Detektory typu Czerenkowa w badaniach tokamaków

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Plan wystąpienia

- Wstęp – efekt Czerenkowa
- Przedstawienie badań wiązek elektronów przeprowadzonych w tokamakach CASTOR, ISTTOK i TORE-SUPRA
- Ostatnie badania elektronów ucieczki (runaway) w tokamaku FTU z wykorzystaniem jednokanałowego detektora Czerenkowa
- Przedstawienie ostatnich jedno- i wielo-kanałowych badań elektronów w tokamaku COMPASS (projekt EUROfusion)
- Podsumowanie, wnioski i plany na przyszłość

Cherenkov Effect

- **The main aim of our project is the development of diagnostic techniques applicable for measurements of fast electron beams in tokamak experiments. These techniques should make possible the identification of electron beams, the determination of their spatial distribution, and measurements of their temporal characteristics. In order to determine emission characteristics of the pulsed electron beams the NCBJ team intends to use detectors based on a Cherenkov effect.**

- **Cherenkov radiation – emitted by charged particle moving through transparent medium with velocity higher than light velocity in this medium.**

If charged particle penetrates transparent medium with velocity (*v*) higher than phase velocity of light in this medium, given by u = c/n, where *n* is refraction coefficient of material,

condition for Cherenkov radiation can be written as:

$$v > c/n \quad \text{or} \quad \beta * n > 1 \text{ where } \beta = v/c.$$

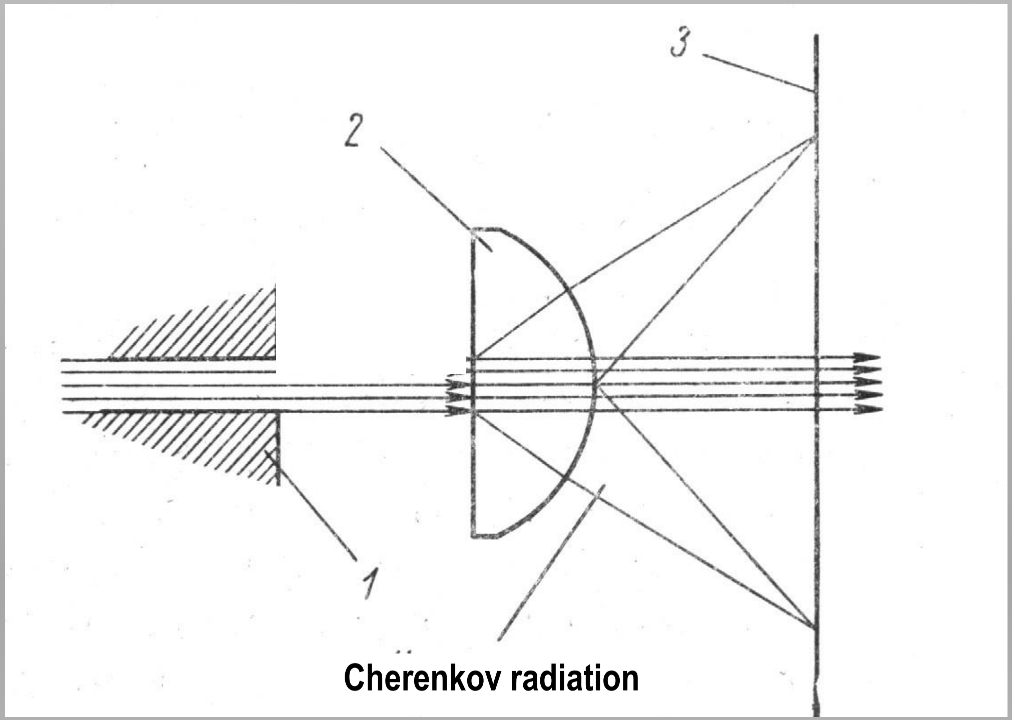
Materials for Cherenkov radiators

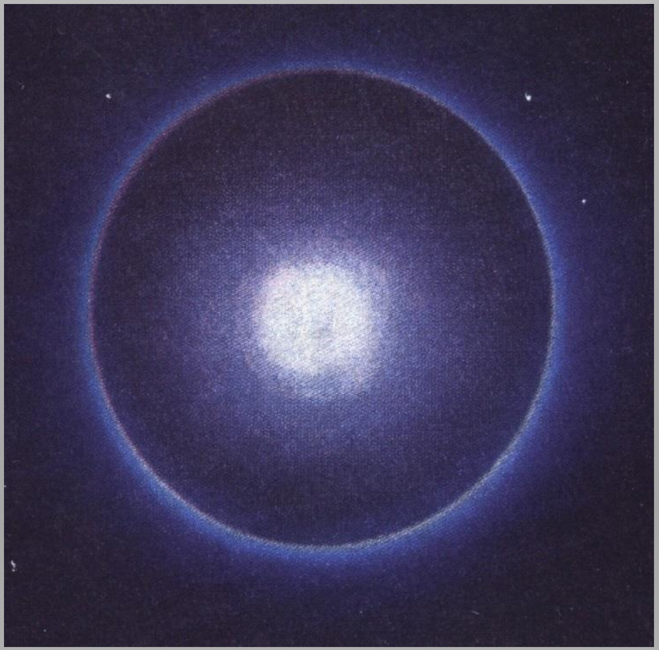
Material	Refraction index	Lower electron energy threshold [keV]	Thermal conductivity [W/cm K]
Glass	1.8	104	0.01
Aluminum-nitride	2.15	66	1.7
Diamond	2.42	51	20
Rutile (TiO_2)	2.9	33	0.12

Characteristic features of the Cherenkov radiation

- Threshold, directional character and continuous spectrum
- Threshold energy is larger for medium with larger refraction coefficient. Thus to record beams of lower energy it is necessary to use diamond or rutile.
- Instantaneous character – radiation is emitted with delay of order of 10^{-10} s. Its intensity in comparison with typical Bremsstrahlung is about two orders higher. **Therefore, under reasonable experimental conditions the Bremsstrahlung emitted by charged particles (e.g. fast electrons) inside radiator may be neglected.**

Diagnostic technique based on Cherenkov effect (i.e. emission of intense radiation by fast electrons in appropriate radiators) ensures direct, spatially well defined and instantaneous measurements of fast electron beams.

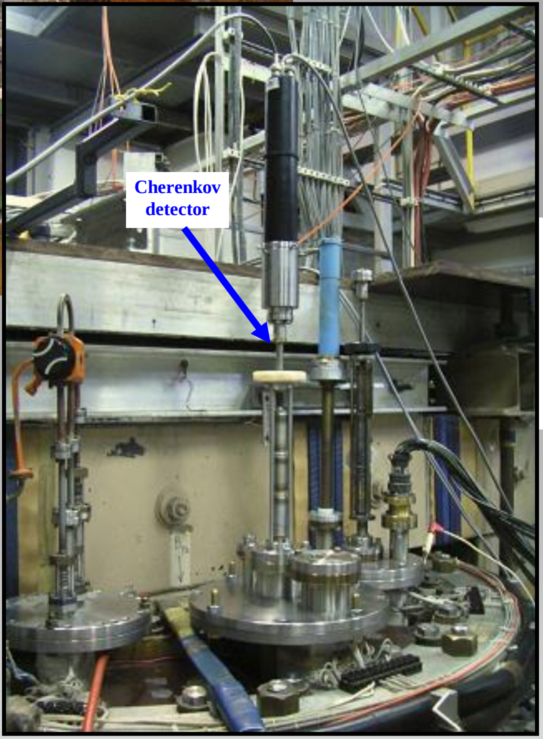


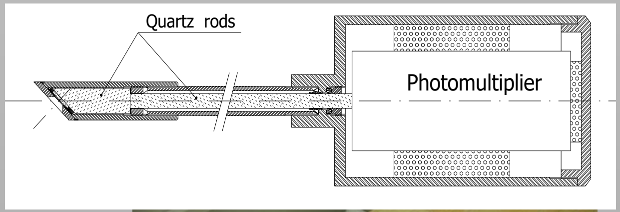


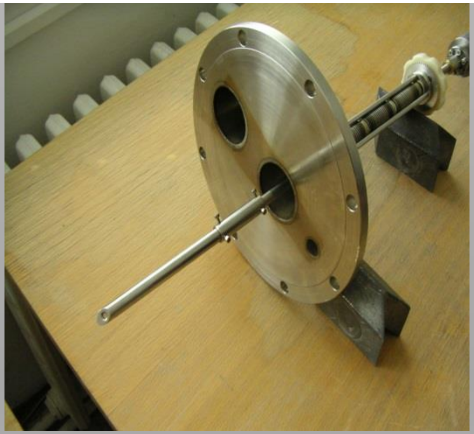
Directional nature of Cherenkov radiation emitted by 660MeV proton beam moved through collimator (1) and lenses (2)
[V. I. Zrelov, Vavilov-Cerenkov radiation and its application in high energy physics, part I (in Russian), Atomizdat, Moscow 1968**].**

CASTOR Tokamak (IPP.CR, Prague)

PARAMETERS	
Major radius	40 cm
Minor radius	8.5 cm
Toroidal magnetic field	0.5–1.5 T
Plasma current	5–20 kA
Pulse length	< 50 ms





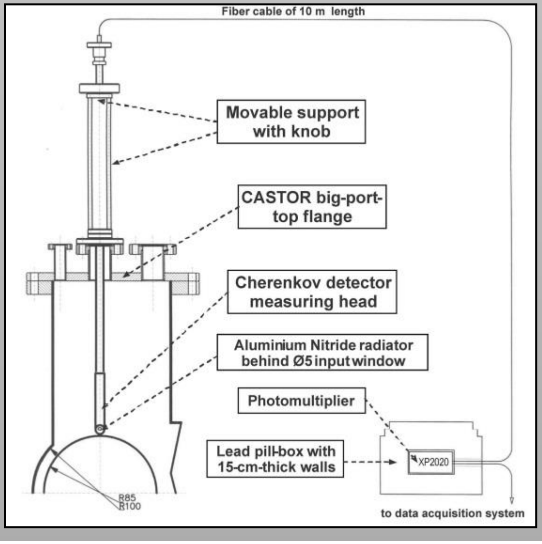


Schematic drawing of a prototype Cerenkov-type detector, designed for the CASTOR experiment (upper picture, not to scale) and its general view after assembling upon a vacuum flange (lower picture).

Picture of the prototype Cerenkov detection system installed upon the upper diagnostic port of the CASTOR tokamak operated at the IPP in Prague.

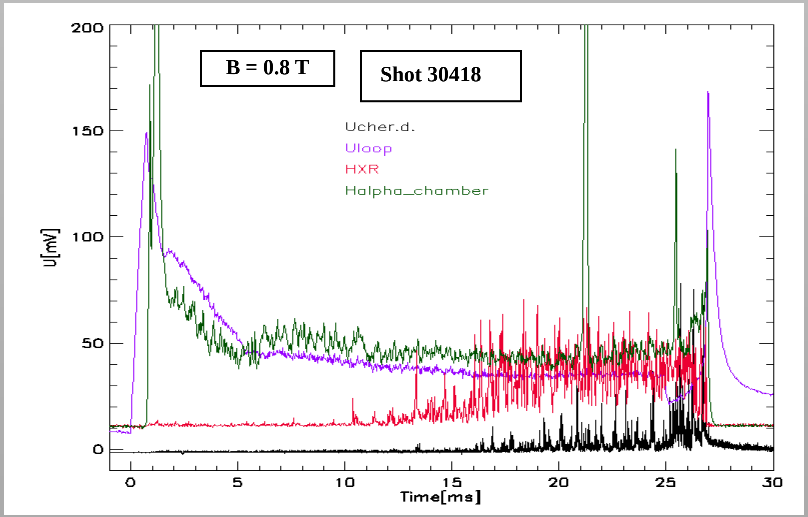
L. Jakubowski, et al., Czech. J. Phys. Vol. 56 No Suppl.B (2006) B98

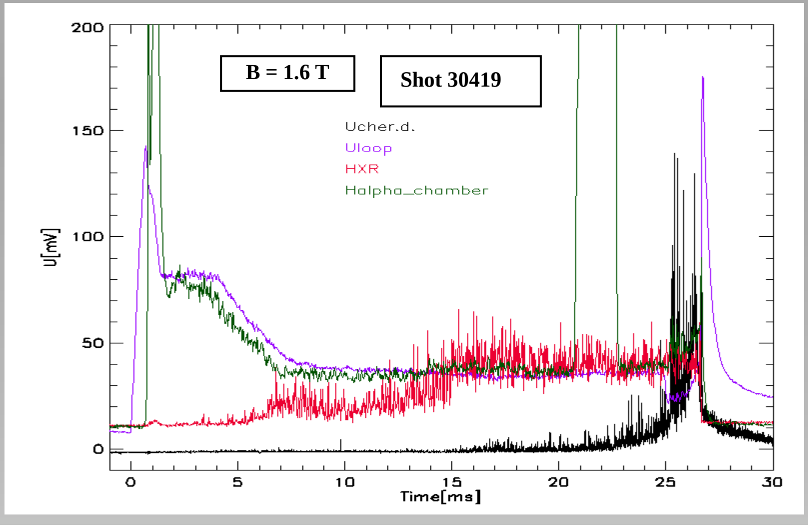
CASTOR

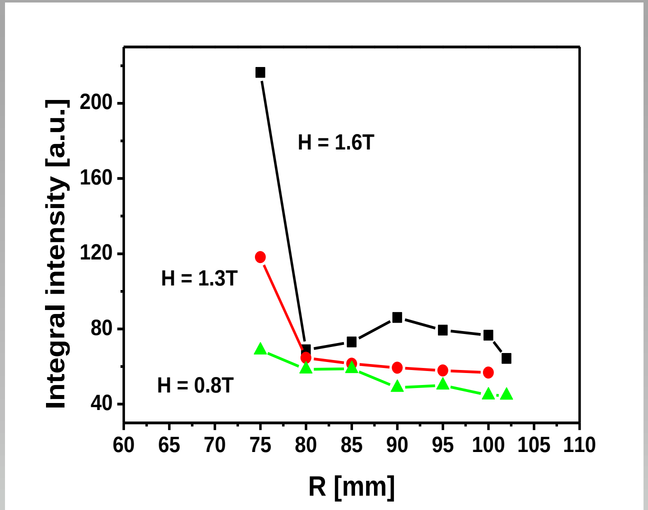


The simplified scheme of the experimental arrangement within CASTOR tokamak.

L. Jakubowski, et al., AIP Conf. Proc. Vol. 996 (2008) 219





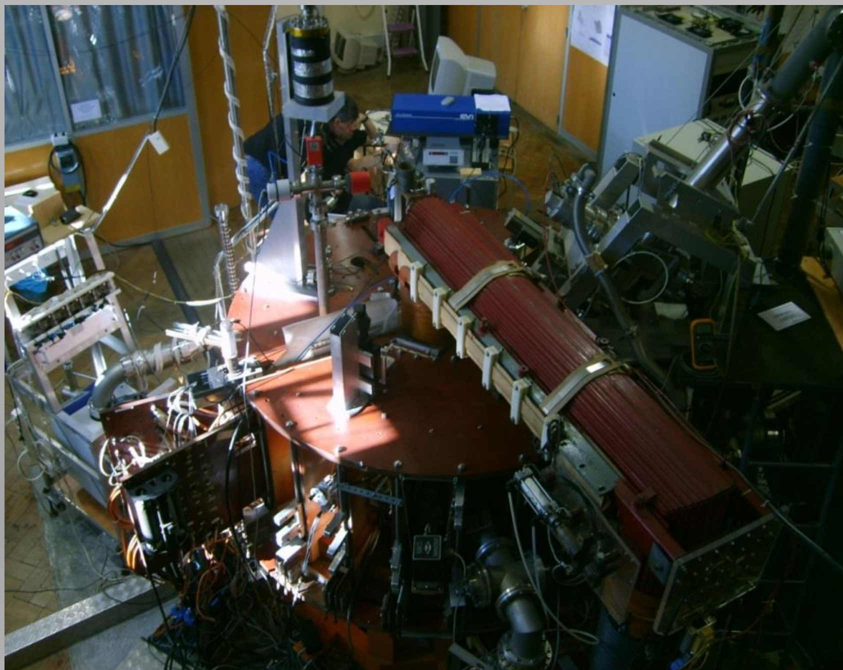


Dependence of integrated intensity of Cerenkov signal on radial position of detector, for different values of CASTOR magnetic field.

Traces recorded during tests of Cherenkov detector in CASTOR facility at different external magnetic fields. Red waveforms - signals from hard X-ray detector (HXR), black curves - signals obtained from tested Cerenkov-detector head, placed at R = 75 mm. The other (violet and green) traces show U-loop and H_α signals, respectively.

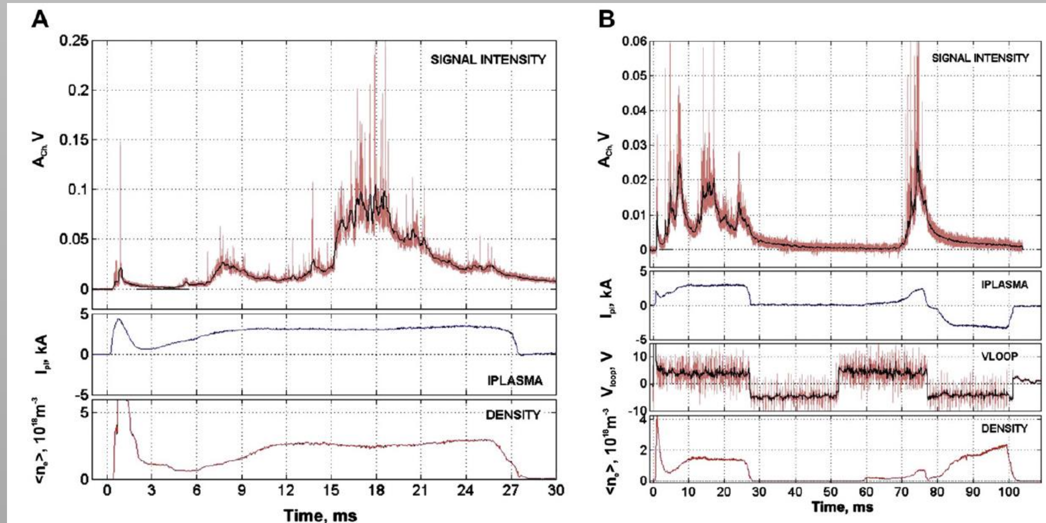
ISTTOK Tokamak (IFPN, IST, Lisbon)

The single-channel Cherenkov detector



General view of ISTTOK Tokamak

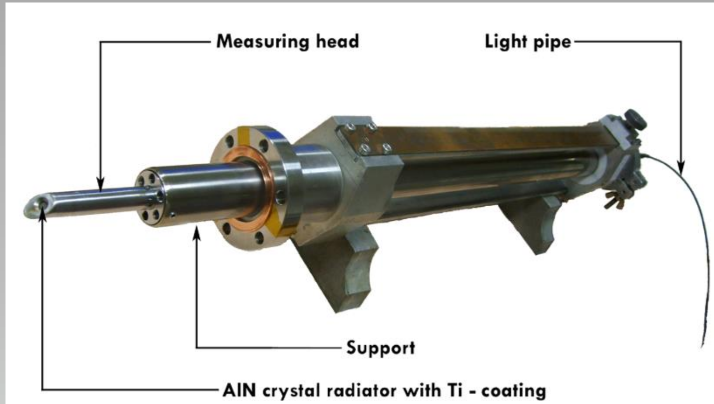
Major radius	46 cm
Minor radius	8.5 cm
Plasma current	~7 kA
Max. magn. field	0,5 Tesla



Comparison of the Cherenkov signal amplitudes A_{Ch} with typical traces of the plasma current I_{pl}, an averaged plasma density $<n_e>$ and a loop voltage V_{loop}, as recorded for two different ISTTOK discharges (A and B).

L. Jakubowski, et al., Radiat. Meas. Vol. 45 (2010) 1014

- ❑ The measuring head: AlN crystal with 10-µm Ti layer, $E_{th} \approx 80$ keV for electrons
- ❑ Photomultiplier: Photonis XP1918 with divider assembly VD108/A, spectral range: 160-650 nm, gain: ~0.8 x 10^6 for supply voltage U= -1400V.



General view of Cherenkov-type detector (together with movable support) used for measurements of fast electrons in ISTTOK.

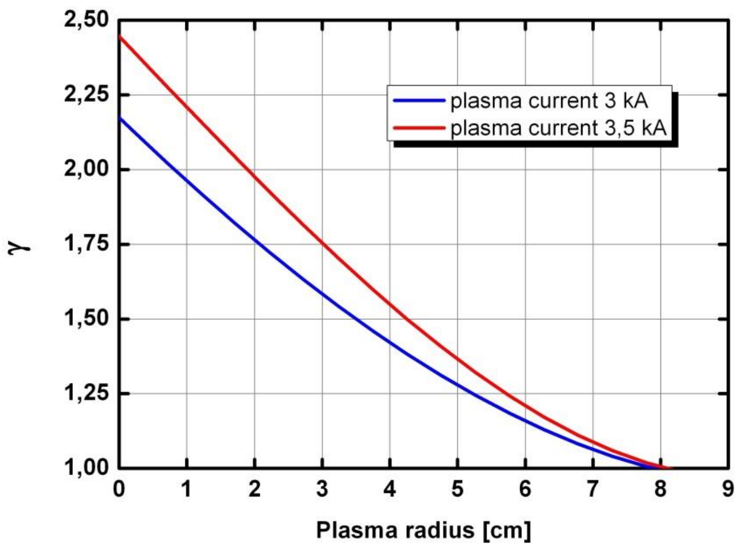
ISTTOK Tokamak

Cherenkov radiation characteristics

The Cherenkov radiation peaks was observed within ISTTOK for multi-cycle alternating flat-top plasma current regime discharges:

- **First positive cycle of plasma current:**
  - **at very beginning for t = 0.5 ÷ 0.8 ms (PRECO discharge),**
  - **during slow increase of plasma current;**
- **Second positive plasma current cycle:**
  - **during slow increase of plasma current,**
  - **at time instant of plasma disruption.**

▪ **Cherenkov emission signals disappear or decrease significantly after increase of average plasma density up to $\langle n_e \rangle = (7\text{-}10)\cdot 10^{18}\ m^{-3}$ during first 0.5-2 ms of discharge**



The maximum energy values of runaway electrons generated at different plasma radii in the ISTTOK, at plasma currents equal to 3 and 3.5 kA.

Modeling of runaway process

■ An outward drift of a runaway electron orbit increases with increase in the runaway energy.

■ The conventional formula, which determines a dependence of γ versus the initial runaway orbit radius (initial position) and plasma current:

$$\gamma = (1 + [(1 - \rho_{RA}/a_{pl}) * 2R_0/a_{pl} * I_{pl}/I_A]^2)^{1/2}$$

where:

ρ_{RA} - initial runaway orbit radius,
a_{pl} - plasma minor radius,
R_0 - plasma major radius,
I_{pl} - plasma current,
and I_A – Alfven current.

■ Here γ is a relativistic parameter directly characterizing electron kinetic energy $W_{kin} = m_e c^2(\gamma - 1)$ and $\gamma = (1 - v_e^2/c^2)^{-1/2}$.

■ The maximum energy limits of electrons for the initial radius of runaway orbits can be estimated.

For the ISTTOK plasma current I_{pl} in the range $3\ kA \le I_{pl} \le 3.5\ kA$, and for the detector measuring head at the radial position $6\ cm \le r_p \le 6.5\ cm$ significant electron beams of energy equal to about 80 keV ($1.15 < \gamma < 1.2$) should be observed.

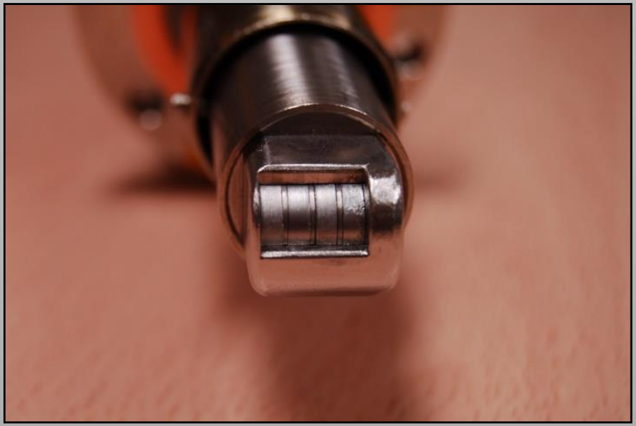
It was consistent with the obtained experimental results.

A Cherenkov probe is capable to detect runaway electrons born not only at the probe position, but all of them generated inside region of the performed measurements.

ISTTOK

Measuring heads with AlN radiators

The measuring head: four AlN polycrystals with different Mo layers,
Photomultipliers: Photonis XP1918



The improved version of the four channel measuring head:

Essential differences between experimental sessions:

A - photomultipliers XP2020Q instead of XP1918,

B - higher effective area of individual radiators,

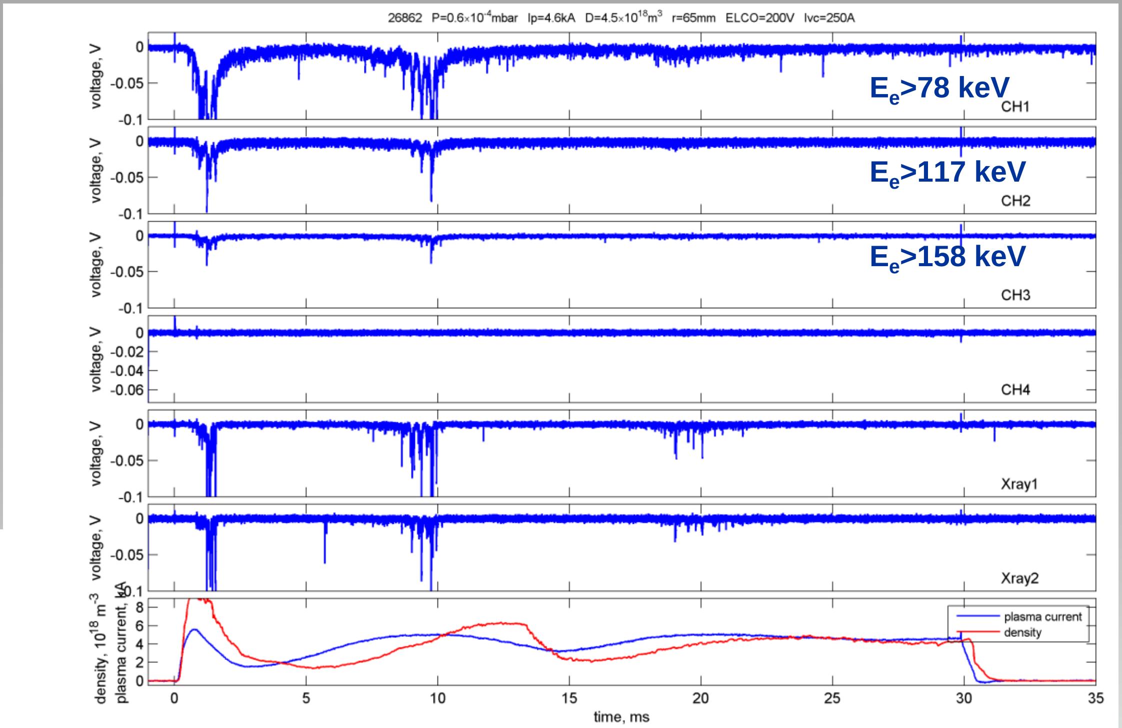
C - better plasma confinement,

D - two-channel hard X-ray diagnostic (HXR-1), placed outside chamber and close to limiter, was additionally applied.

In consequence: higher signal intensities and improved signal to noise ratio.

Dependence of minimum electron energy value on thickness of applied Mo-filter

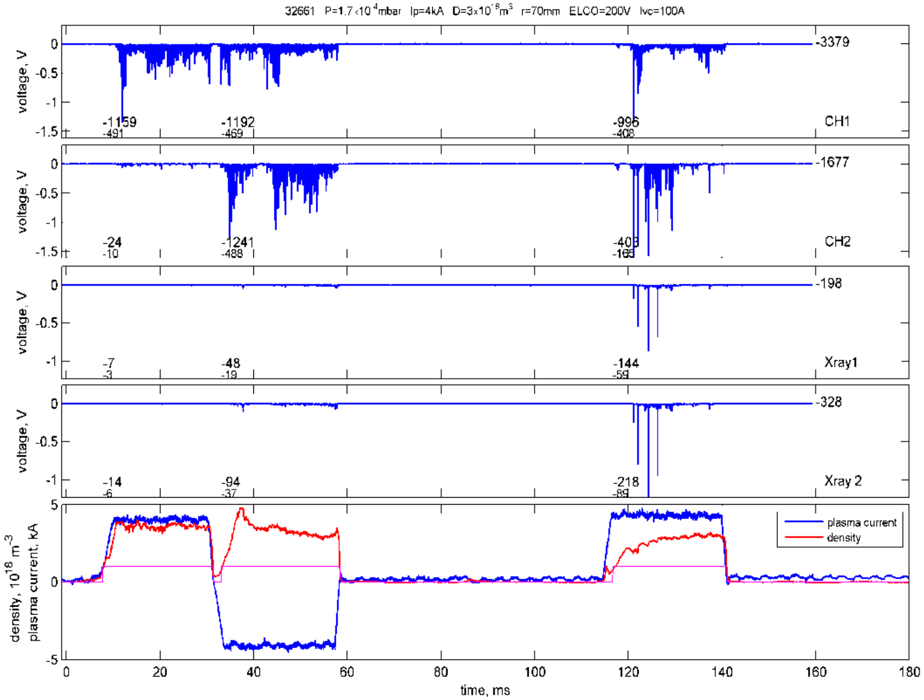
Thickness [µm]	1	3	7	10	20	50	100
E_{min} [keV]	69	75	87	95	120	180	260



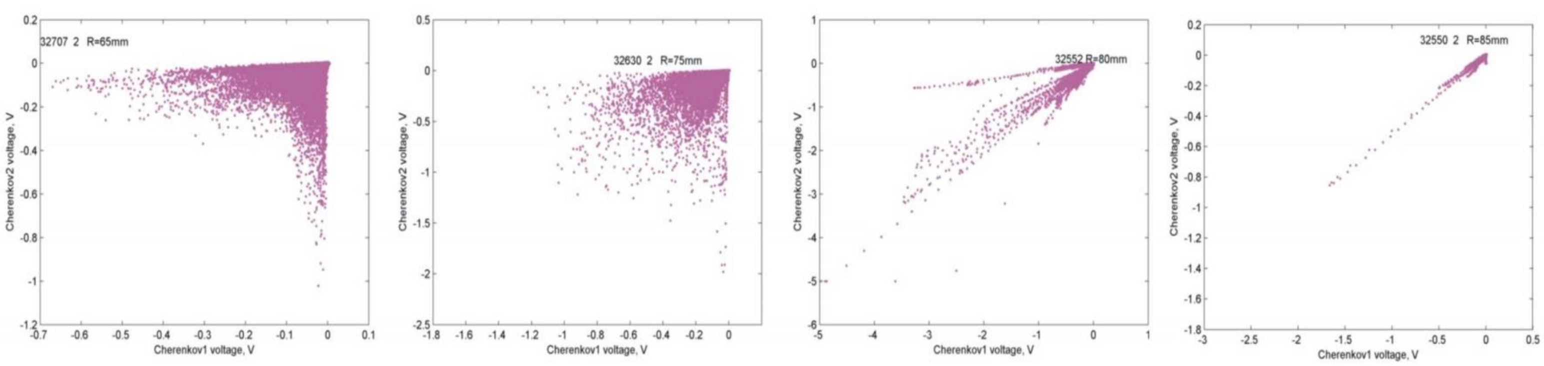
Comparison of electron-induced signals (CH1, CH2 and CH3), hard X-rays (Xray1 and Xray2) with discharge current and plasma density traces.

ISTTOK

The view of the new, two-channel measuring head of the Cherenkov probe with diamond radiators.



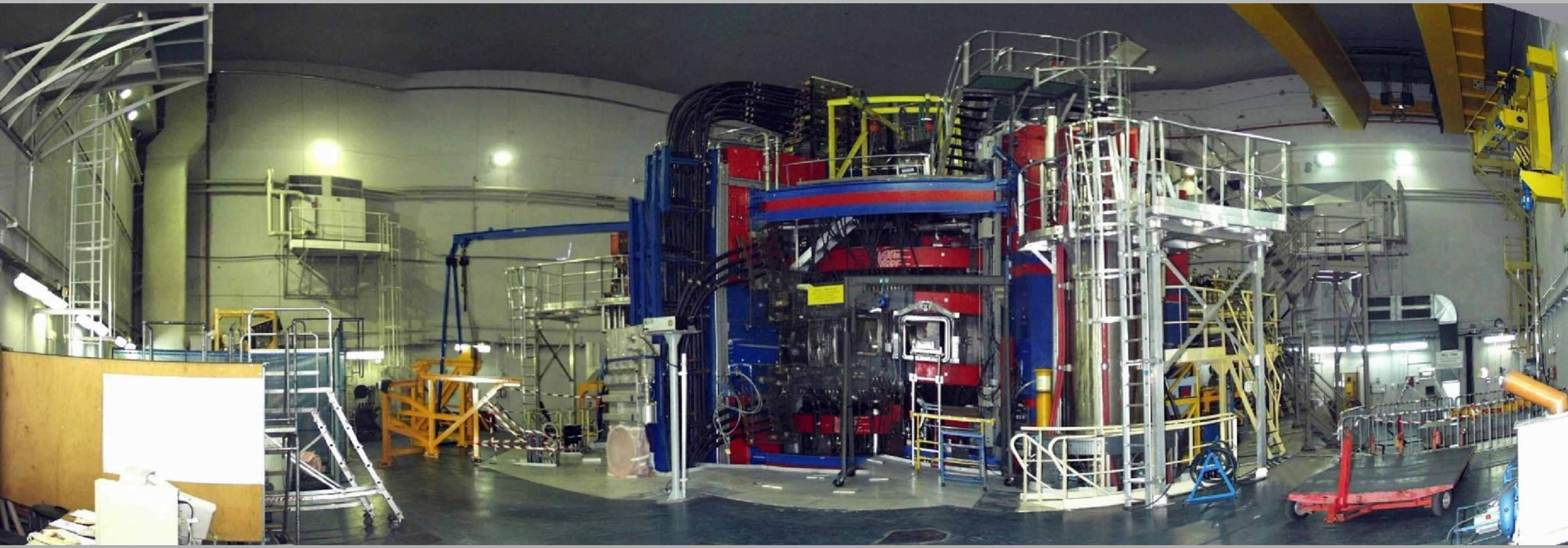
Temporal changes of intensities of electron beams (traces CH1-CH2), and hard X-rays (traces Xray 1-2) in relation to the discharge current and plasma density (two bottom traces) for ISTTOK discharge .



r = 65 mm r = 75 mm r = 80 mm r = 85 mm

Dependence of correlation of intensities of electron signals CH1 and CH2 on measuring head position for series of ISTTOK plasma discharges .

Tokamak Tore-Supra (CEA, Cadarache)



Major radius	238 cm
Minor radius	75 cm
Plasma current	~2 MA
Max. magn. field	4,5 Tesla

Detector design assumptions

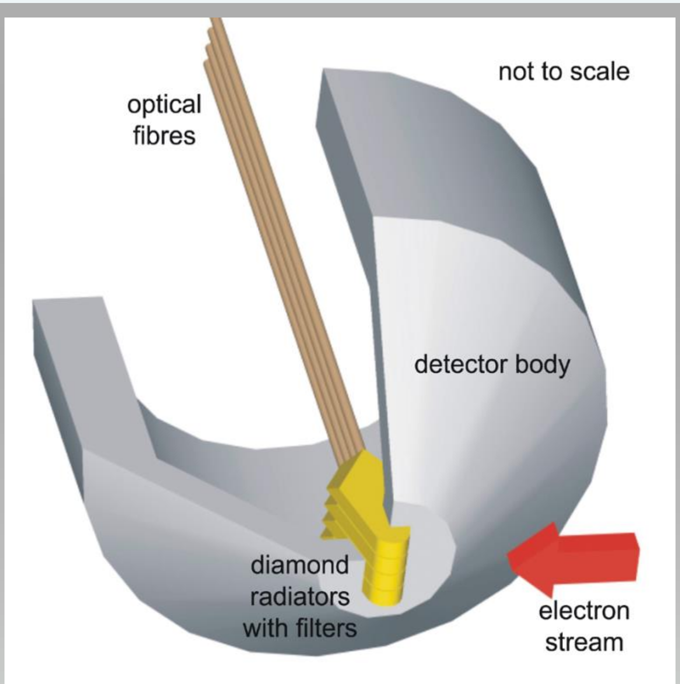
- Electron energy spectrum from ~50 keV to >300 keV
- Electron current density up to ~2 mA/cm^2
- Heat loads ~500 W/cm^2

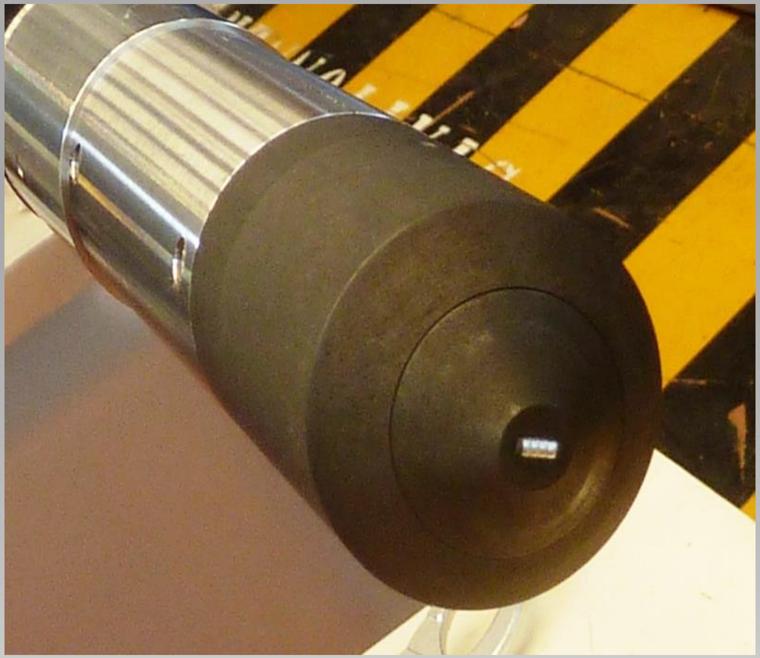
It requires the use of:

- high temperature resistant materials, having high thermal conductivity, and with a relatively high refractive index.
- the performance of all measurements during a relatively short time.

Solution

- Radiator made of a diamond crystal –
  - excellent thermal conductivity (four times higher than that of copper) enabling to dissipate heat deposited upon the surface
  - refractive index high enough to observe electrons with energy of ~ 50 keV.
- Relatively thick massive metal substrate (heat capacitor) to which the diamond plate should be mounted.
- Continuous measurement replaced with the sequence of short pulses (detector introducing and withdrawing from the bulk plasma of discharge Δt ~100 ms).

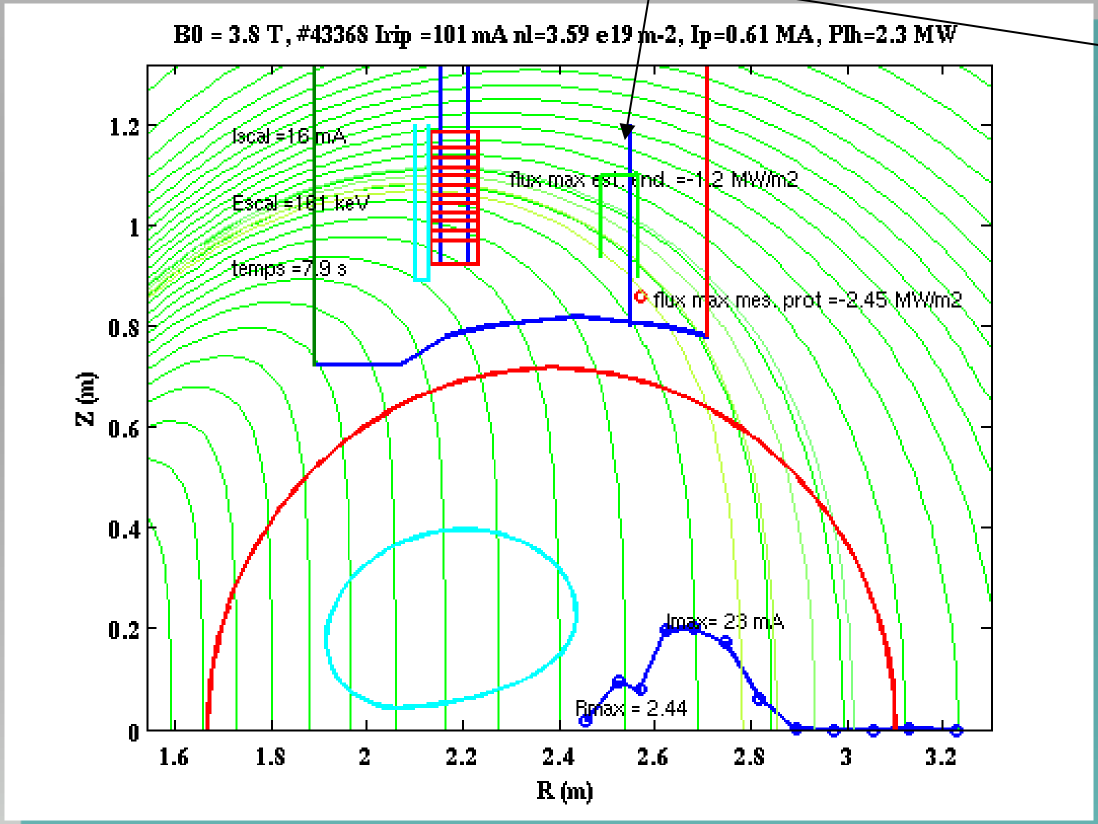




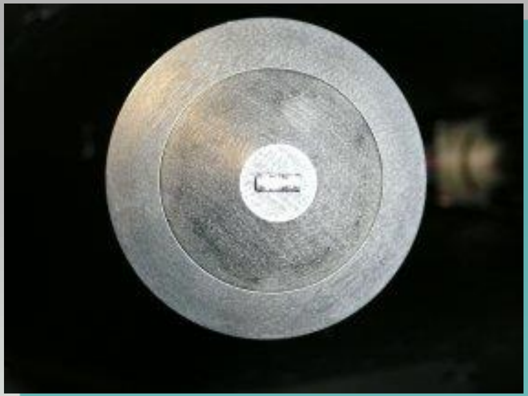
Scheme and view of the modified Cherenkov measuring head designed for the Tore-Supra experiment. L. Jakubowski, M.J. Sadowski, et al., RSI 84 (2013) 016107

Tore-Supra
Diagnostics configuration

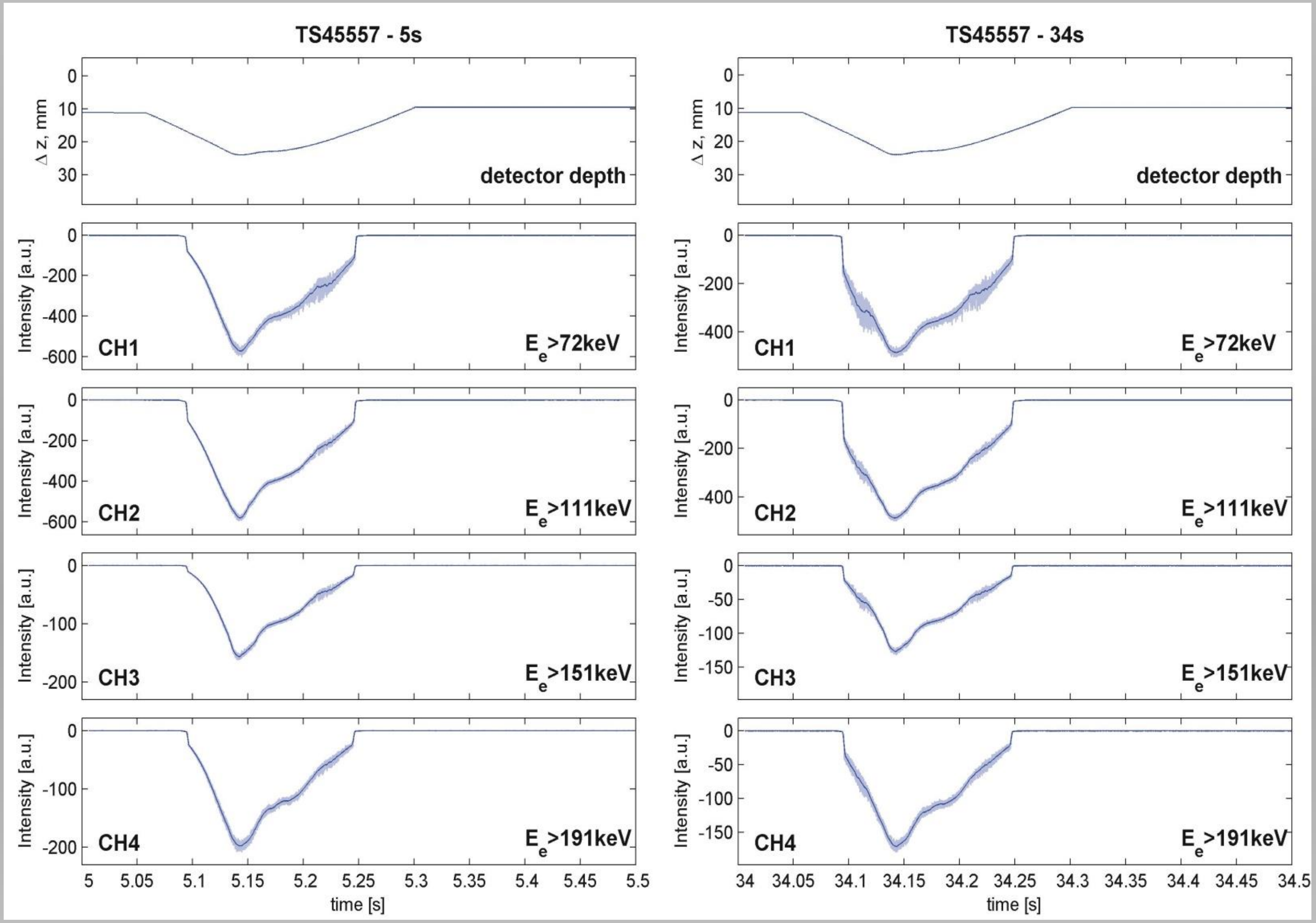
DRIPPLE **Cherenkov detector**



R



Tore-Supra



- Signals obtained from the Cherenkov detectors for the shot TS45557 at two different instants t_1 = 5 seconds and t_2 = 34 sec.
- Conclusion:
  - electron energies < 151 keV,
  - big contribution of electrons from 111 keV to 151 keV

FTU Tokamak (ENEA, Frascati)

The FTU stainless steel vacuum chamber

- toroidal limiter made of molybdenum
- outer molybdenum poloidal limiter
- vertical poloidal lithium limiter

Major radius	93,5 cm
Minor radius	30 cm
Plasma current	~2 MA
Max. magn. field	2-8 Tesla

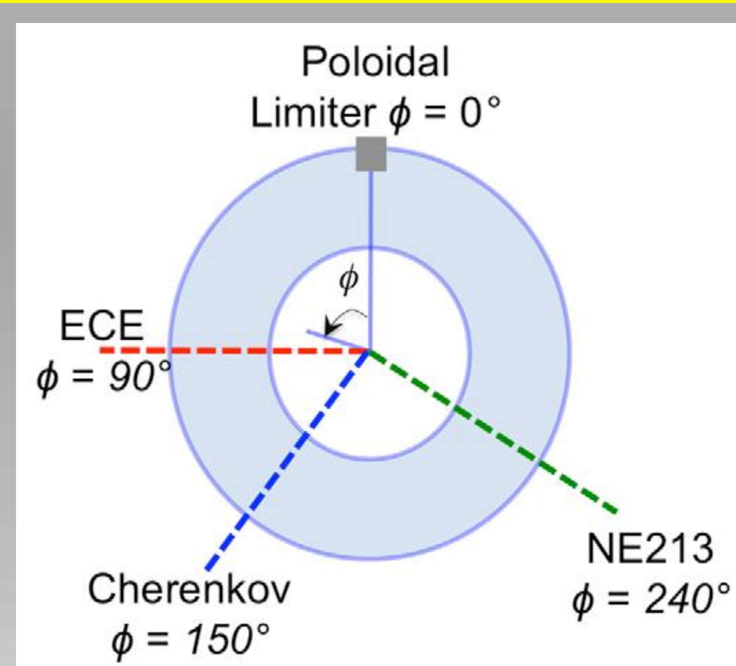
Additional heating system:
140 GHz electron cyclotron (EC) system up to 1.5MW
8.0 GHz lower hybrid system up to 2.0MW.

FTU

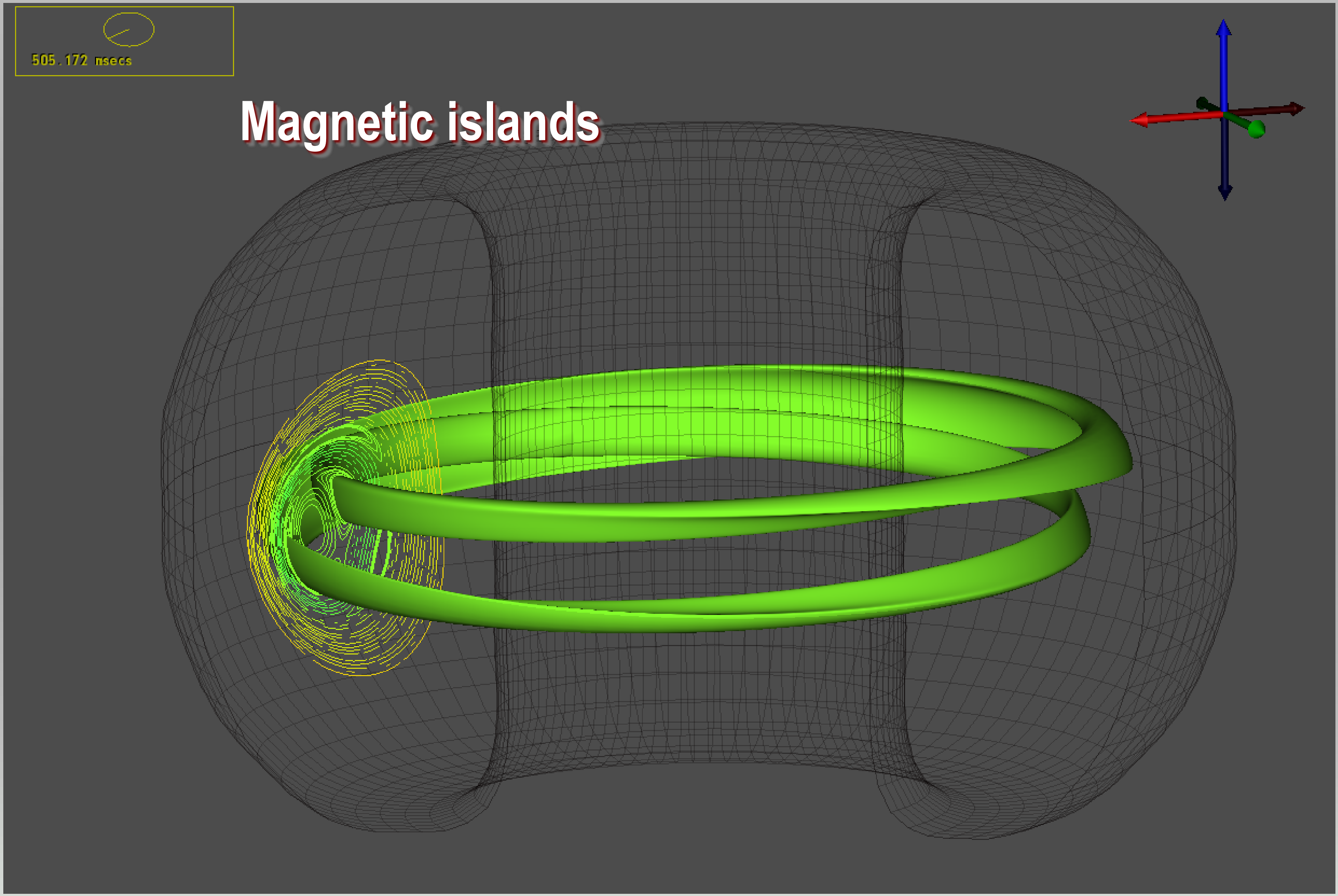
The FTU measuring head

The FTU Cherenkov detector movable support

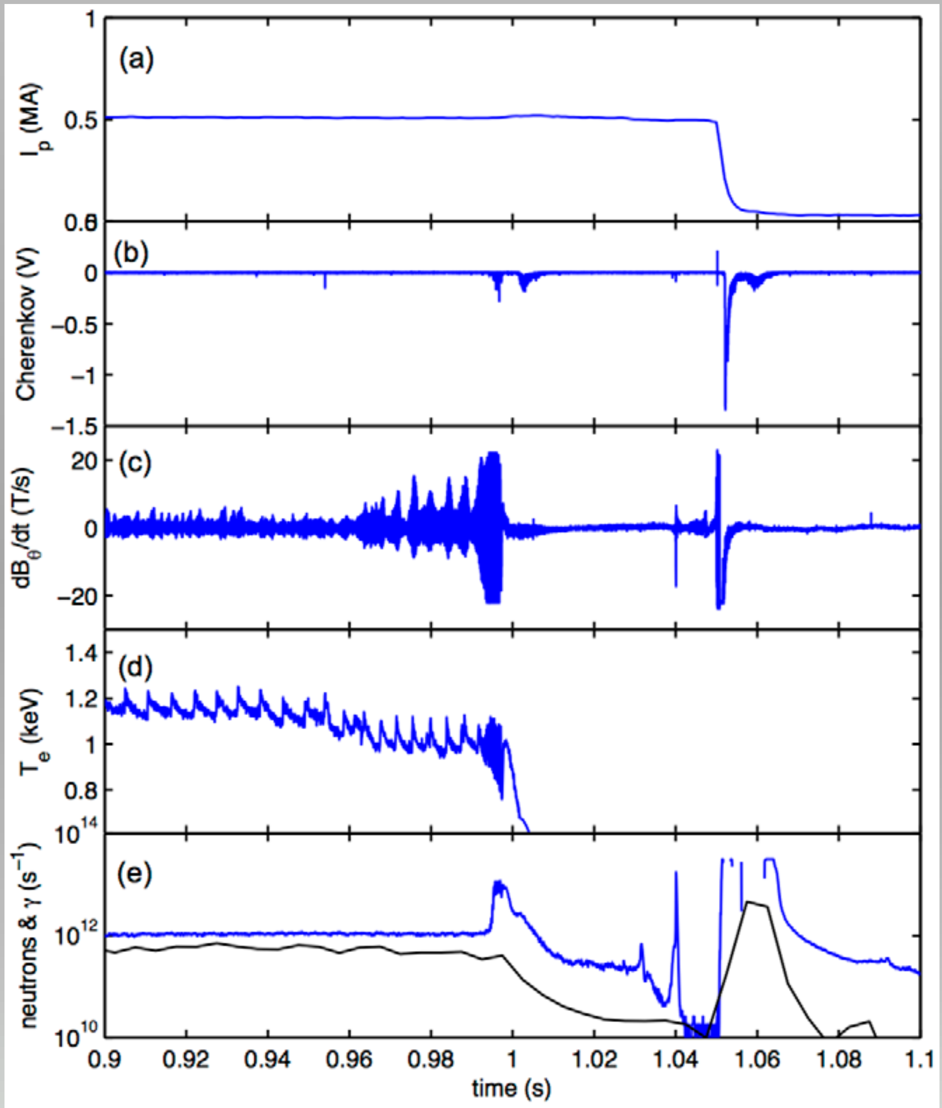
[1] F. Causa, P. Buratti, B. Esposito, G. Pucella, E. Giovannozzi, **L. Jakubowski, K. Malinowski, M. Rabiński, M.J. Sadowski, J. Żebrowski** and the FTU Team “Cherenkov emission provides detailed picture of non-thermal electron dynamics in the presence of magnetic islands”
Nucl. Fusion Vol. 55 (2015) 123021(9pp);

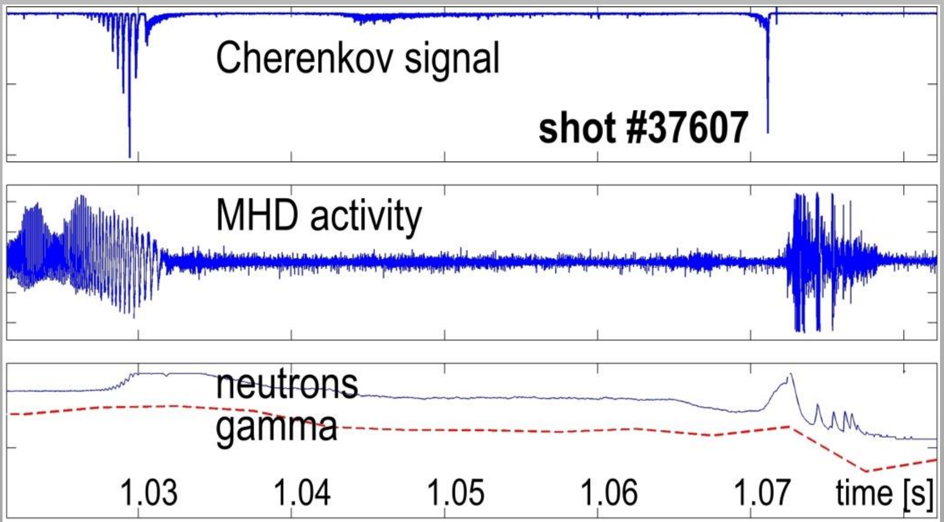


Top view schematic of the equatorial section of FTU with positions of relevant diagnostics [1].


505.172 msecs
Magnetic islands

FTU

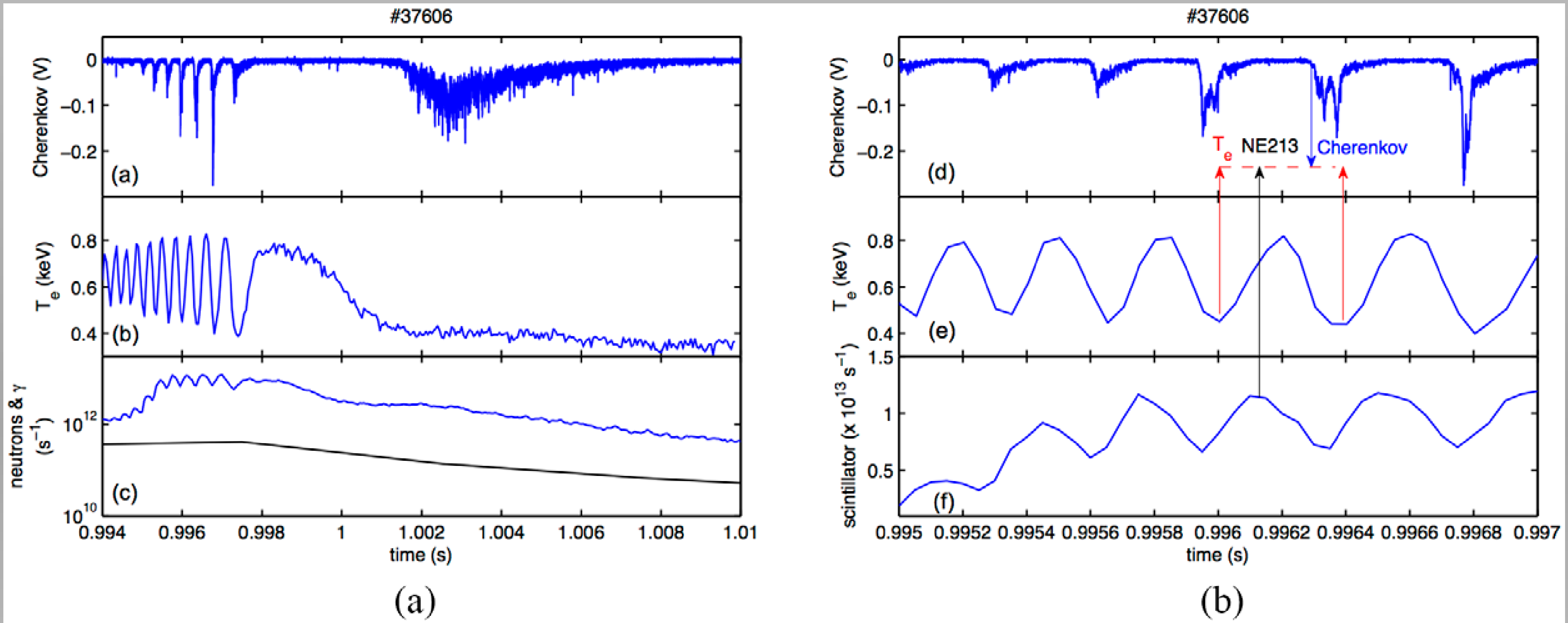




FTU pulse #37607; Traces: Cherenkov signal, Mirnov coils, NE213 and BF3 (brown line) signals.

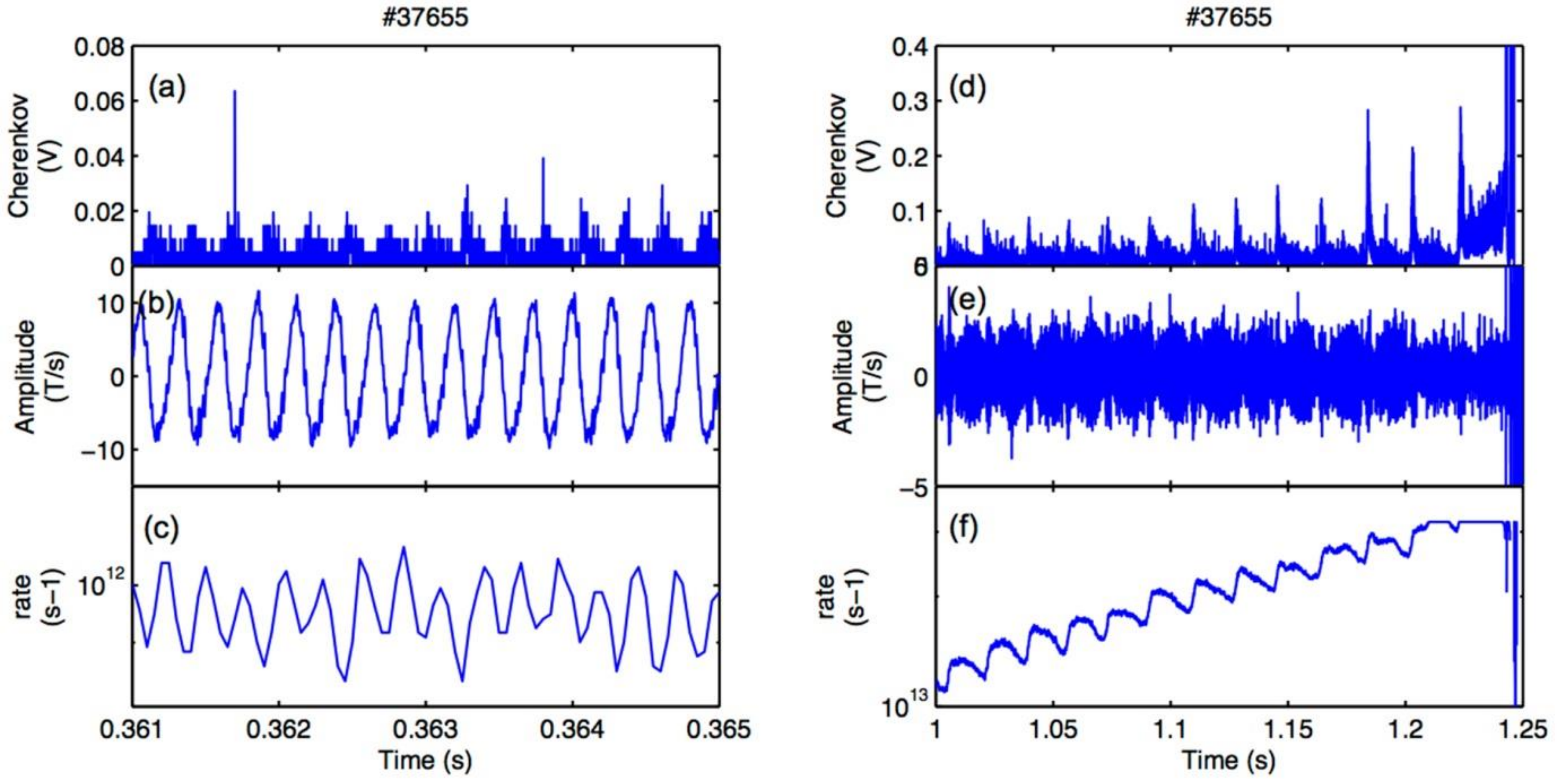
Scenario involving tearing modes (FTU pulse #37606 *B* = 5.3 T, *I* = 0.52 MA): (*a*) plasma current, (*b*) Cherenkov signal, (*c*) Mirnov coils amplitude signal (channel 26), (*d*) NE213 and BF3 (black line) signals [1].

FTU



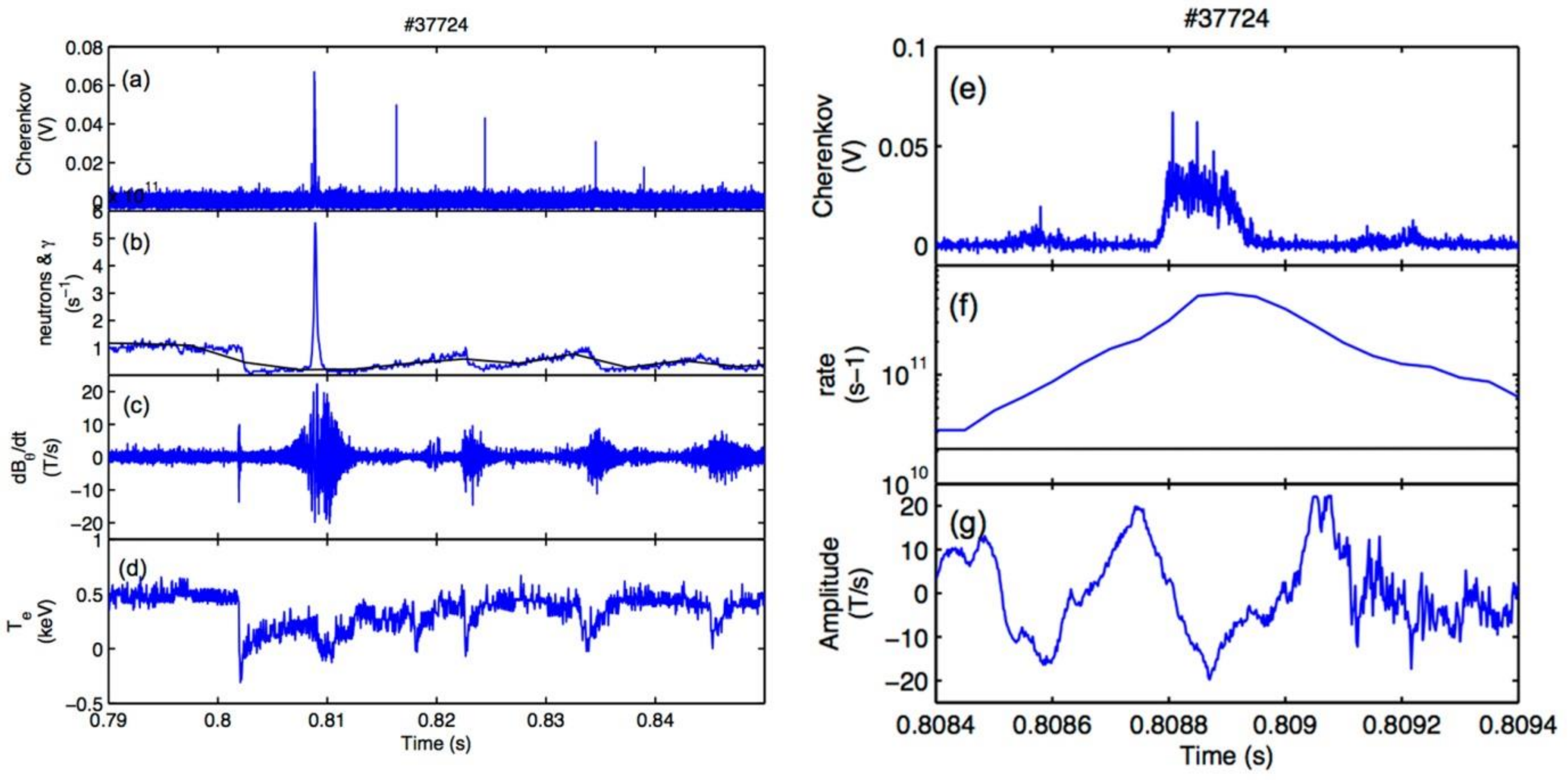
Scenario involving tearing modes (FTU pulse #37606): (*a*–*c*) modulation of (*a*) Cherenkov, (*b*) ECE and (*c*) gamma ray signals during island rotation, growth and locking; and (*d*–*f*) detail showing the relative timing of the same signals [1].

FTU



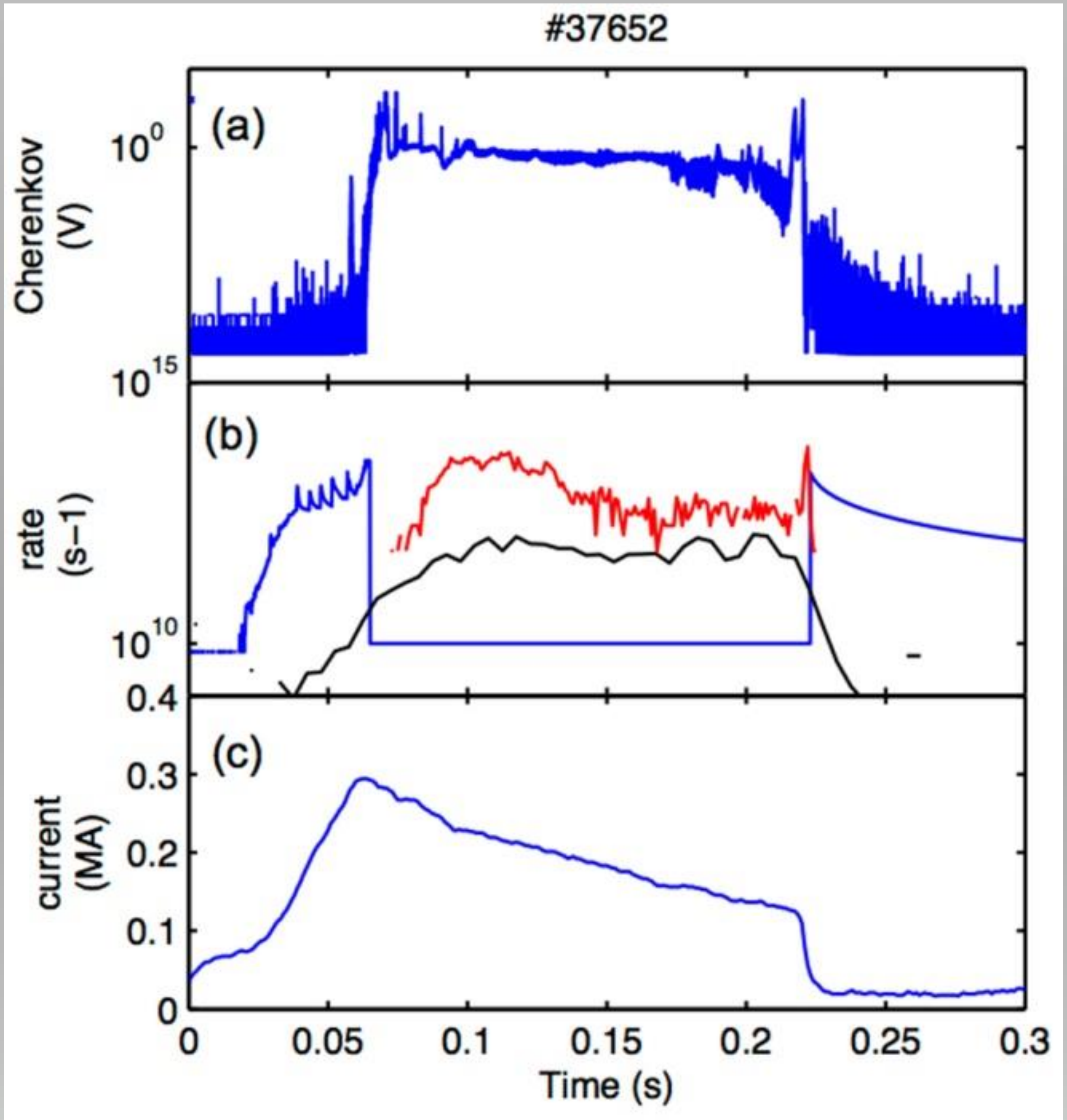
Scenario involving BAE excitation (FTU #37655): (*a*–*c*) initial magnetic island rotation during the growth phase, and (*d*–*f*) the signals obtained in connection with the slow rotation of the island and BAEs. Signals shown: (*a*) and (*d*) Cherenkov signal; (*b*) and (*e*) Mirnov coil signal amplitude (channel 26); (*c*) and (*f*) NE213 signal [1].

FTU



Pellet injection scenario (FTU pulse #37724): (*a*–*d*) overview of the pellet injection event, and (*e*–*g*) zoom-in on plasma dynamics immediately after pellet injection. Signals presented: (*a*) and (*e*) Cherenkov signal, (*b*) and (*f*) NE213 and BF3 (black curve), (*c*) and (*g*) Mirnov coil signal amplitude (channel 26), (*d*) electron temperature (ECE channel 2, *R* = 0.861 m) [1].

FTU



Soft stop for high levels of runaways in a standard discharge (FTU pulse #37652, *B* = 6 T, *I* = 0.5 MA): (*a*) Cherenkov; (*b*) NE213, BF3 (black line) and fission chamber signal (channel neutrn.fc144.statn2) (red curve) signals and (*c*) plasma current [1].

Summary and conclusions

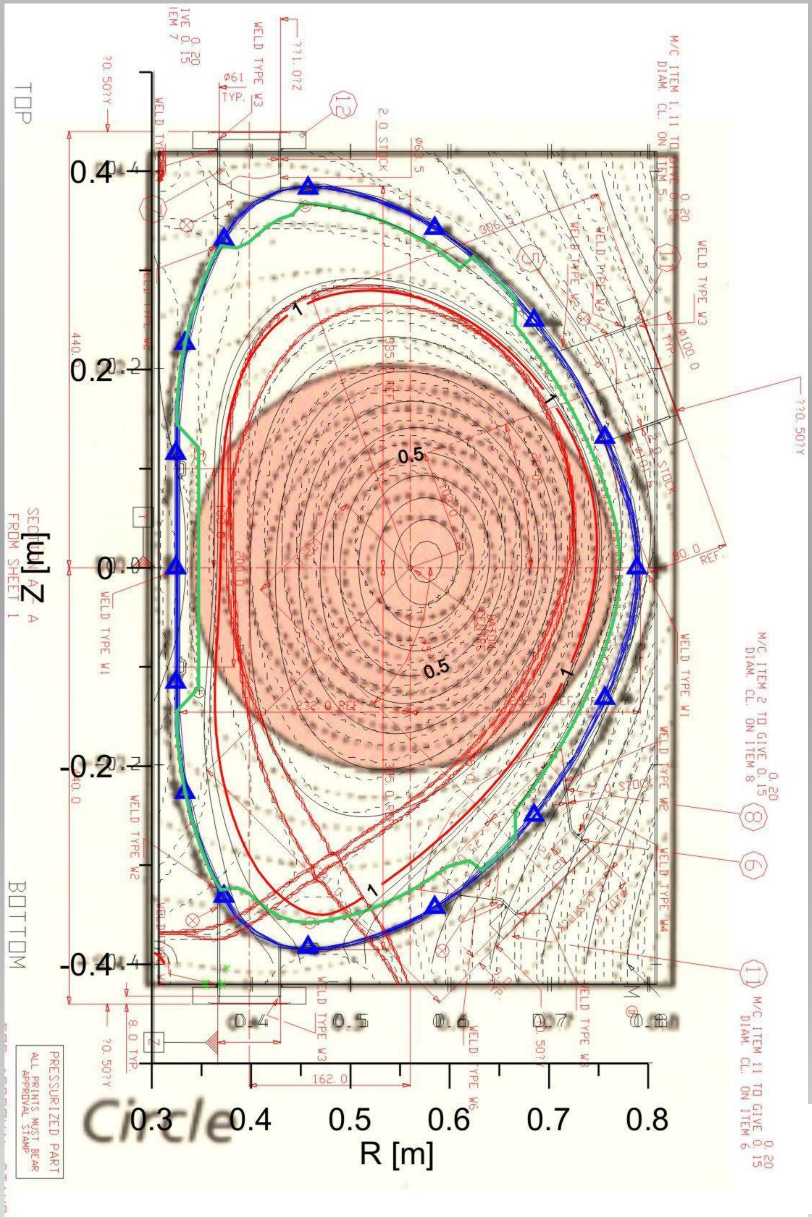
- Cherenkov probe sensitive to RE losses in connection with magnetohydrodynamic activity,

  and generally, with magnetic perturbations and reconnection events.

- Cherenkov probe signals show that RE expulsion mechanisms are due to magnetic perturbation of magnetic island and its amplitude fluctuations.

- Microsecond resolution of Cherenkov diagnostics permits (for the first time with non-magnetic diagnostics) detection of high frequency signals linked to perturbations of magnetic island width, known as beta-induced Alfvèn eigenmodes (BAEs).

COMPASS Tokamak (IPP CAS, Prague)



Cross-section of COMPASS tokamak chamber

The COMPASS tokamak at IPP Prague, the third biggest European device with clear H-mode and the ITER-relevant geometry (linear plasma dimensions of 1:10 to ITER plasma).

Major radius	56 cm
Minor radius	23 cm
Plasma current	< 400k A
Max. magn. field	1.15 Tesla
Pulse lenght	~0.3 sec

EUROfusion WP15-MST2-9 Project „Studies of generation and mitigation of runaway electrons in the COMPASS tokamak” (IPP CAS)

COMPASS

2014 experimental campaign

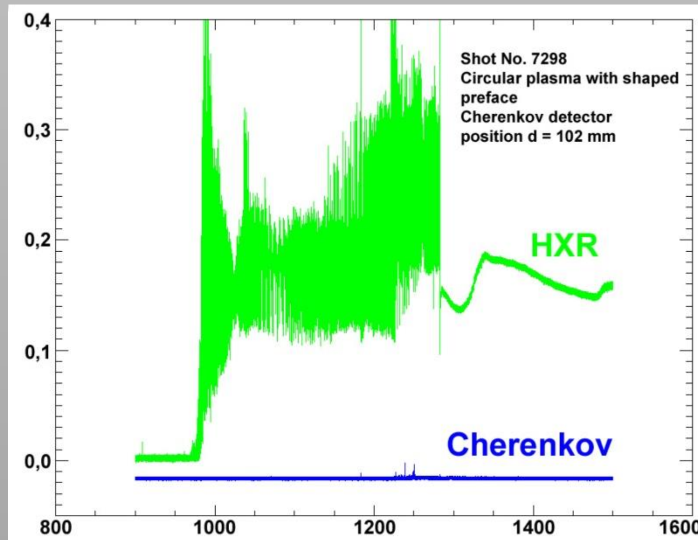
View of single-channel Cherenkov detector for electron beams measurements within COMPASS with movable support.

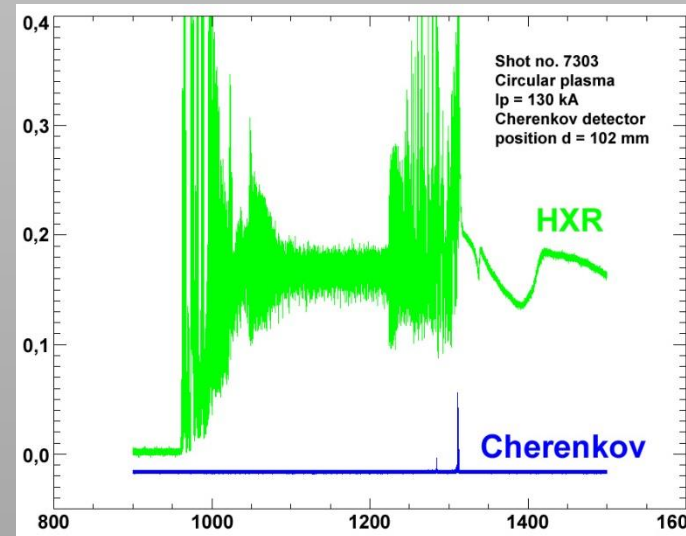
The measuring head: AlN radiator with 10-μm Ti layer, $E_{th} \approx 80$ keV for electrons. Shielding made of graphite**.**

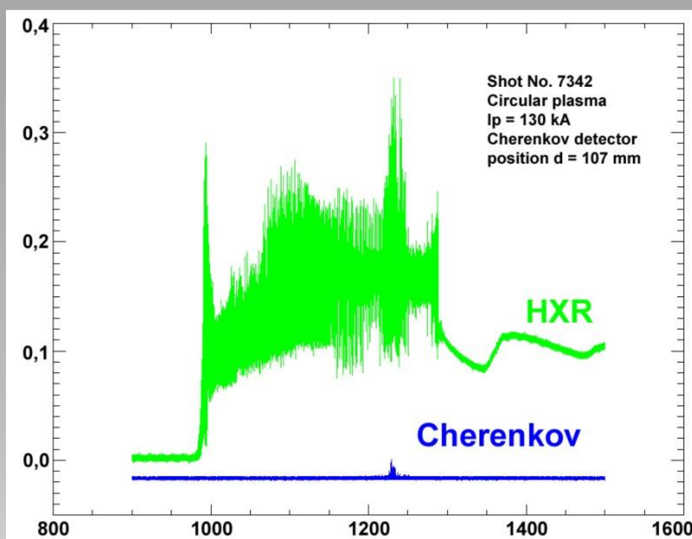
Appearance of detector measuring head after experimental session

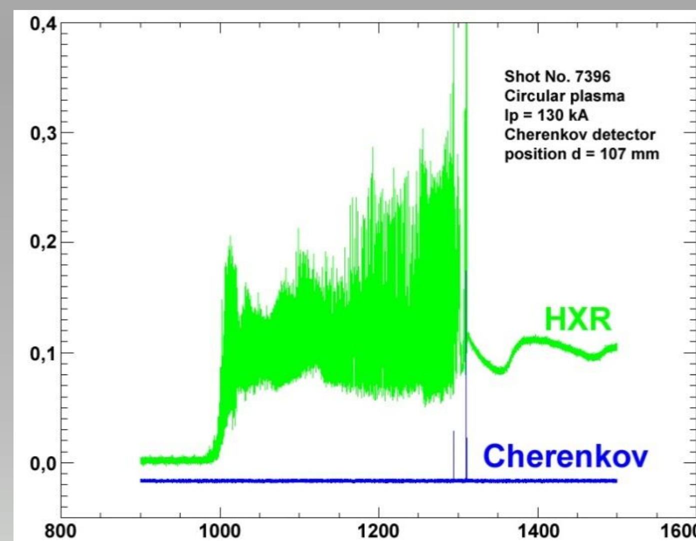
COMPASS

2014 experimental campaign









Fast runaway electrons were recorded during discharge disruption only.

Comparison of hard X-ray signals (HXR) and electron-induced signals from single-channel Cherenkov detector (signal intensity [V] versus time [ms]) for set of four shots.

COMPASS
1st 2015 experimental campaign

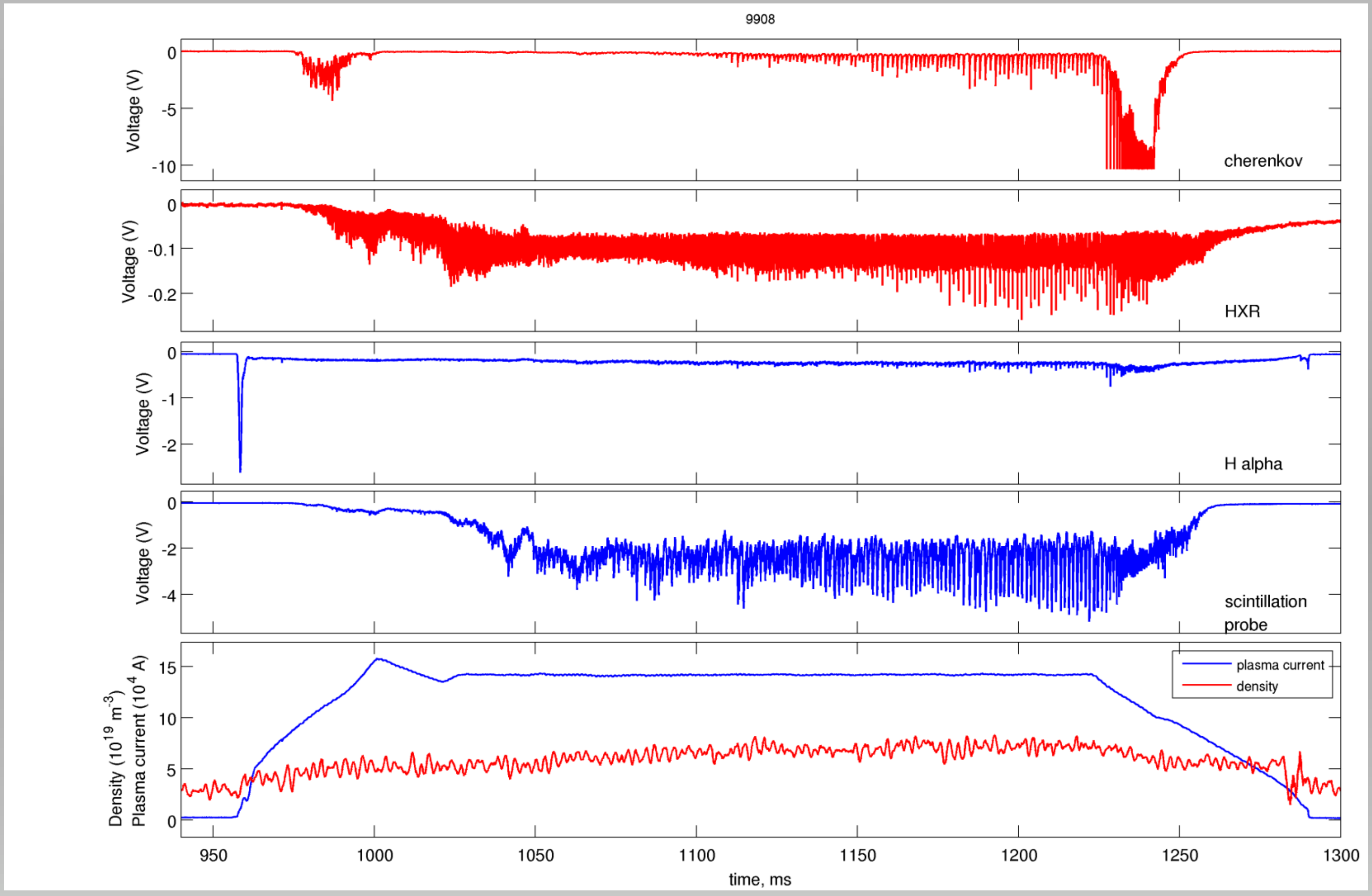
View of single-channel Cherenkov-type detector with diamond radiator.

Characteristics of a diamond radiator:

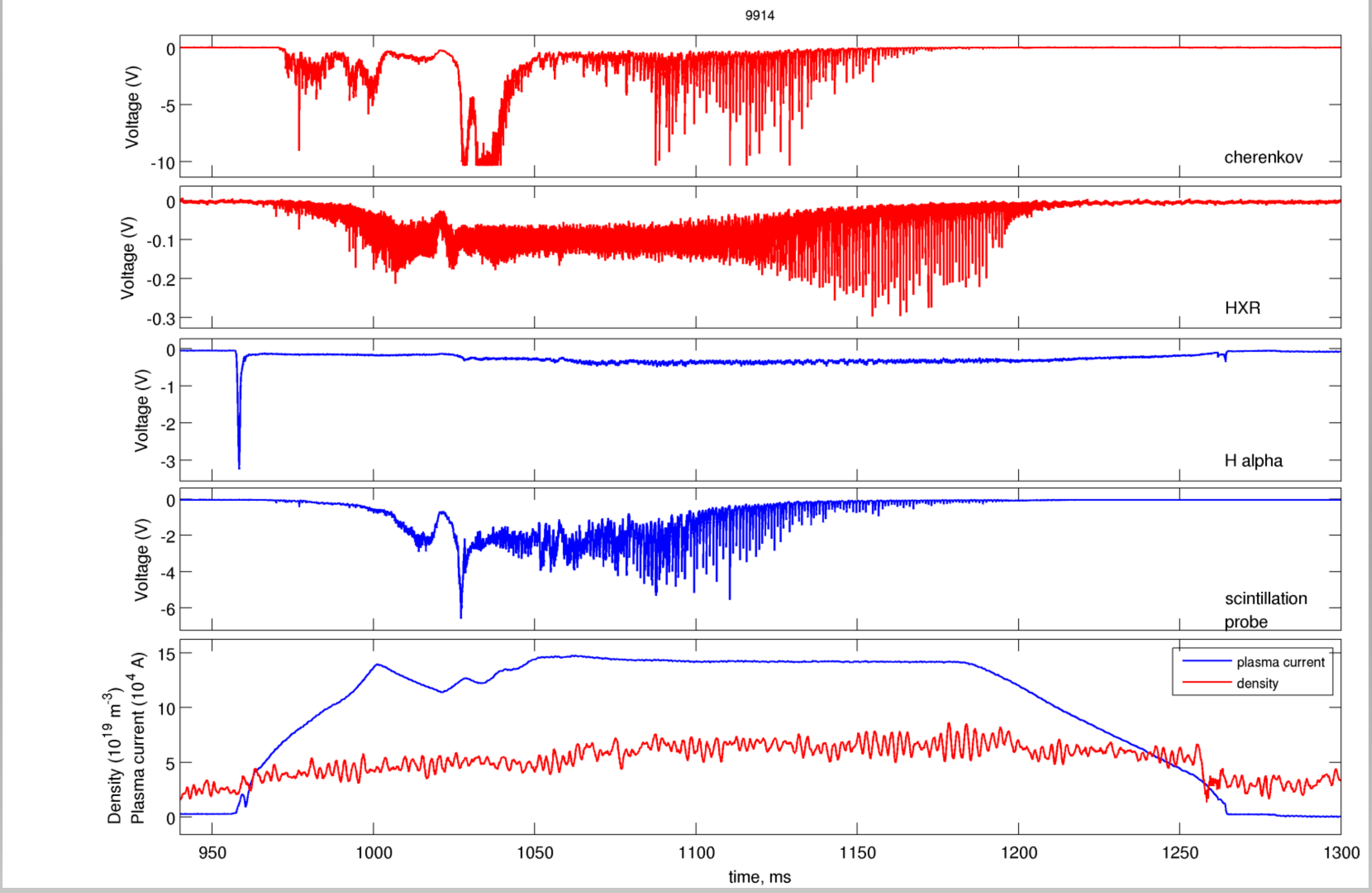
- Diamond of the CVD type;
- Shape – tablet of 8mm in diameter and 1mm in thickness;
- Interlayer upon the surface made of Ti/Pt/Au of thicknesses 100/200/1000nm;
- Lower energy threshold for electrons equal to 58 keV.

COMPASS

1st 2015 experimental campaign



Shot No. 9908 (24/04/2015) Plasma „D-shape" I_P = 155 kA, Δt = 320 ms, R_Cher = 768 mm (d = + 20mm), U_{PMT}(Cher) = -1600V, R_L = ~5 kOhm



Shot No. 9914 (24/04/2015) Plasma circular shape I_P = 144 kA, Δt = 292 ms, R_Cher = 768 mm (d = + 20 mm), U_{PMT}(Cher) = -1600V, R_L = ~5 kOhm

COMPASS

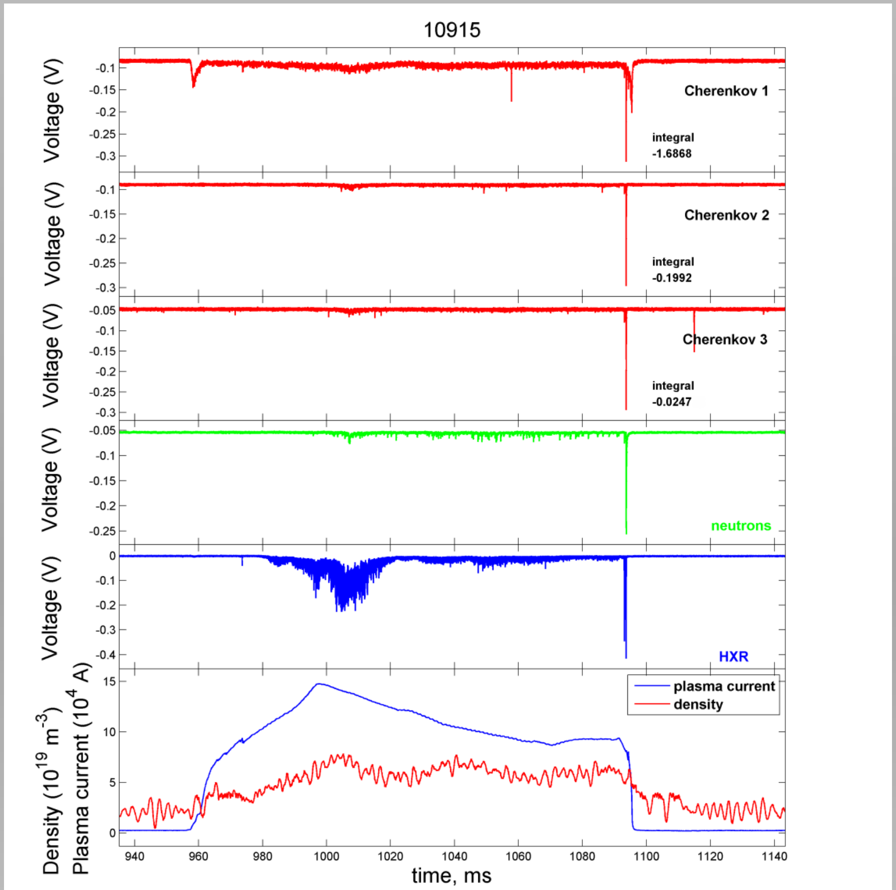
2nd 2015 experimental campaign

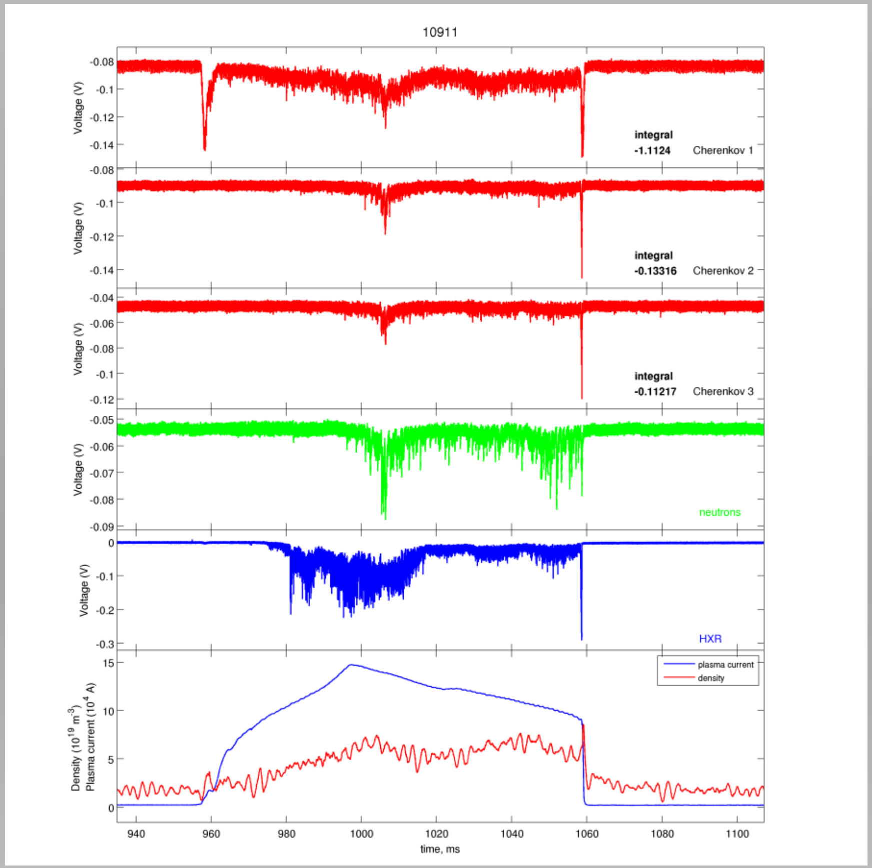
View of three-channel measuring head of Cherenkov-type detector, which was equipped with diamond radiators (left), and view of Cherenkov detector with movable support mounted to COMPASS chamber equatorial port.

Channel No 1	**-**	**E_{thr} = 58 keV**
Channel No 2	**35 μm Mo**	**E_{thr} = 145 keV**
Channel No 3	**77 μm Mo**	**E_{thr} = 221 keV**

COMPASS

2nd 2015 experimental campaign





Shot No. 10915 (16/10/2015) I_P = 99 kA, Δt = 292 ms, R_Cher = 768 mm (d = + 20 mm), U_{PMT}(Cher) = -1600V, R_L = ~5 kOhm

Shot No. 10911 (16/10/2015) I_P = 145 kA, Δt = 102 ms, R_Cher = 768 mm (d = + 20 mm), U_{PMT}(Cher) = -1600V, R_L = ~5 kOhm

Podsumowanie i wnioski

- **Jednokanałowy detektor Czerenkowa został z powodzeniem zainstalowany w FTU w celu monitorowania emisji elektronów ucieczki.**
- **Dane uzyskane z sondy Czerenkowa zostały skorelowane z kilkoma innymi diagnostykami, co umożliwiło przeprowadzenie szczegółowych badań dynamiki nad-termicznych elektronów dla różnych scenariuszy pracy układu oraz identyfikację kluczowych mechanizmów usuwania elektronów ucieczki powodowanych zaburzeniami magnetycznymi.**
- **Zdolność sond Czerenkowa do rejestrowania emisji elektronów ucieczki dla różnych scenariuszy, czyni je potencjalnie interesującymi dla aplikacji służących przewidywaniu i kontroli zjawisk związanych z silną aktywnością MHD i zerwaniami sznura plazmowego.**

Plany na przyszłość

- **Kontynuacja współpracy z FTU, uruchomienie sondy trzy-kanałowej.**
- **Dalsza współpraca z tokamakiem COMPASS, uzyskanie korelacji z niestabilnościami MHD.**
- **Współpraca z tokamakiem WEST (CEA, Cadarache) jako kontynuacja prac na Tore-Supra.**
- **Nawiązanie współpracy z tokamakiem TCV w Lozannie**

Dziękuję za uwagę

Podziękowania:

„Praca naukowa finansowana ze środków finansowych na naukę w latach 2013-2015 przyznanych na realizację projektu międzynarodowego współfinansowanego”