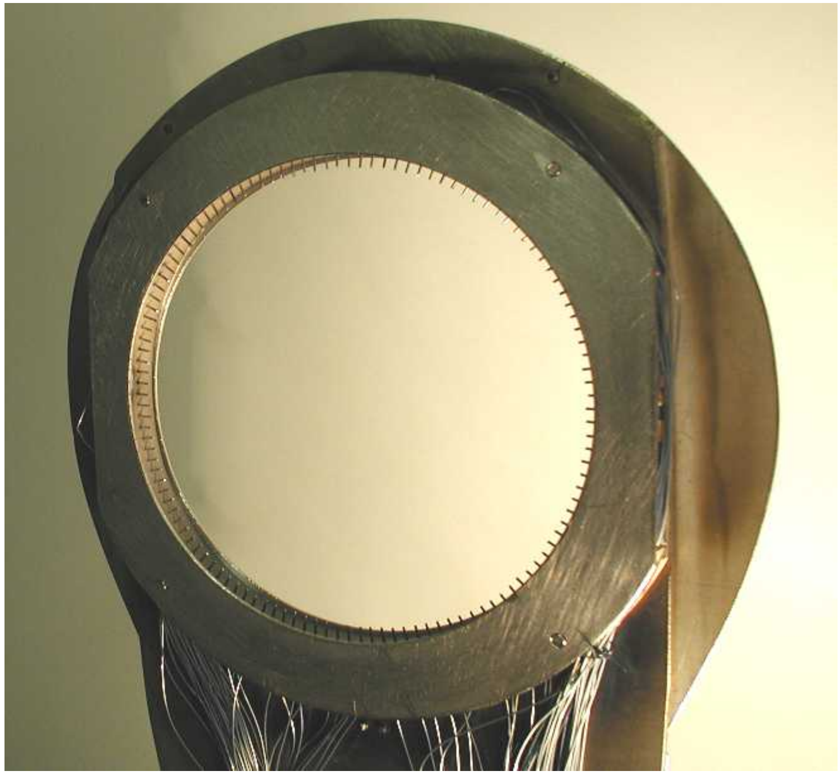


Movies: 1000 frames by 1 μs ⇒ Total duration = 1 ms

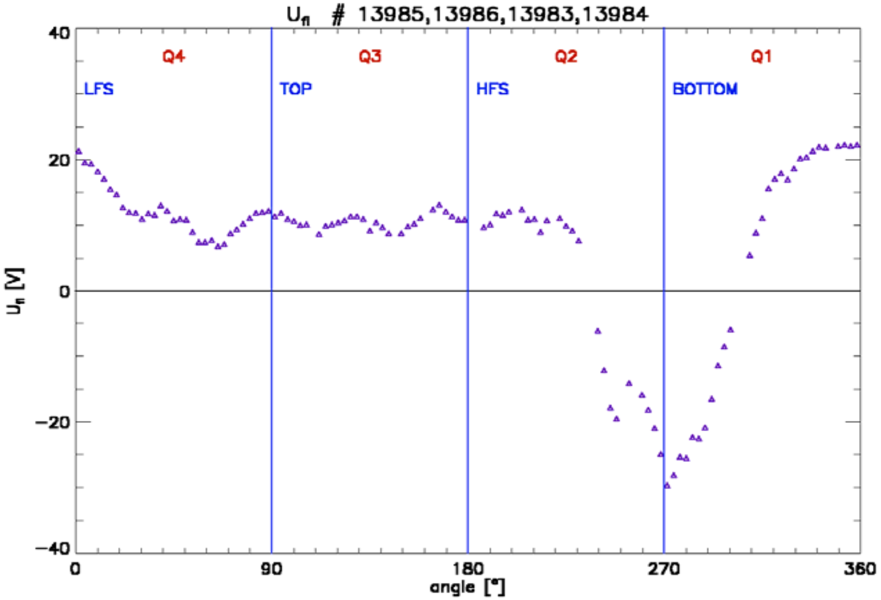
Poloidal array of 124 probes

Around the whole poloidal circumference
Poloidal resolution θ = 2.9 deg (3 mm)
64 fast channels (1 μs sampling available)
signals of one half of the ring can be monitored simultaneously.

The second example

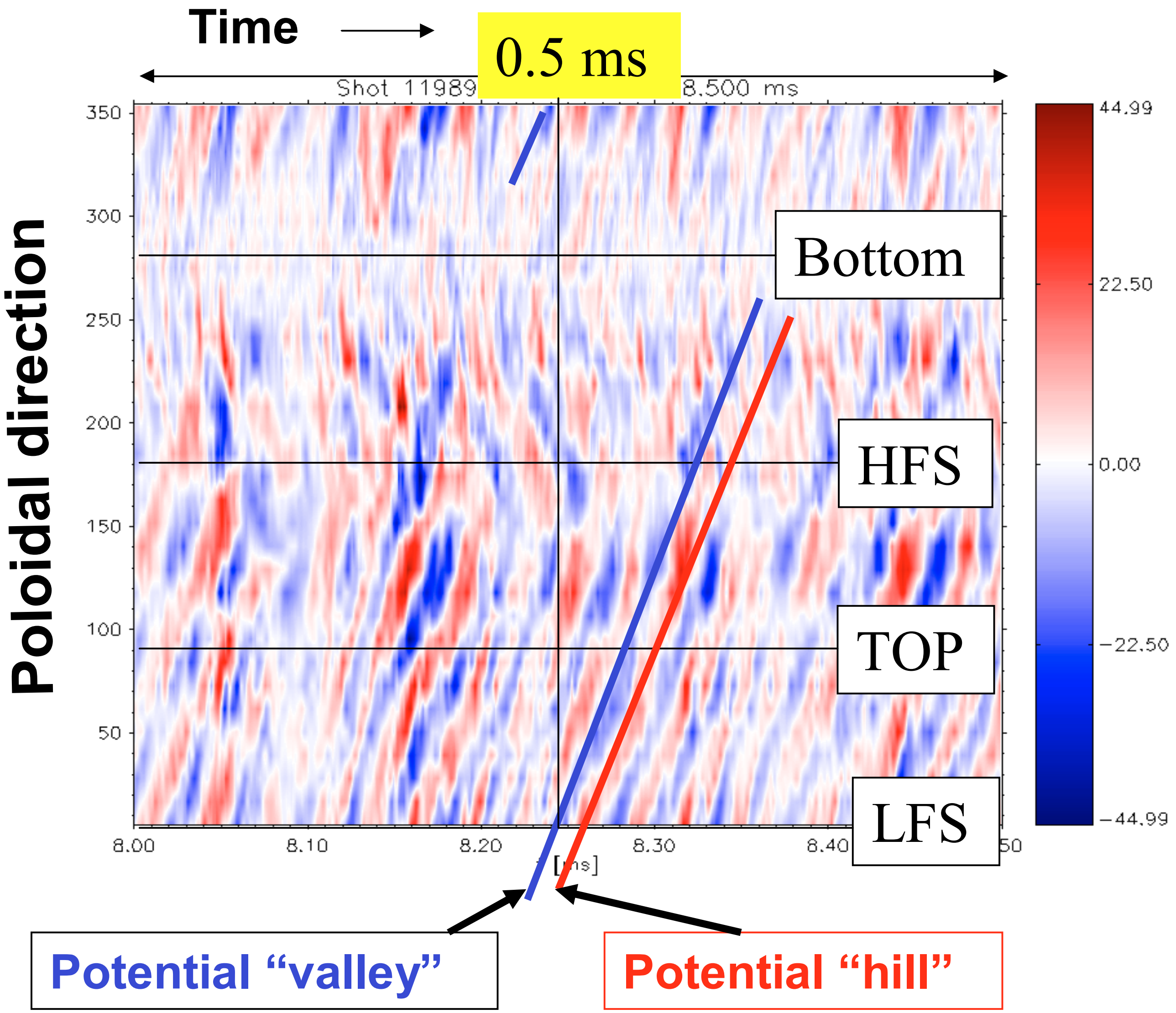


Poloidal Distribution of Mean Floating Potential



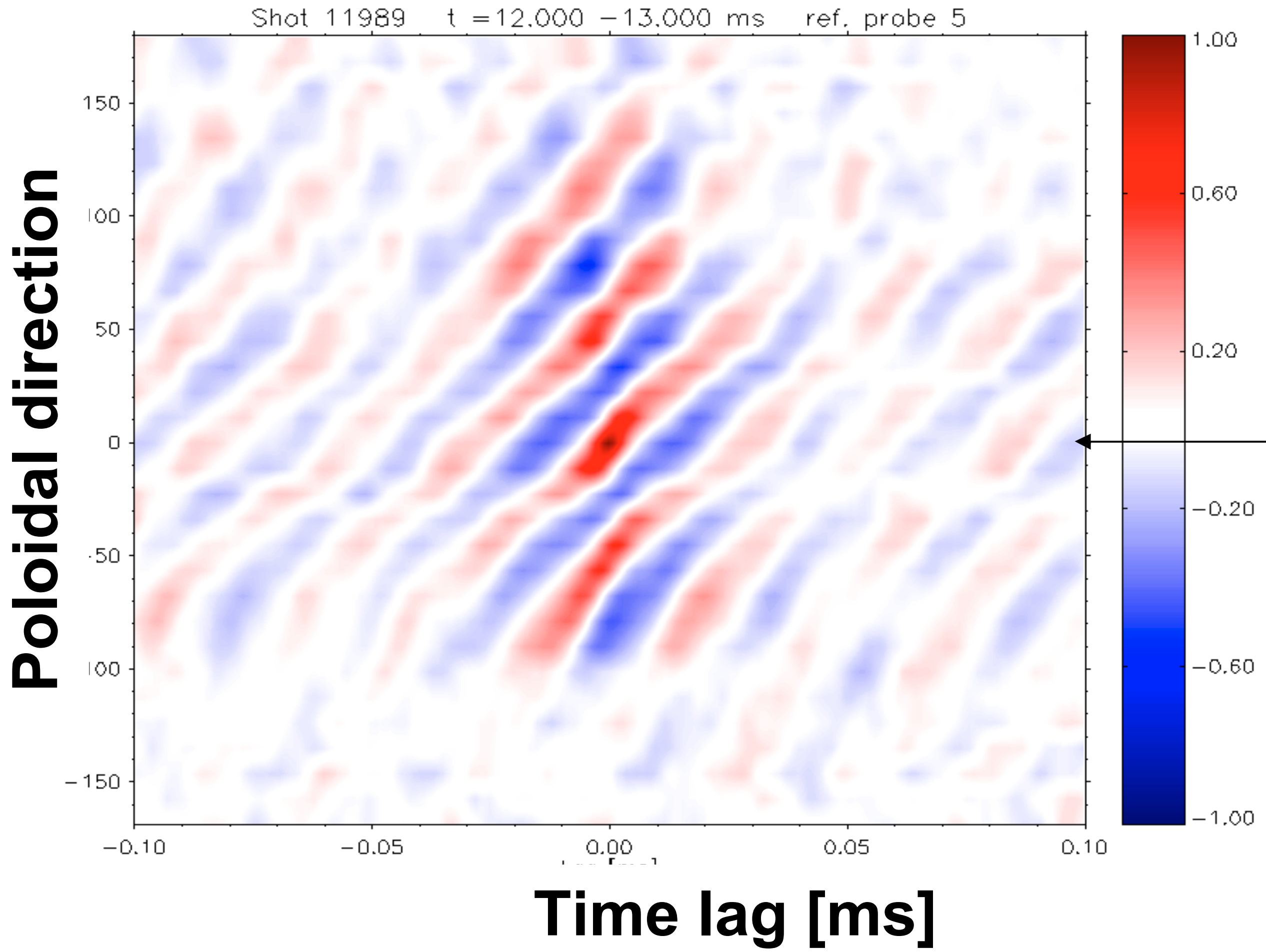
Poloidal – temporal plot of raw data

(floating potential)



Poloidally periodic patterns (bipolar) propagating poloidally are evident.

Cross-correlation in the poloidal direction

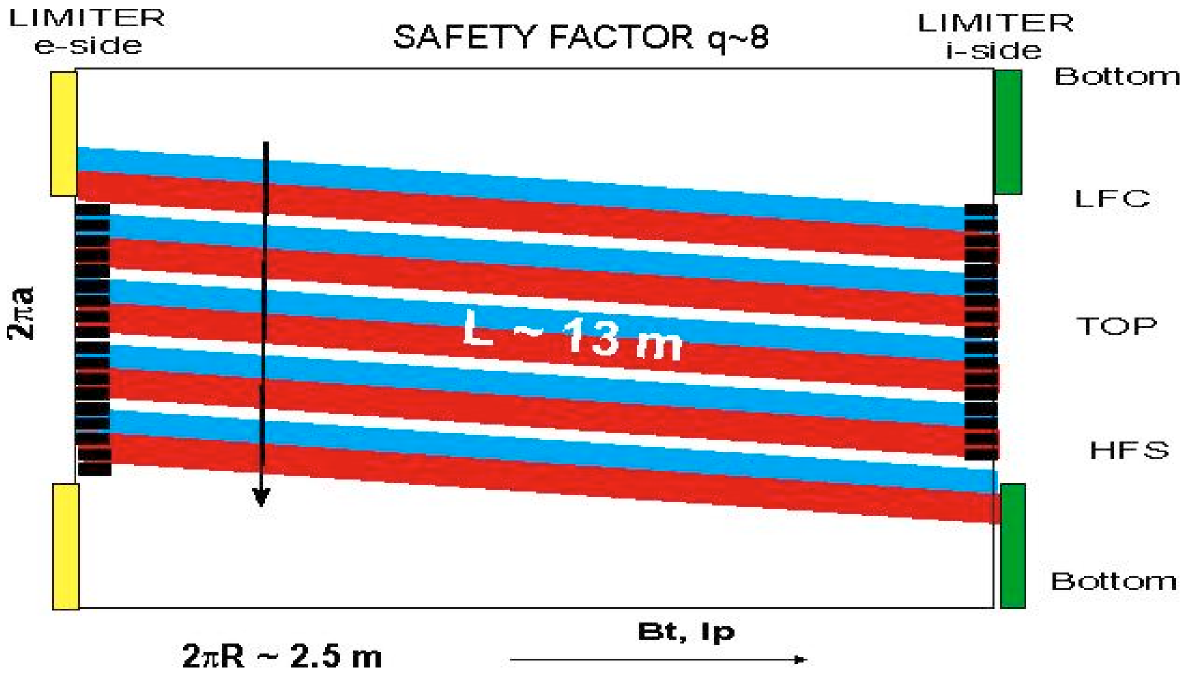


Poloidal periodicity as confirmed by cross-correlation analysis

The reference probe is located at the top of the torus

Dominant mode (m = q, a = 1)

„Unfolded“ magnetic surface
In the SOL (L >> 2πR)



- Single turbulent structure (dipole), which snakes around the torus
- Follows a helical magnetic field line
- Starts at one side and terminates at the opposite side of the poloidal limiter
- Rotates poloidally due to the $E_r x B_t$ drift
- „Dyes“, when the contact with the limiter surface is lost
- Exists at a background of broadband turbulence
- Flute-like instability (model Nedospasov-Endler)

The third example

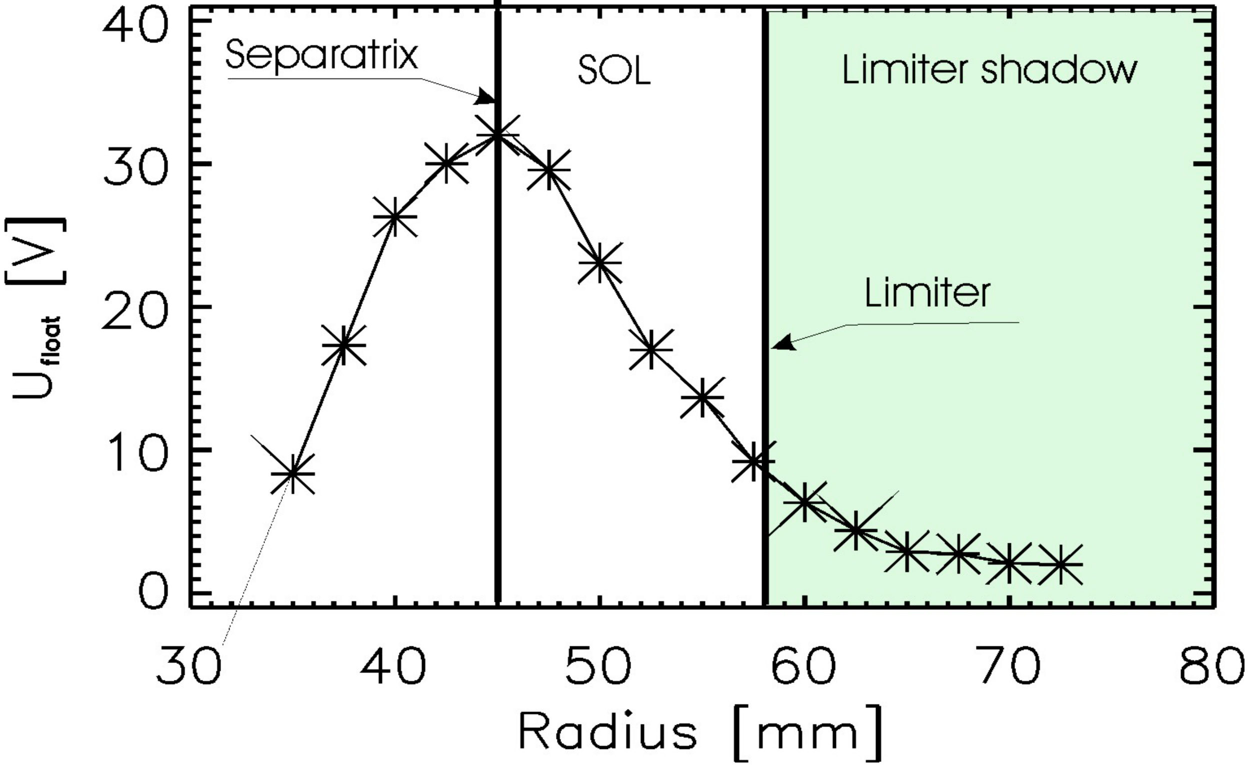
Rake probe

- **Distance 2.5 mm**
- **Total length 35 mm**

Radial distribution of floating potential

$$E_r = -\frac{d\varphi}{dr} < 0$$

$$E_r = -\frac{d\varphi}{dr} > 0$$



Measured by the rake probe in a single shot

Radial electric field in tokamaks

Generate the poloidal rotation because of $E_r x B_{tor}$ drift

$$\vec{v}_{poloidal} = \frac{\vec{E}_{rad} \times \vec{B}_{tor}}{\left|\vec{B}_{tor}\right|^2} = \frac{E_{rad}}{B_{tor}}$$

Simultaneous measurements of E_r and plasma flow velocities (poloidal as well as toroidal) is extremely important.
<u>Many consequencies:</u>
When E_r (v_{pol}) is sheared – turbulent structures are destroyed and the transport across the magnetic field reduced (regimes with improved confinement, H-mode)!

Biasing experiments on CASTOR

Motivation

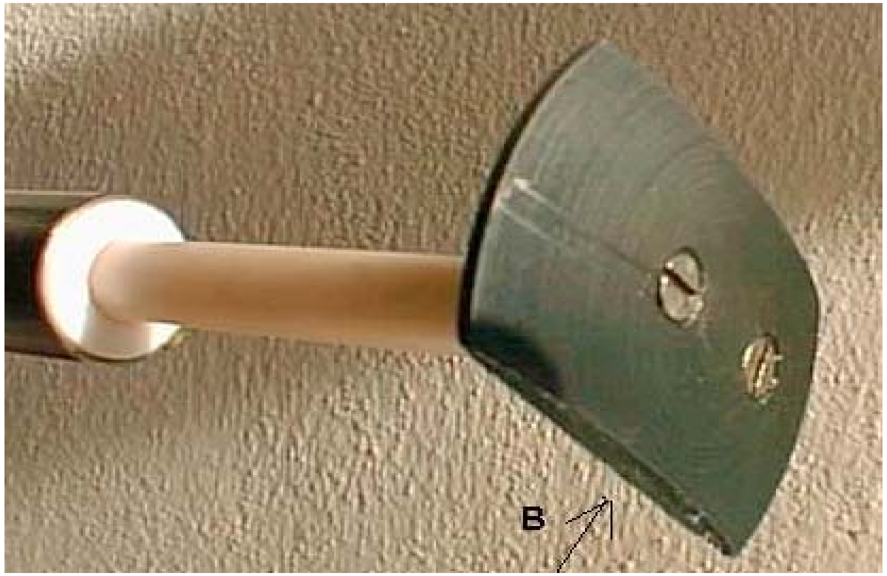
⇒ Amplify electric fields at the plasma edge

⇒ manipulate with ion flows via ExB drift

⇒ reduce plasma fluctuations

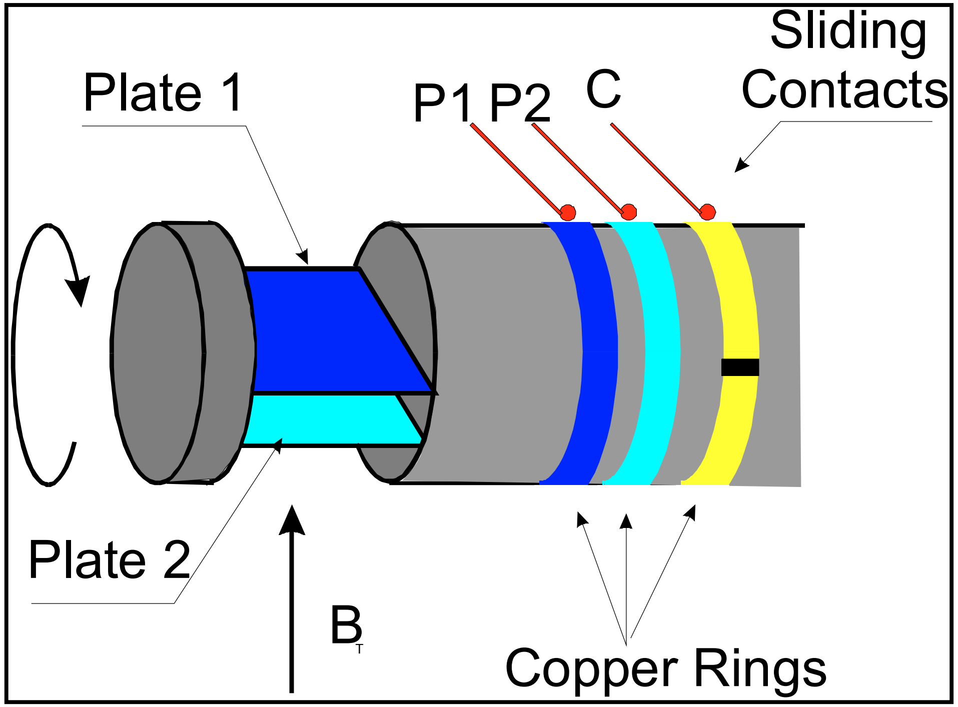
⇒ improve particle&heat confinement

Massive graphite electrode
is inserted in the edge plasma
and biased with respect to
the vessel



Rotating Mach Probe

Measurement of toroidal and poloidal rotation - Mach numbers

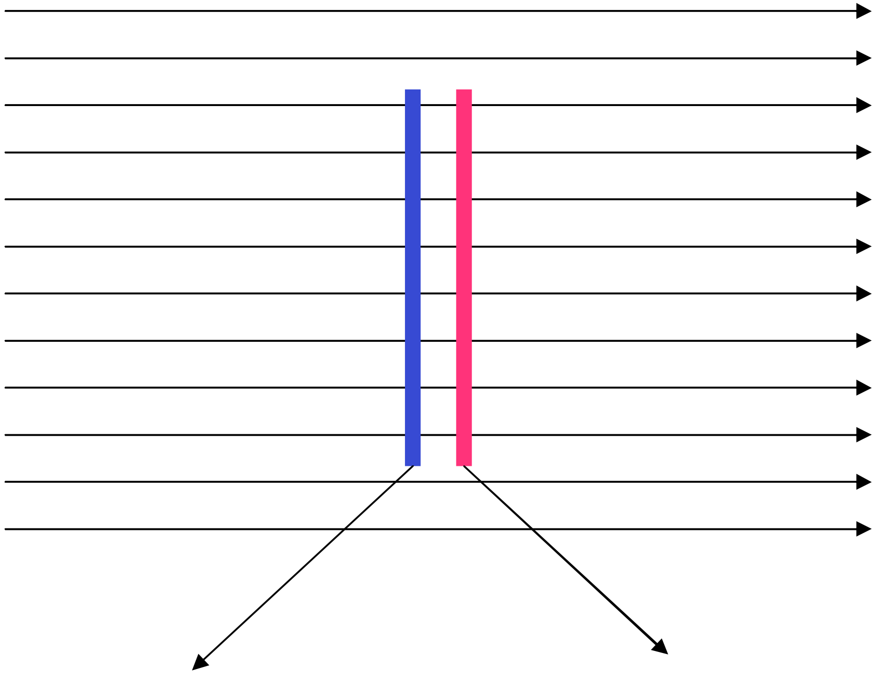


Electric drive in vacuum
Single revolution > 3 ms
Two rectangular plates
2 mm radially x 5 mm

Advantages: simple geometry straightforward interpretation
Disadvantages: limited temporal resolution, complicated construction

Measurement of ion flow velocity

Planar (Mach) Probe



v_{II} II B

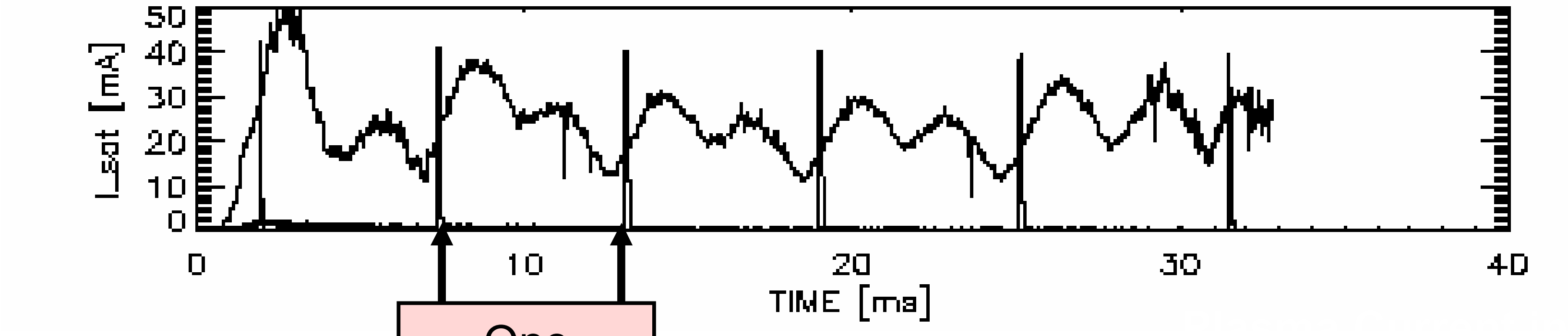
I_{sat}(upstream)

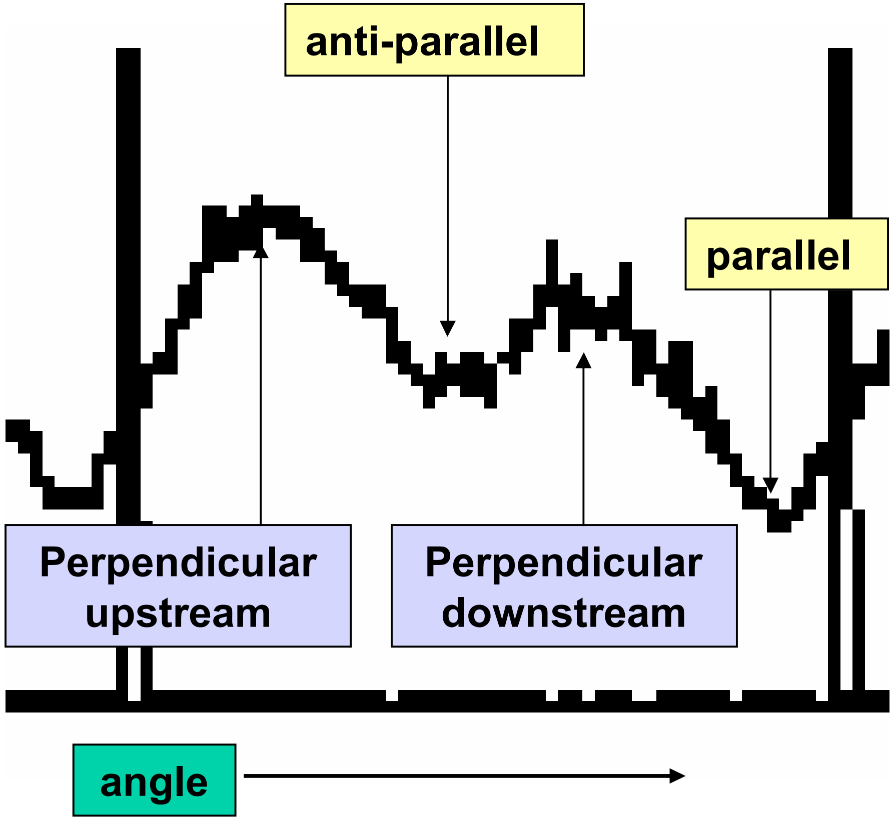
I_{sat}(downstream)

Mach number in the direction parallel to the magnetic field lines is calculated from measured ion saturation currents

$$M_{II} = 2.3\ln\left(I_s^{up}/I_s^{down}\right)$$

Temporal Evolution of the signal of Rotating Mach Probe





Different amplitude of maxima
- signature of toroidal flow

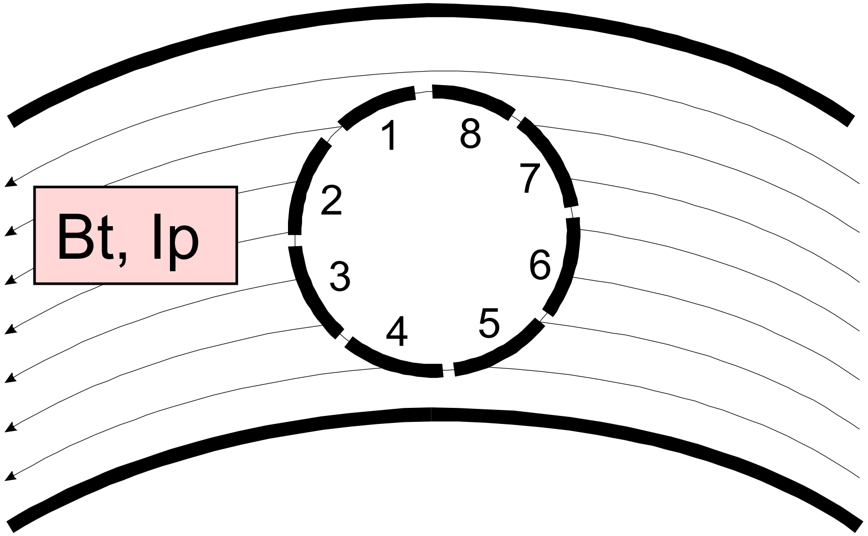
Different amplitude of minima
- signature of poloidal flow

Corresponding Mach numbers can be determined
(by comparison with a model)

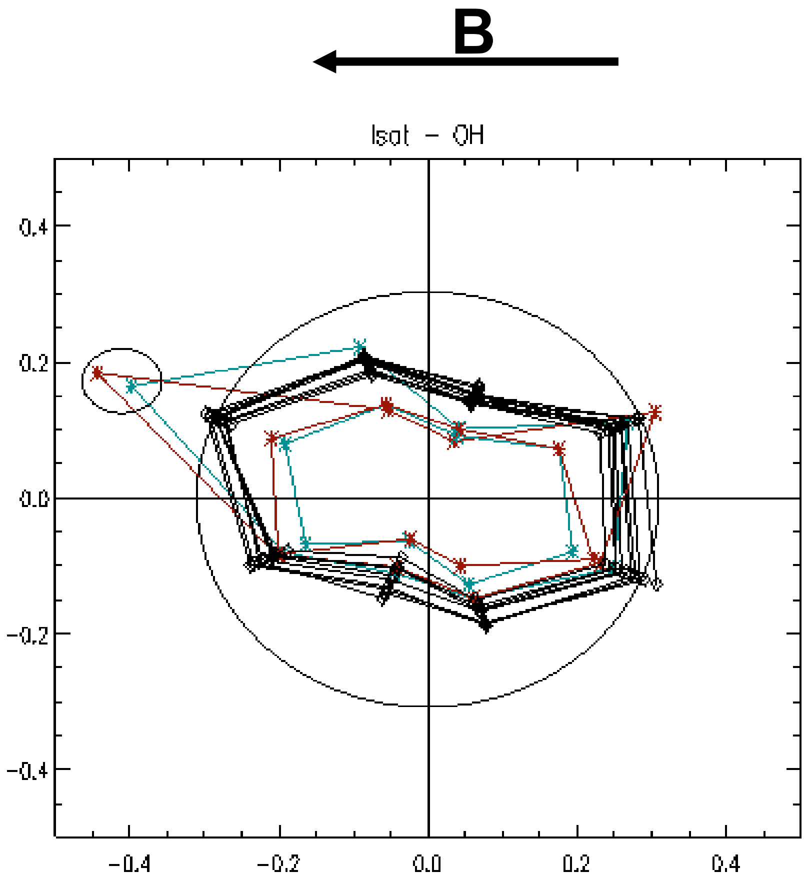
Alternative approach - Gundestrup Probe

with a high temporal resolution

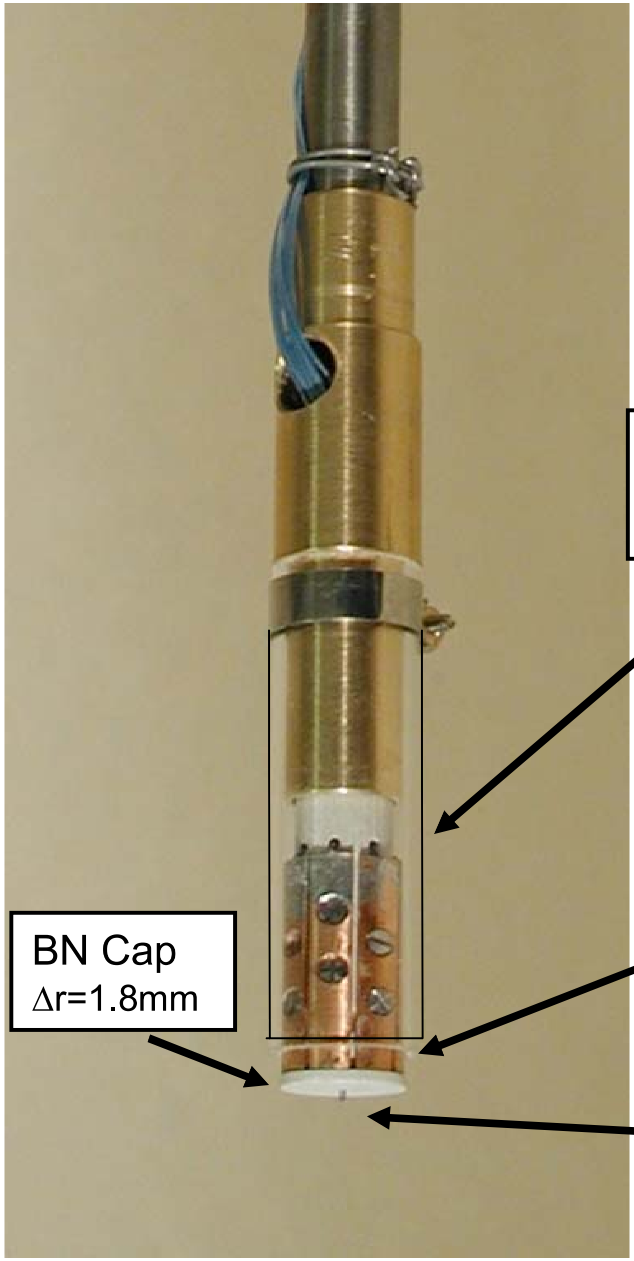
Top View



Polar diagram of
Ion saturation current



Gundestrup Probe



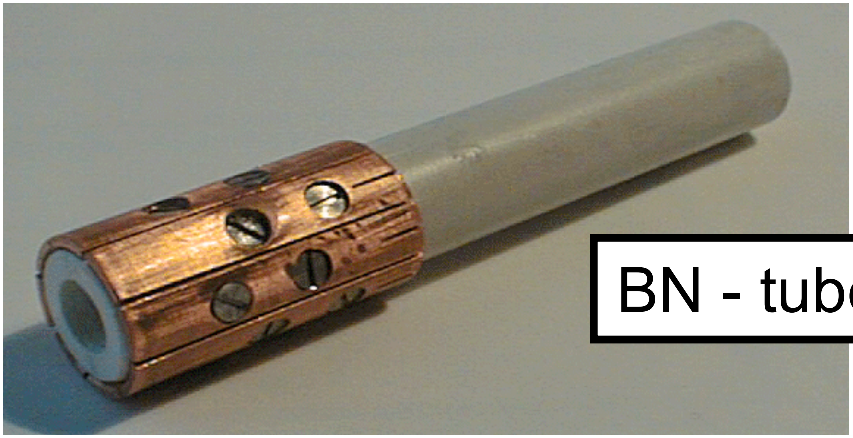
Quartz Sleeve
(transparent)

BN Cap
Δr=1.8mm

Radial resolution
Δr = 2.2 mm

Single Langmuir Probe
ϕ = 0.60 mm, l = 1.25 mm

8 segments (Cu), ϕ = 11.4 mm

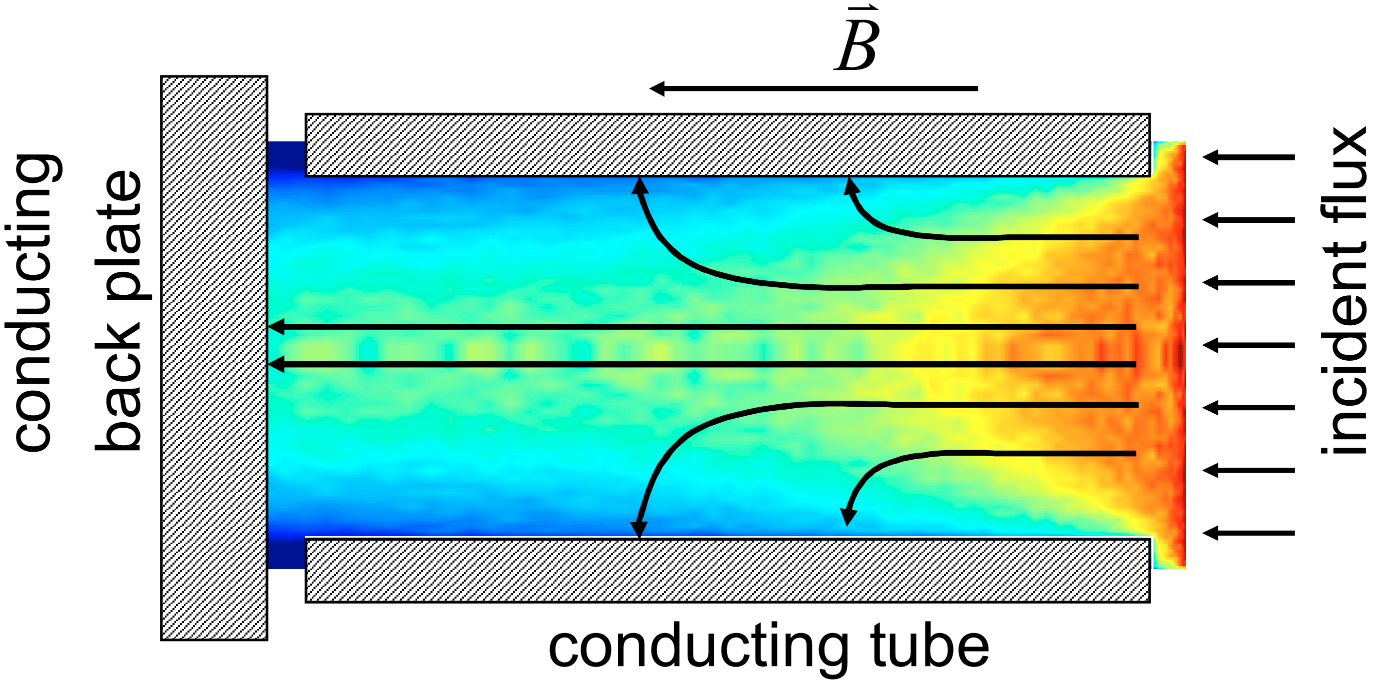


BN - tube

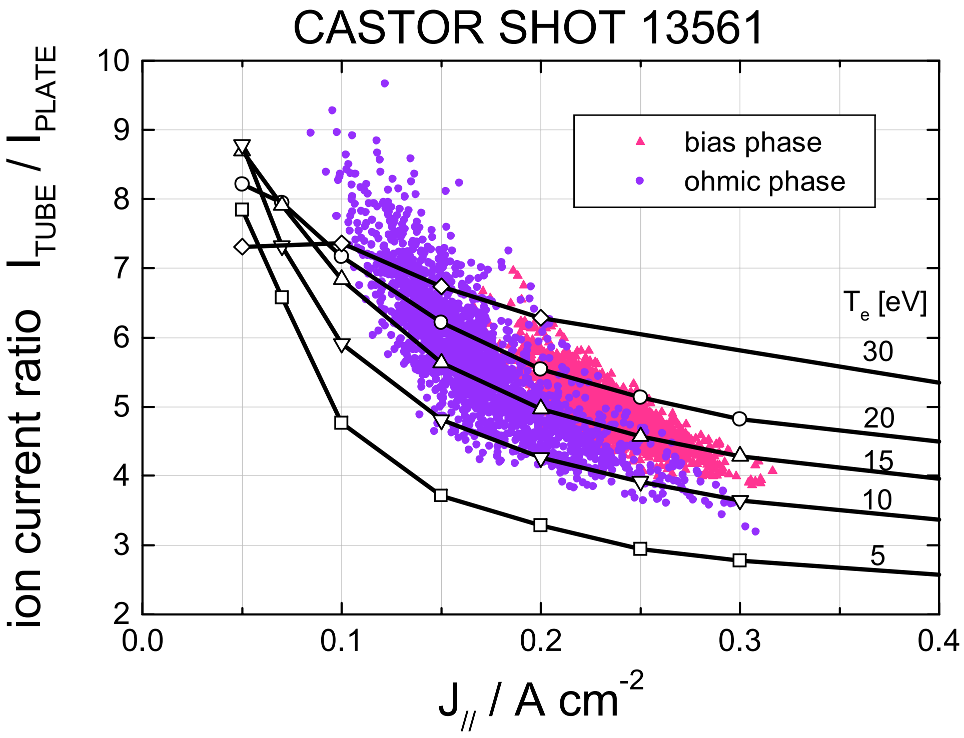
Novel diagnostics for fast measurement of electron temperature - Tunnel probe

PIC simulation shows that the ration of ion saturation currents on tunnel and back plate is a strong function of electron temperature

Low-cost and robust - only two DC signals of ion saturation are measured. Temporal resolution is determined by data acquisition system - no expensive electronics. Immediate acces to fluctuating quantities.



Prototyp tunnel probe for CASTOR



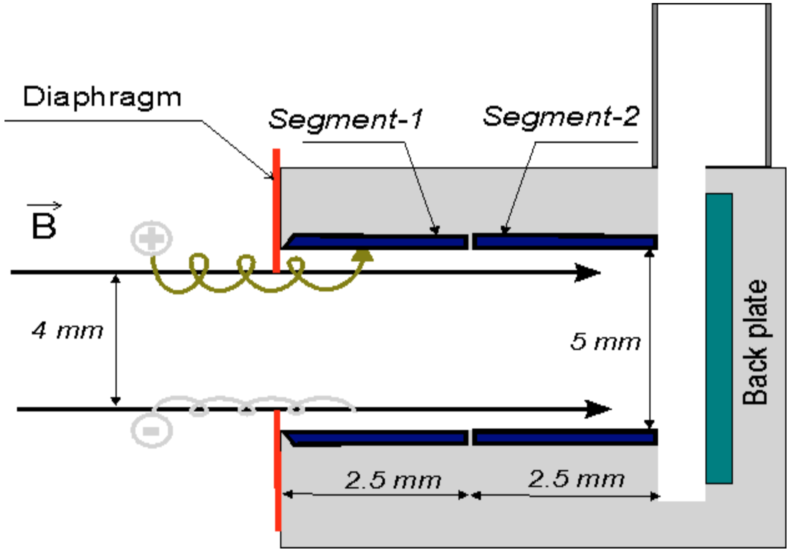
Color points – experiment **Lines - simulation**

Tunnels of the diameter 2.5, 4.0, and 5.0 mm were tested

Modified tunnel probe (ion temperature measurements)

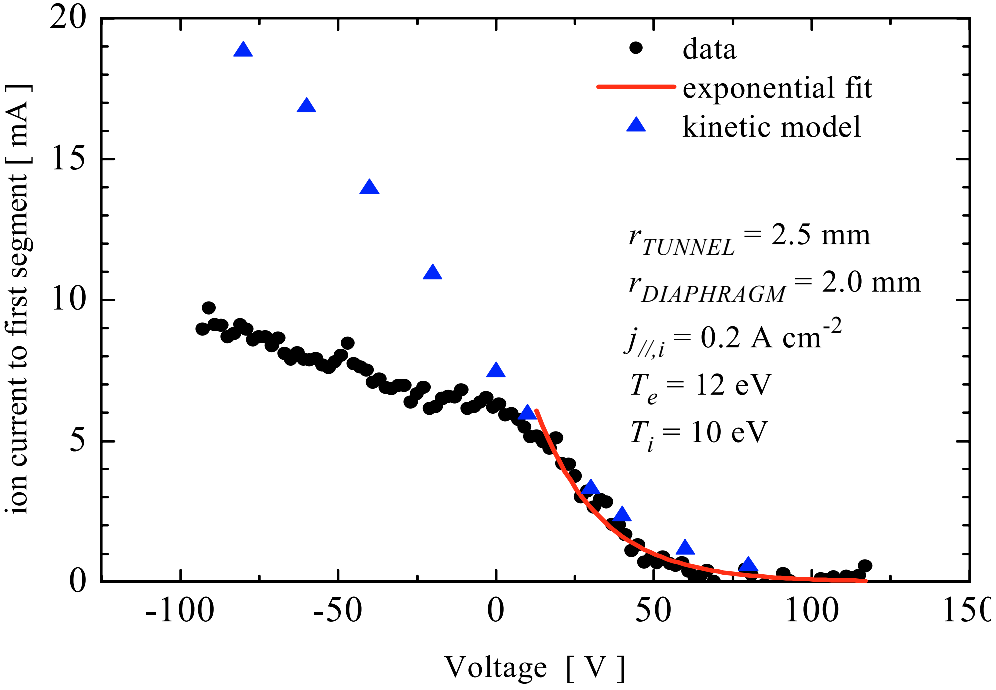
Diaphragma installed in front of the tunnel,
Protects collection of elektrons

$r_{tun}-r_{dia} \sim \rho_i >> \rho_e$



Ions are repulsed, when the potential of the tunnel is more positive than the plasma potential

CASTOR shot 16431 averaged from 7-14 ms



Tools for edge plasma diagnostic and fluctuation measurements

(Summary of electric probes)

- **Classical Langmuir probes** – IV characteristics, local Te, ne, Ufl at the plasma edge, routine measurements
- **Radial & Poloidal & 2D arrays** of Langmuir probes for spatially-temporaly resolved measurements of plasma fluctuations
- **Oriented probes** - Rotating Mach probe, Gundestrup probe for flow measurements during biasing experiments
- **Emissive probes** – Direct measurement of plasma potential
- **Advanced probes** – Tunnel probe - a quite novel concept for fast Te measurements

Conclusions

CASTOR – a small tokamak experiment, but still competitive.

- Testing of advanced diagnostics
- Investigation of edge physics (turbulence)
- Suitable for education of students

Collaboration IPP - Ghent University

Specific relationship (Prof. Guido Van Oost – Member of IBA)

- **Fusion research** (EURATOM & INTAS project)
  - Plasma manipulation by biasing of material objects
  - Advanced probes (emissive, tunnel, Gundestrup,..)
  - Feedback control of edge turbulence

- **Applied plasma physics and technology**
  - Total waste treatment by using plasma technologies
    Water stabilized plasma torches, Corona discharges
    Bilateral collaboration Flanders – Czech Republic

- **Exchange of students**
  - Vacation stays of students - Ine Seaux
    diploma works 2003 - Pieter De Beule, Thibaut Van Rompuy
  - International Association for the Exchange of Students for Technical Experience (IAESTE)
  - ERASMUS project with the Charles University in Prague

Pratical Training of students

Unique features of CASTOR tokamak are exploited for practical education

SUMer TRAIng Course on CASTOR
(organized together with Hungarian colleagues)
The CASTOR tokamak is completely available for students (both undergraduate&PhD) to measure and process data from basic diagnostics.

First attempt
SUMTRAIC 1 - June 2003 (one week – 12 hungarian students)

This year
SUMTRAIC 2 - June 2-11, 2004 (10 days, more international (students from Hungary, Slovakia, Bulgaria, Belgium)

Future plans – to organize it on the annual basis