Studies of the nonthermal electrons in high density plasma in the T-10 tokamak

P.V.Savrukhin, A.V.Sushkov

RRC Kurchatov Institute, Moscow, Russia

9th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems

November 10, 2005, Takayama, Japan

RUSSIAN RESEARCH CENTRE KURCHATOV INSTITUTE
РОССИЙСКИЙ НАУЧНЫЙ ЦЕНТР "КУРЧАТОВСКИЙ ИНСТИТУТ"

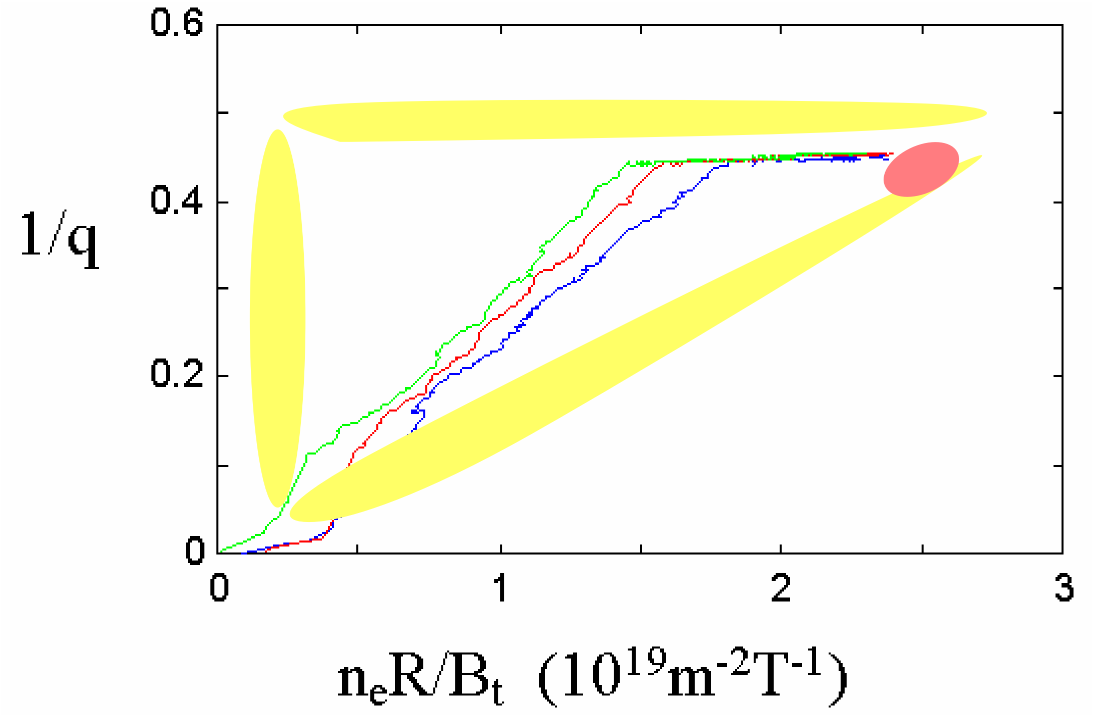
Outline

- **Introduction** *(nonthermal electrons and plasma disruption)*
- **Diagnostic techniques**
- **Experimental studies**
- **Summary**

Non-thermal electrons in tokamaks

Non-thermal electrons are observed in previous **experiments** in tokamaks

- in plasma with **low density**
- at the **initial stage** of the discharge ,
- during powerful **auxiliary heating**,
- **during/after major disruptions**



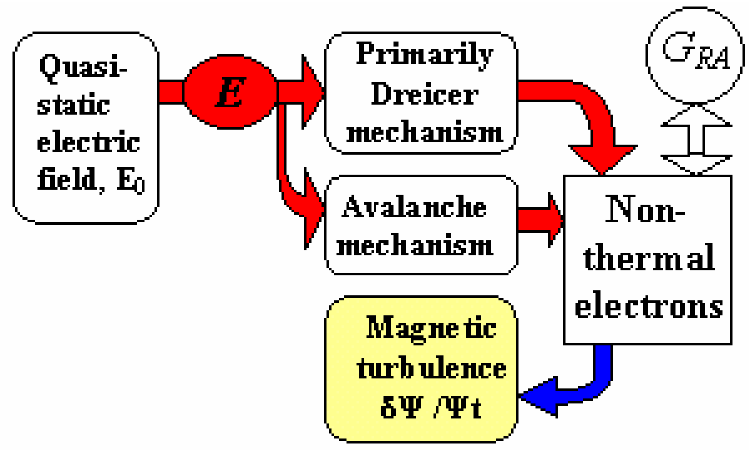
High-density OH plasma is considered in present experiments

Effect of standard runaway formation can be neglected

"…Extensive experimental and theoretical studies have identified physics basis of runaway formation, loss and wall interaction in both present and reactor scale tokamaks…"

[ITER,NF99]

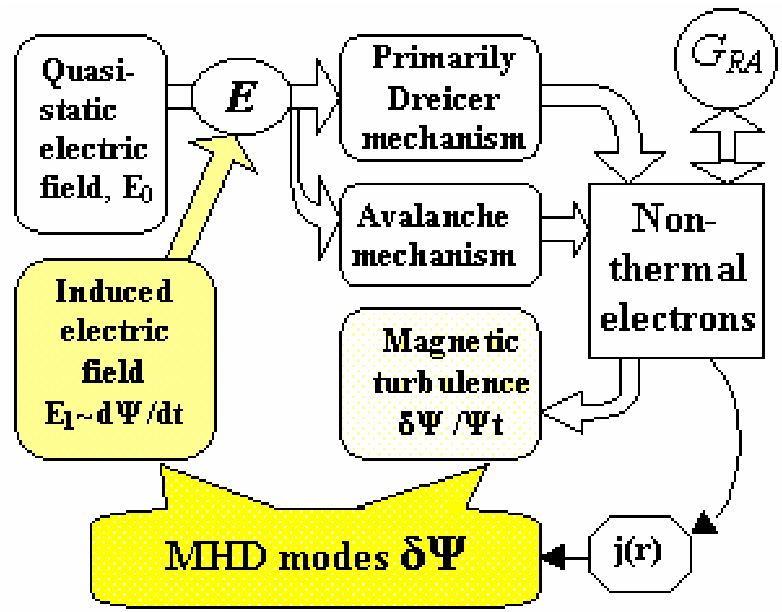
$$\partial N_r/\partial t + \nabla(\mathbf{v}_r N_r) = n_e/\tau_{dr} + N_r/\tau_{av} - \nabla \Gamma_{\mathbf{loss}}$$



Growth of the runaway avalanches depends critically on the primary population of the fast electrons

☑ *The primary beam formation is generally believed to be connected with Dreicer electron acceleration in longitudinal electric field after an energy quench*

Analysis have indicated, however, that primary electron acceleration can be connected with strong electric fields (E up to 50 V/m) induced during magnetic reconnection



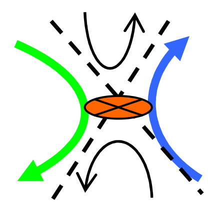
$$dN_r/dt = n_e/\tau_{dr} + N_r/\tau_{av} - N_r/\tau_{loss}$$

$$\tau_{dr}^{-1} \approx 0.3\ \nu_e\ \varepsilon_d^{-3(Zeff+1)/16} \exp\left(-1/4\varepsilon_d - ([Z_{eff}+1]/\varepsilon_d)^{1/2}\right)$$

$$\varepsilon_d = E/E_c \qquad E_c = e^3 n_e Z_{eff} \ln\Lambda/(4\pi\varepsilon_0^2 m_e v_{th}^2)$$

$$\tau_{av}^{-1} \approx eE/2m_e c \ln\Lambda a(Z_{eff})$$

$$\tau_{loss}^{-1} \approx D_m/\delta r^2 \qquad D_m \approx (\pi R_0 q v_r)(\delta B/B_t)^2 \qquad \delta r \sim w_1$$



$$\delta B/B_t = s_1 w_1^2/(16 r_1(R_0 + r_1))$$

$$E_1 \sim (1-q_0) r_1 B_{p1}/4t_{crash}$$

MHD modes :

- are considering generally as a source of magnetic turbulence and loss mechanism of the runaway electrons
- can in fact provide seed population of non-thermal beams with subsequent formation of the strong runaway avalanches

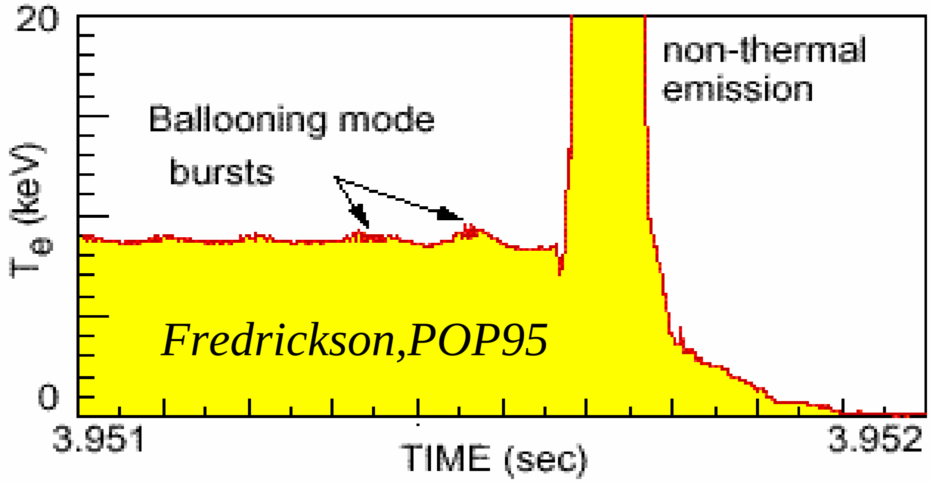
Non-thermal electrons and disruptions

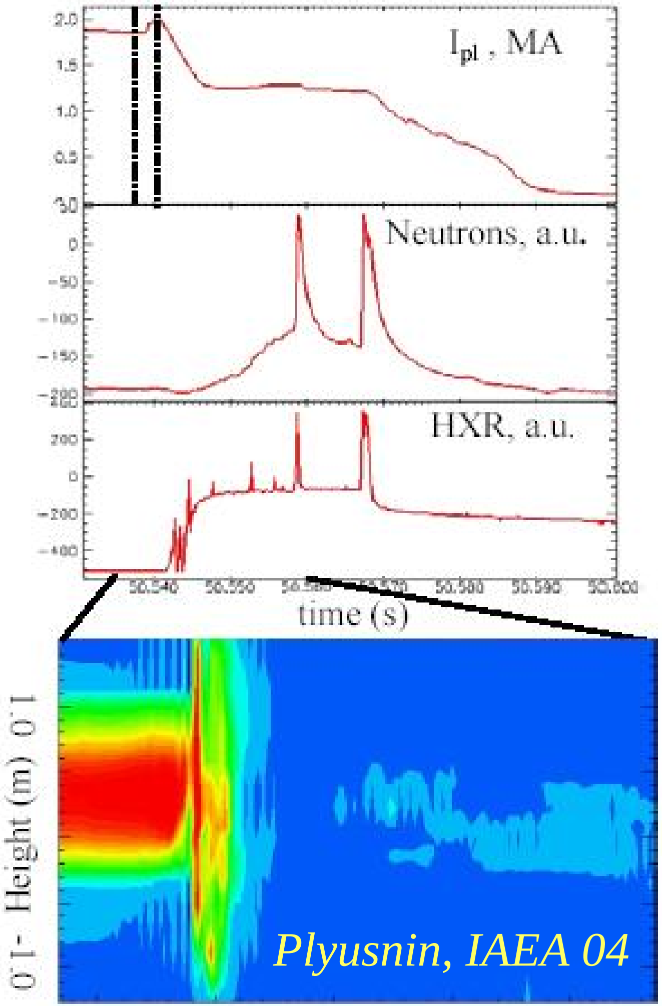
Acceleration of electrons to suprathermal energies, E_γ~>*100keV*, is a typical feature of plasma disruptions

- **disruptions at high I_p, B_t (JET)**

  $I_{RA} \sim 0.6\, I_p$

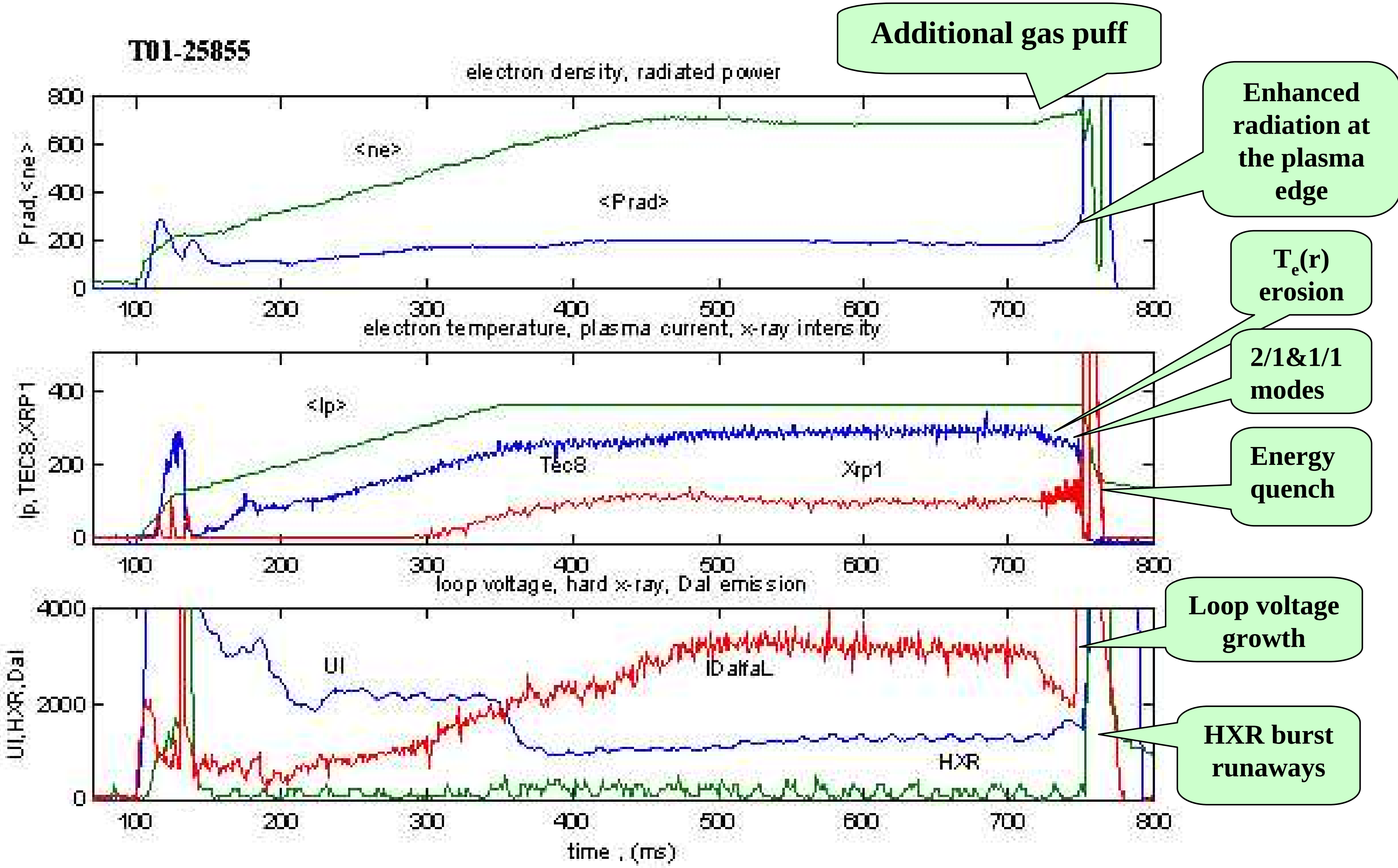
- **disruptions at high beta (TFTR)**



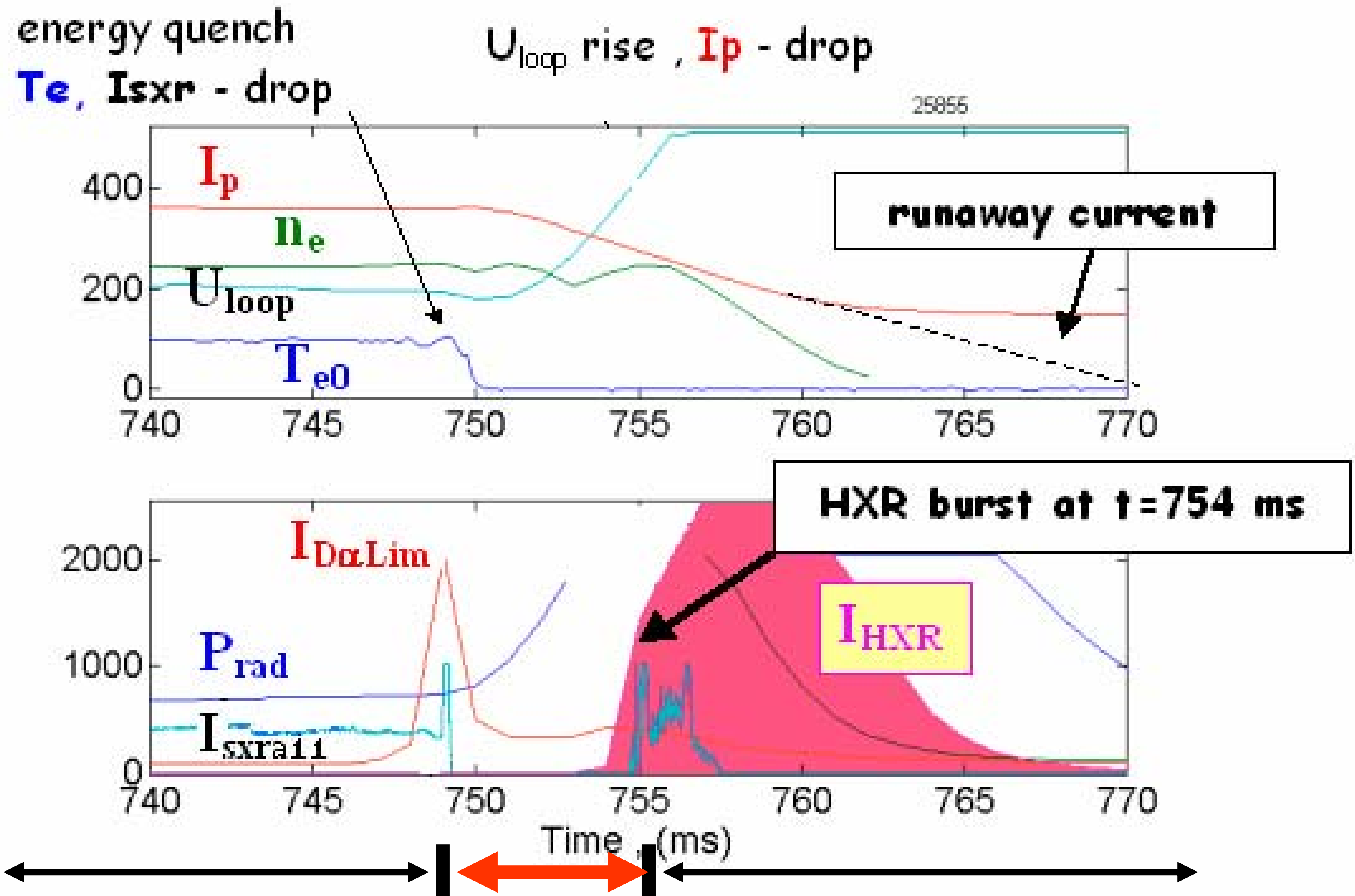


Previous experiments:
Detailed analysis of the precursor perturbations
Scattered data on the post-quench analysis

RADIATIVE DENSITY LIMIT DISRUPTION IN T-10 OHMICALLY HEATED PLASMA



Standard hard x-ray burst are observed 5ms AFTER the energy quench during runaway interaction with the “wall”

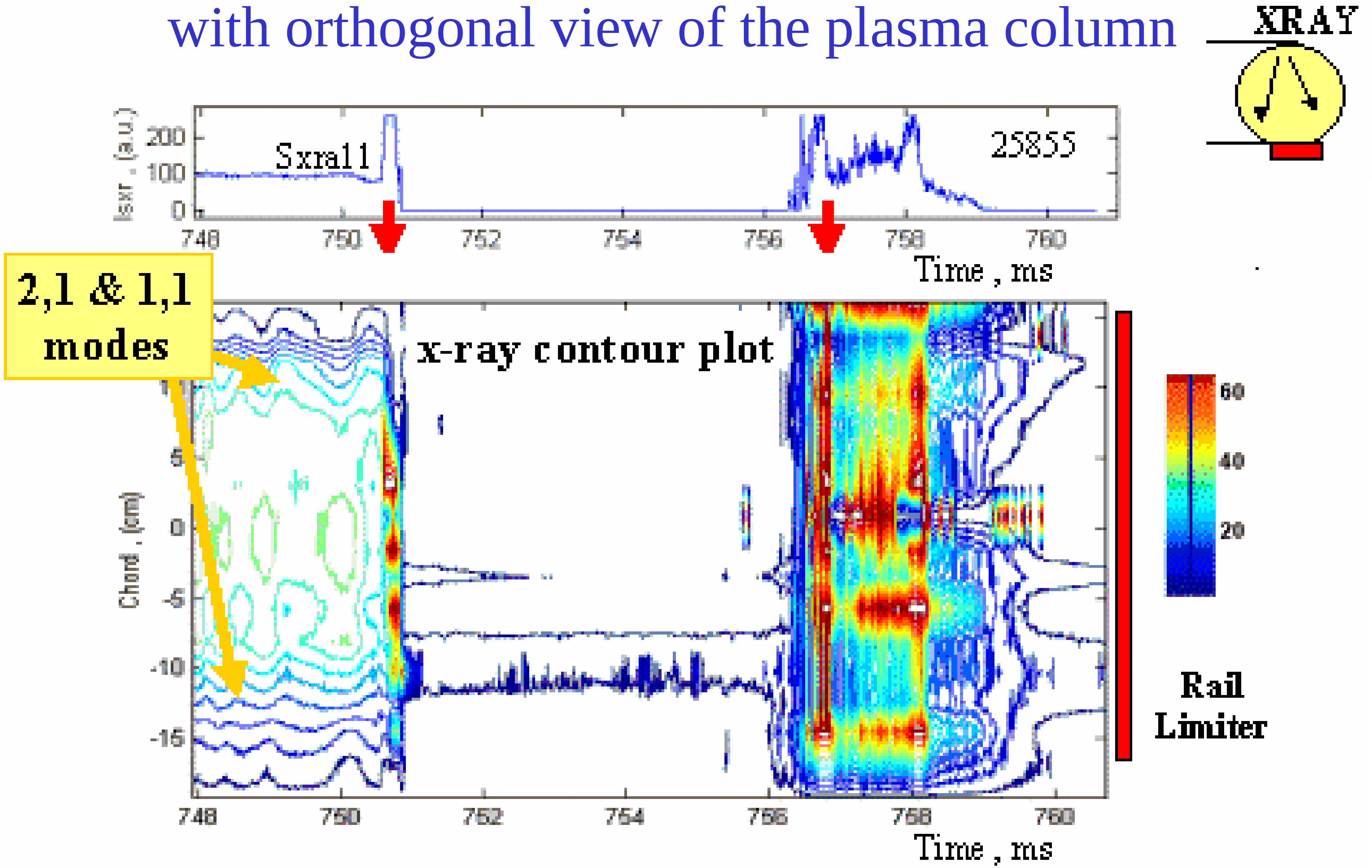


Stage I
pre-disruptive

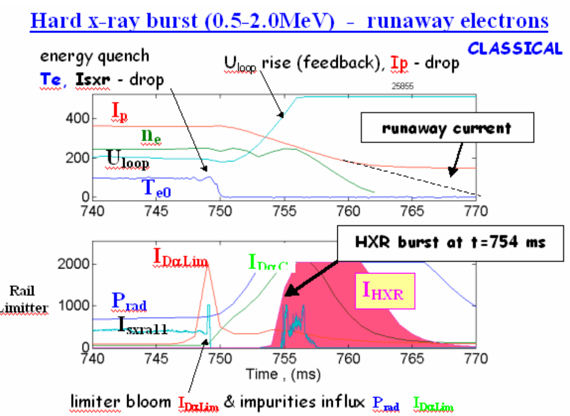
Stage II energy quench and runaway formation

Stage III
runaway avalanche

Structure of the bursts during runaway wall interaction can be identified using standard X-ray imaging systems with orthogonal view of the plasma column

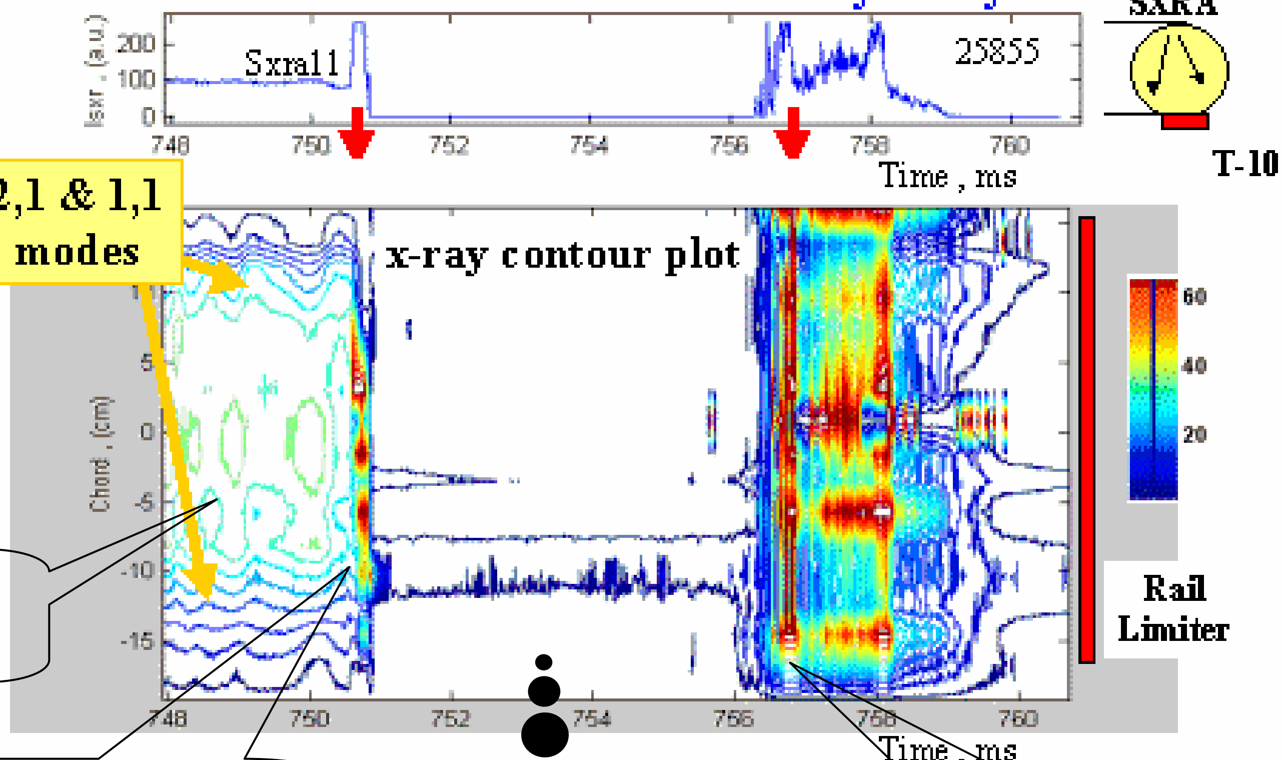


Identification of the non-thermal electrons in-flight is a complicated task



"Classical" hard x-ray bursts during density limit disruption

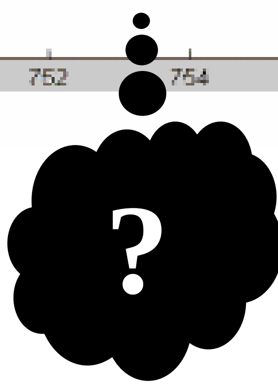
observed with conventional x-ray arrays



2,1 & 1,1 modes

Pre-disruptive plasma

X-ray spikes during the first energy quench



X-ray spikes during the runaway-wall interaction

Mystery of the runaway growth

Objectives of present experimental studies:

Analysis of formation and loss of the non-thermal electron beams during disruption instability in the T-10 tokamak

The following questions are addressed in the experiments

- What is the structure of the internal MHD perturbations at the onset of the non-thermal spikes?
- What is the origin of the primary non-thermal x-ray bursts observed during the first energy quench?
- What is the structure of the secondary x-ray bursts?
- What determines stability of the runaway beam?
- Characterisation of the runaway - wall interaction?

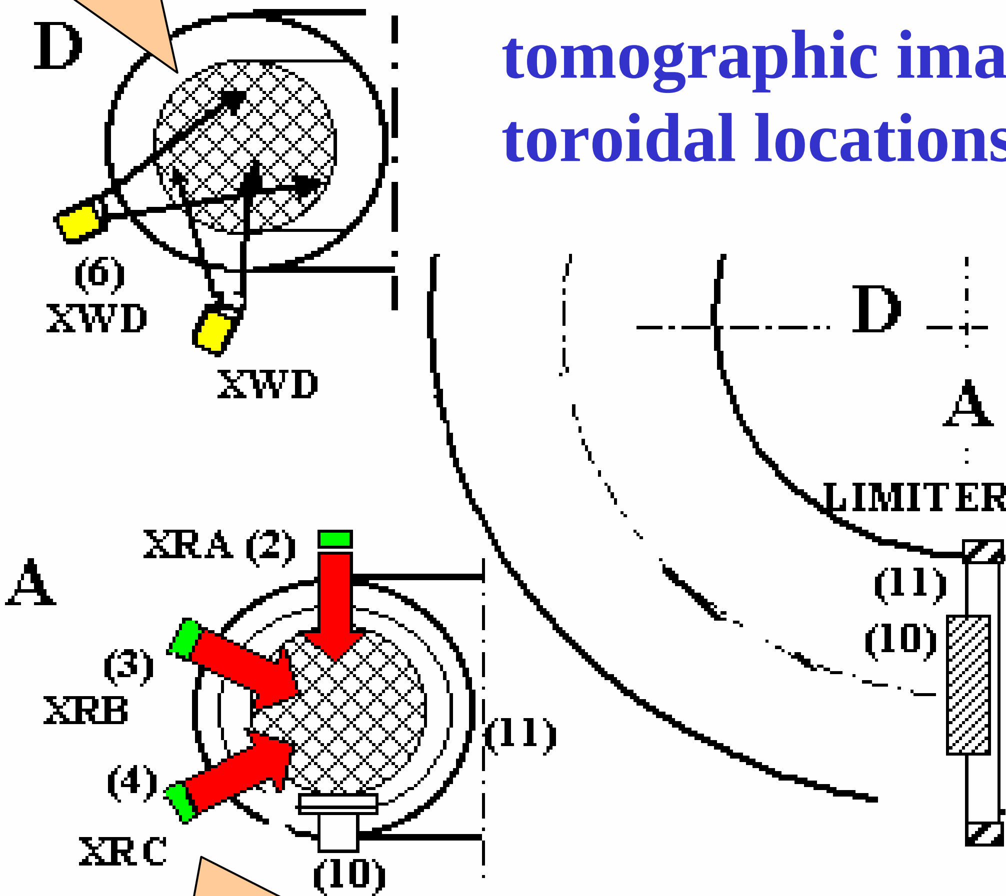
Do we have adequate diagnostics for reliable identification of the localized suprathermal electrons beams in a tokamak plasma?

Outline

- **Introduction**
- **Diagnostic techniques** *for studies of the nonthermal electrons during a disruption*
- **Experimental studies**
- **Summary**

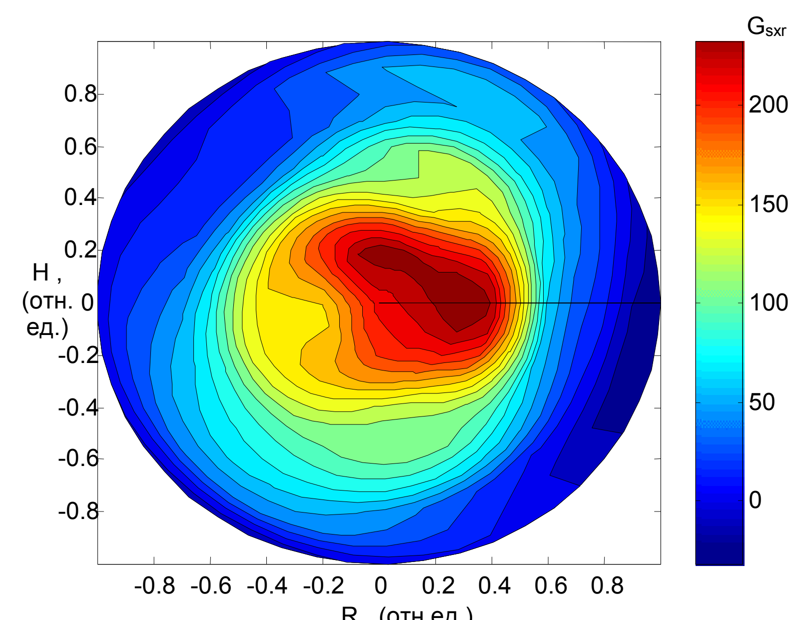
Internal structures of the MHD modes are identified in T-10 tokamak using soft x-ray tomographic imaging systems placed at two toroidal locations

x-ray gas detectors XWD (32+32)

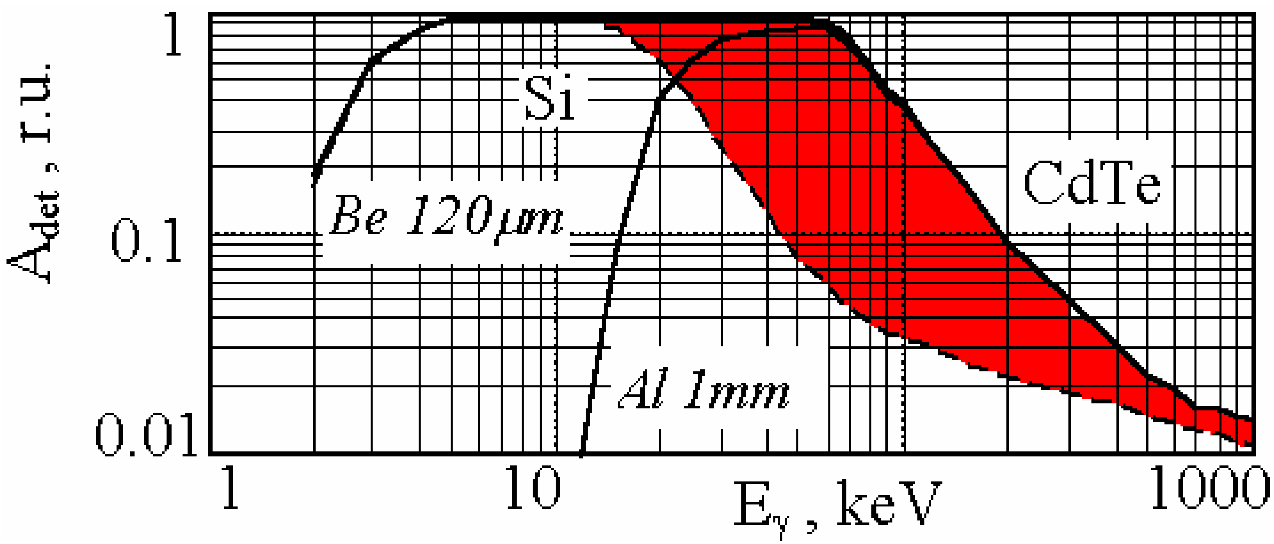


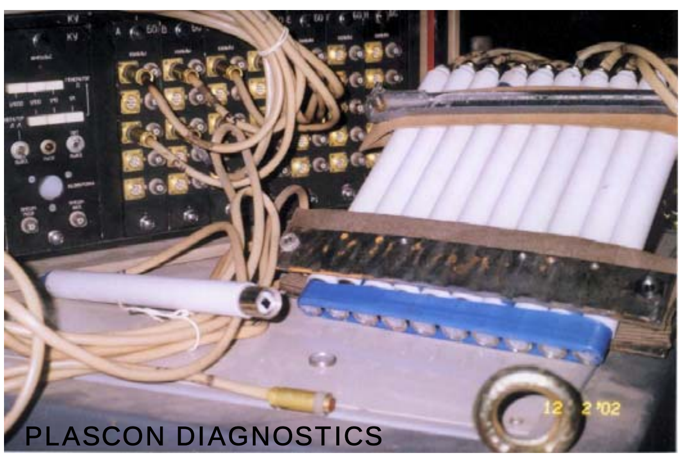
Si surface barrier tomographic arrays (20+19+19 detectors)

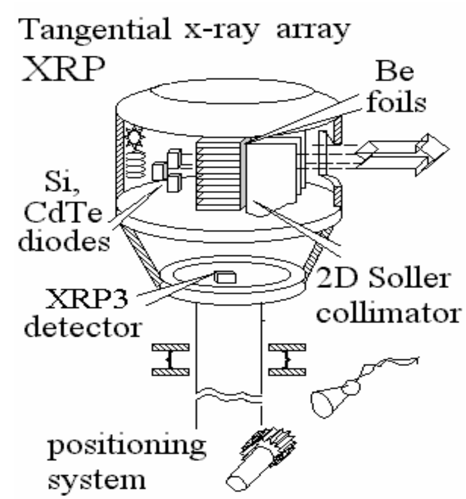
- *Reliable tomographic reconstruction of the MHD modes (up to m=2)*
- *Limited energy range E_γ<15keV*



CdTe detectors - enhanced sensitivity at 10 - 200 keV



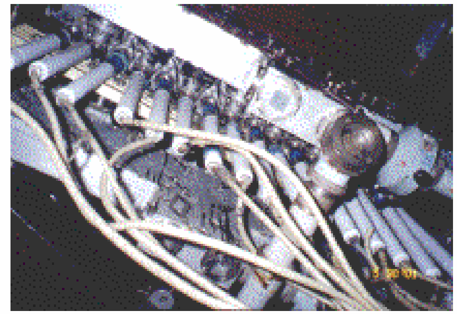


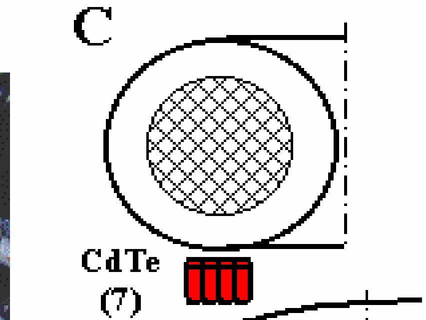


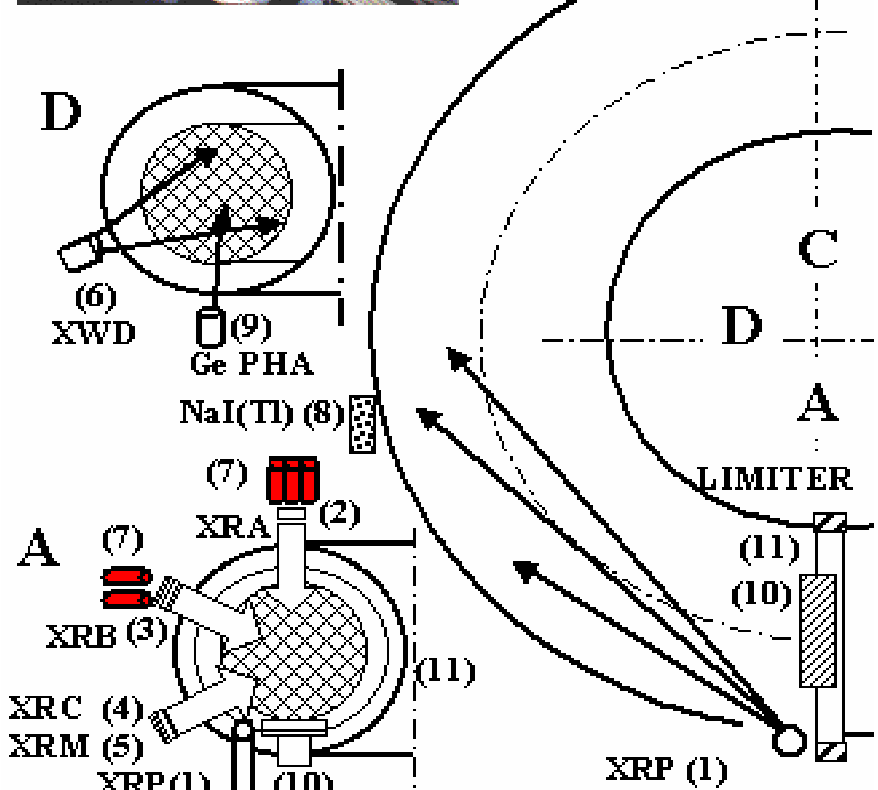
Rev. Sci. Instrum., 73 (2002) 4243
Rev. Sci. Instrum., 72 (2001)1668

CdTe detectors with orthogonal view of the plasma column are placed at various locations around the torus

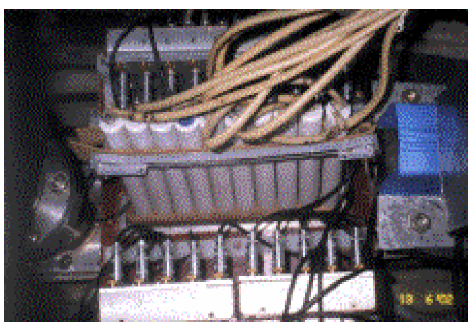
array of 16 detectors was placed temporally at the interferometer waveguides (E_γ>40keV)



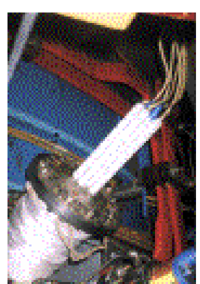




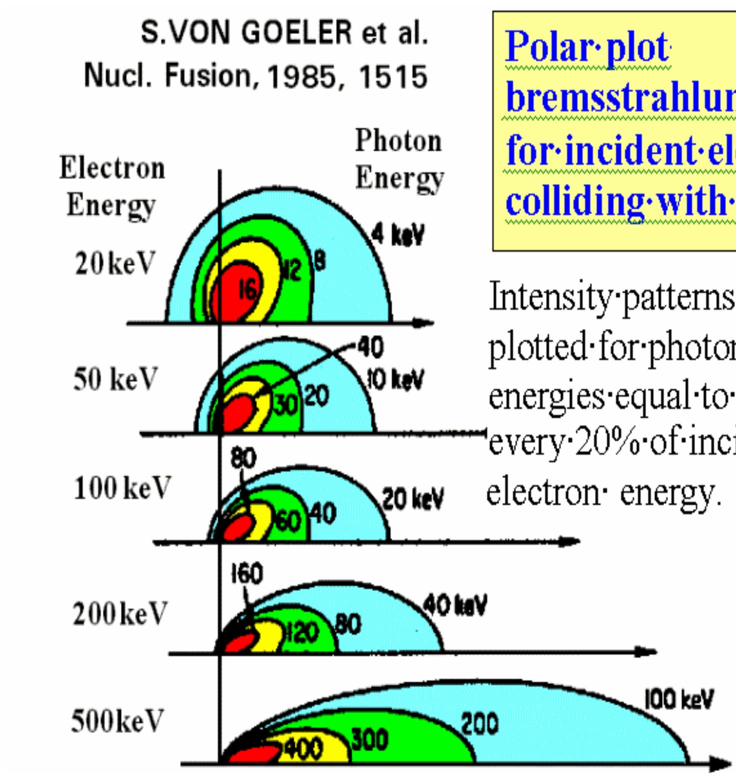
array of 10 detectors vertical view Θ = +90°



array of 6 detectors vertical view Θ = +30°

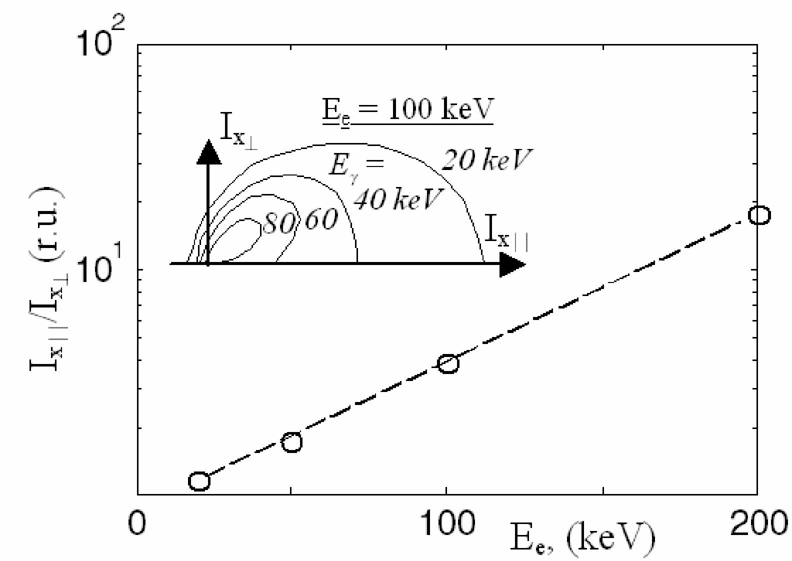


CdTe detectors with orthogonal view of the plasma column are insensitive to the non-thermal electrons with x-ray emission in limited forward cone along the electron lines of flight



Polar plot bremsstrahlung intensity for incident electrons colliding with protons

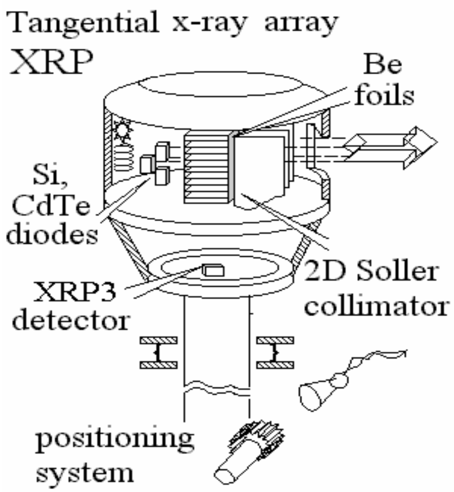
Intensity patterns are plotted for photon energies equal to every 20% of incident electron energy.

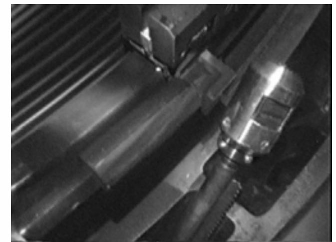


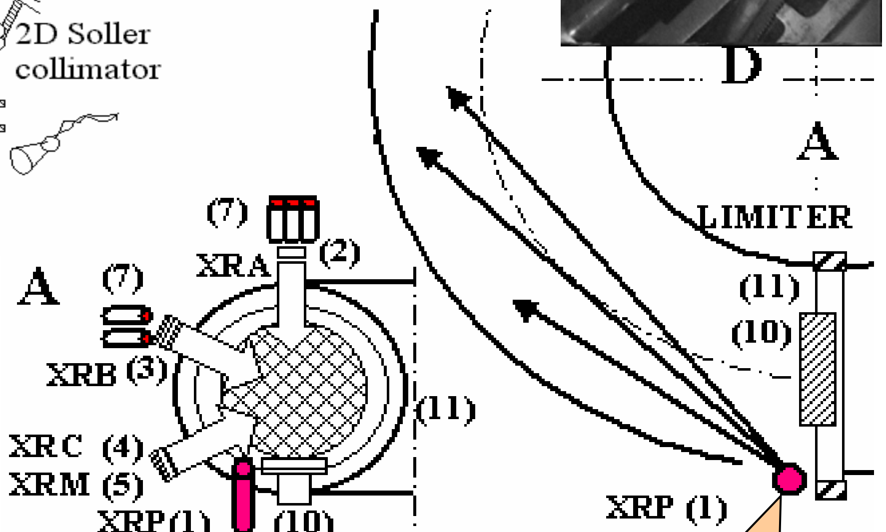
for original data see [*S.VonGoeler, et al., Nucl. Fusion* **25**, *(1985) 1515*]

X-ray measurements in direction tangential to the plasma column can provide enhanced sensitivity to the non-thermal electrons

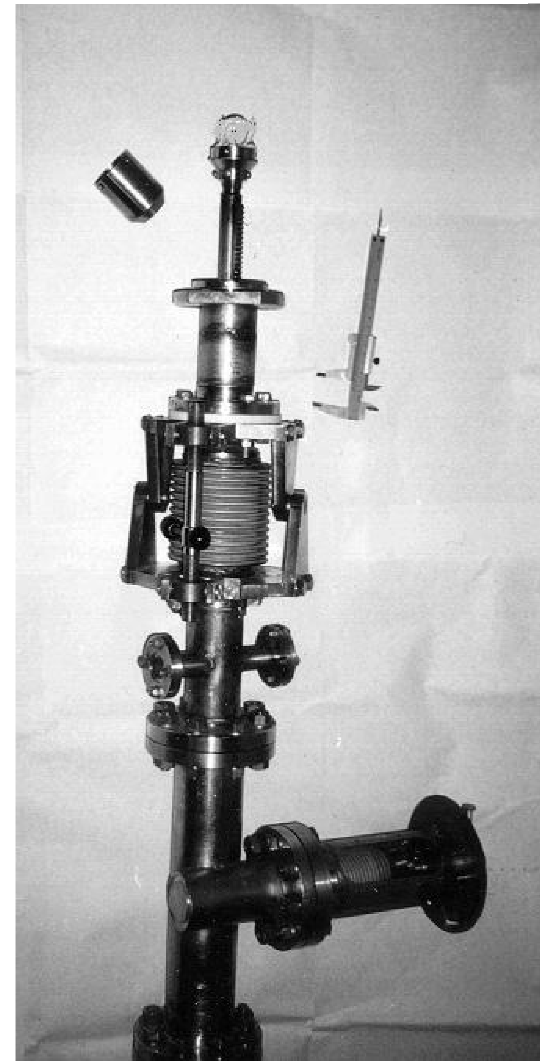
CdTe detectors with tangential view of the plasma column are placed inside the T-10 vacuum vessel

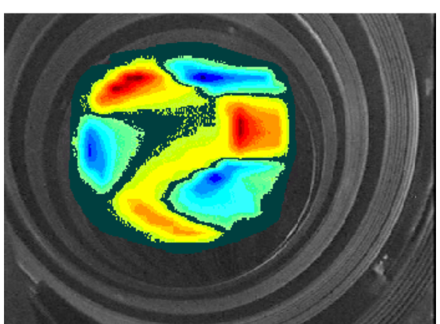




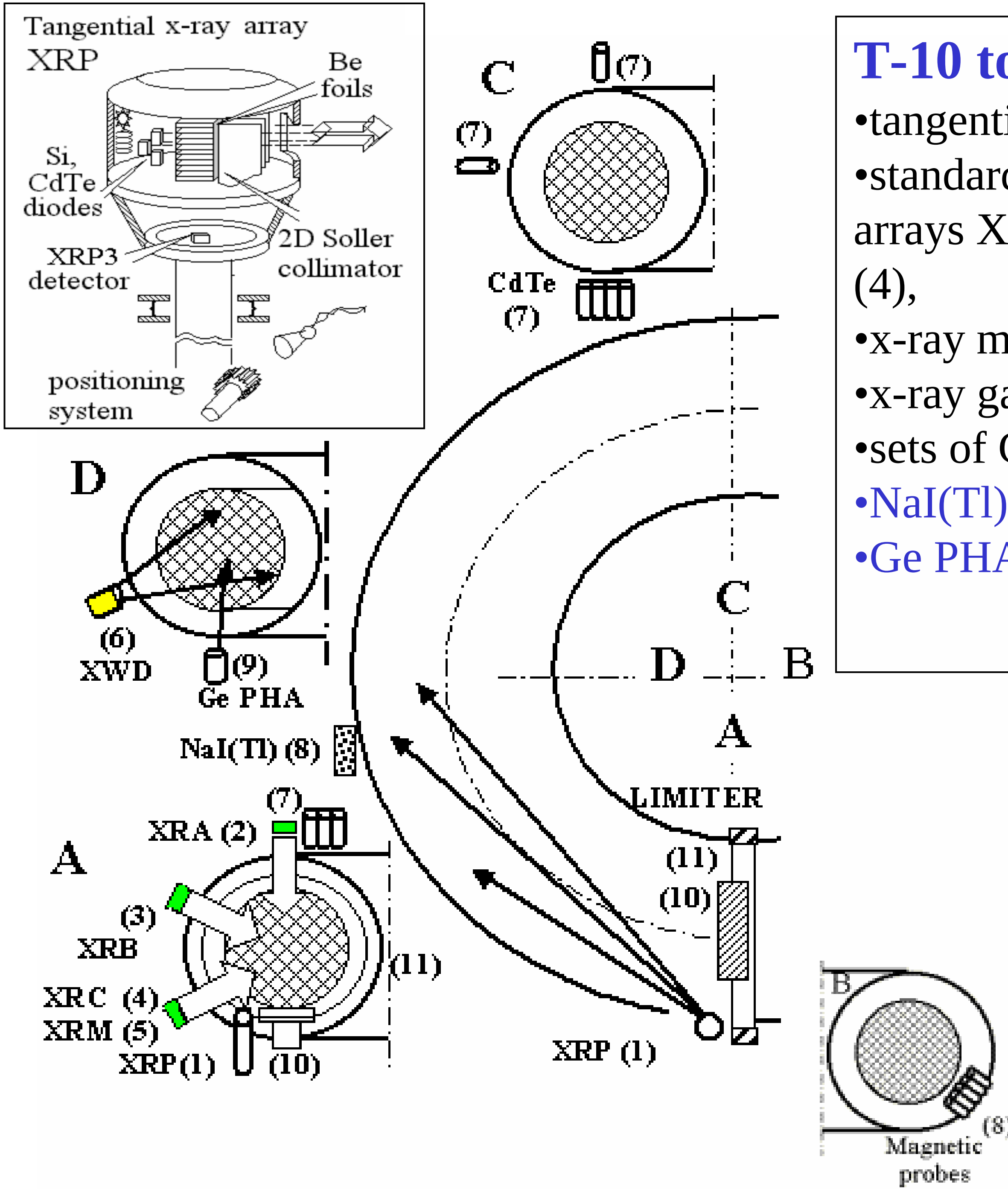


In-vessel array
3 *Si* and 1 *CdTe*
detectors





Tangential view (simulation)



T-10 tokamak (R=1.5,a=0.3m)

- tangential x-ray array XRP (1),
- standard x-ray tomographic arrays XRA (2), XRB (3), XRC (4),
- x-ray matrix array XRM (5),
- x-ray gas detector XWD (6),
- sets of CdTe detectors (7).
- NaI(Tl) monitor (8) and
- Ge PHA system (9).

Outline

- **Introduction**
- **Diagnostic techniques**
- **Experimental studies**

Structure of the internal MHD perturbations at the onset of the non-thermal spikes

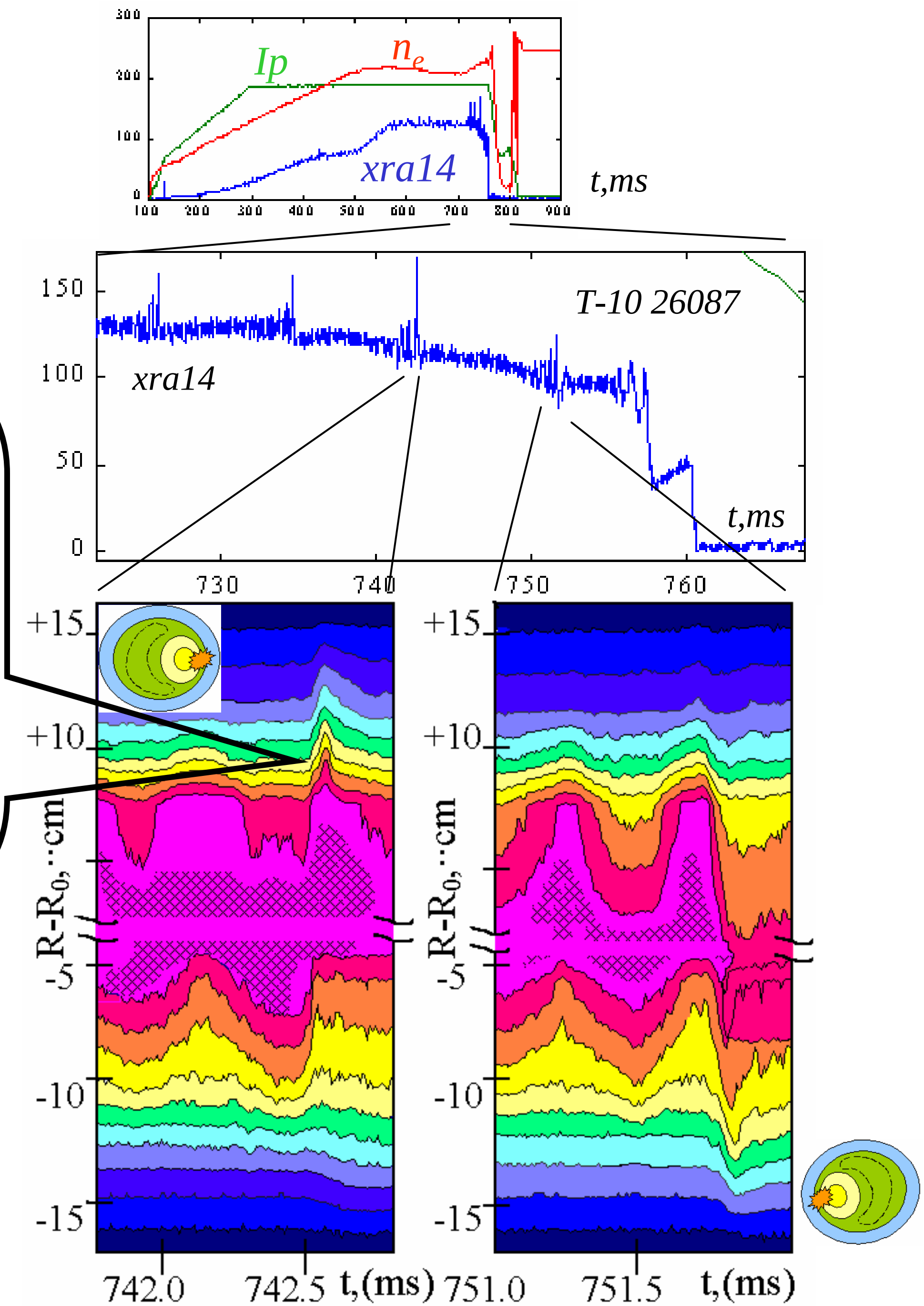
Origin of the primary non-thermal x-ray bursts observed during the first energy quench

Structure of the secondary x-ray bursts

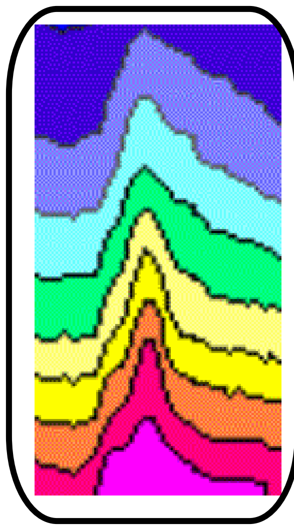
Stability of the runaway beam

- **Summary**

Energy quench at the density limit is proceeded by series of sawteeth



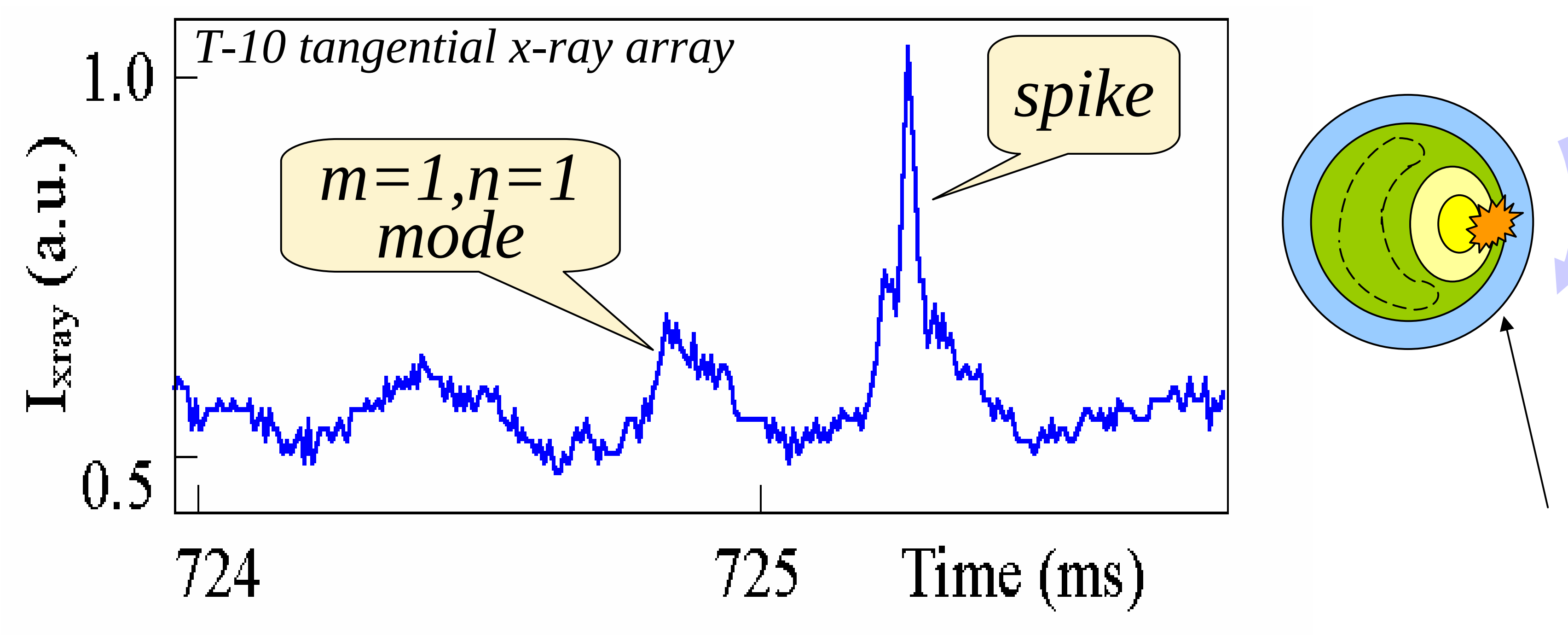
The sawteeth are accompanied with spikes (“rib”) superimposed with the m=1 mode



The spikes are observed at low and high field side of the torus

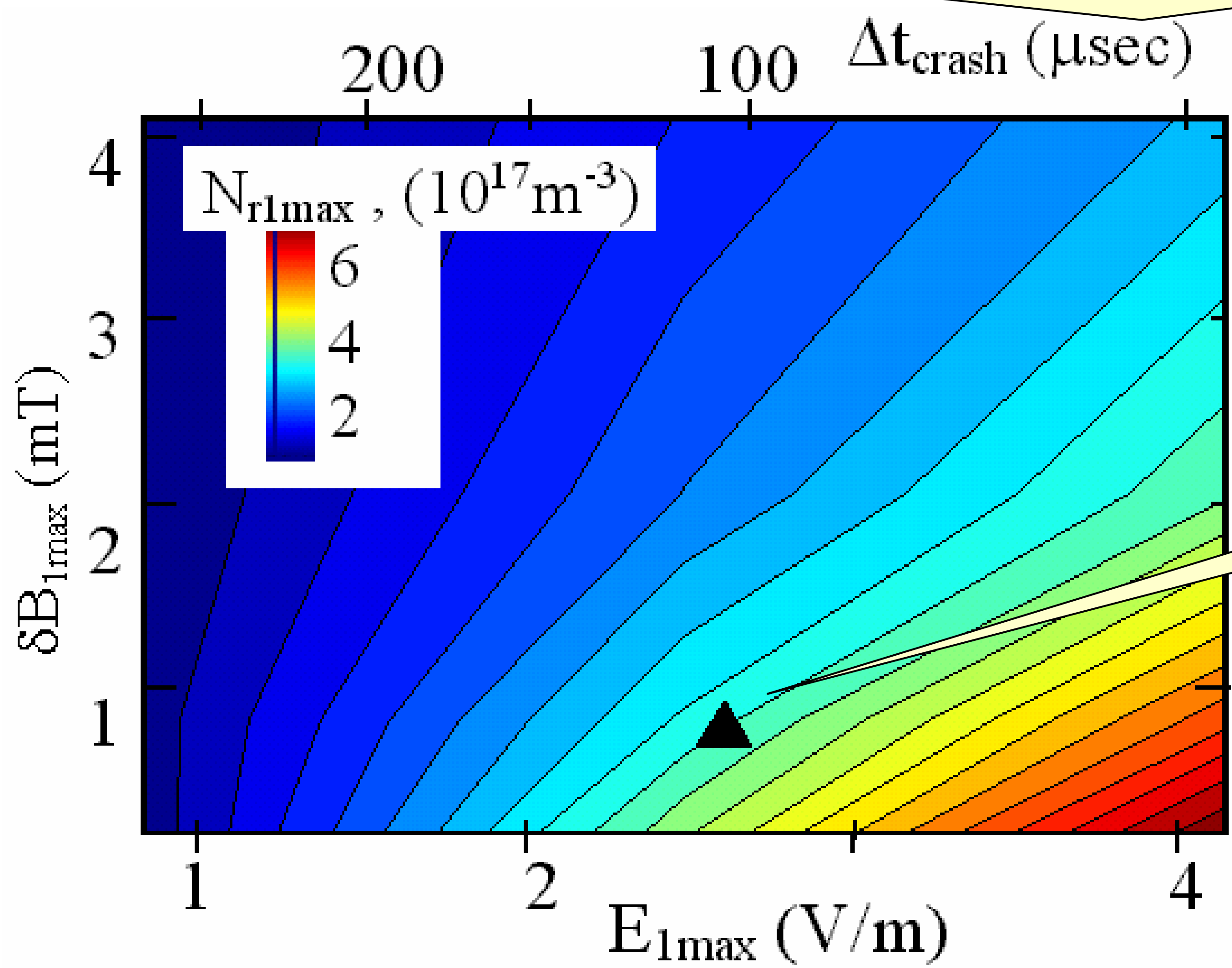
Observed previously in TFTR, DIIID
E.Fredrickson , PP98

The non-thermal x-ray spikes are observed more clearly using tangentially viewing x-ray array



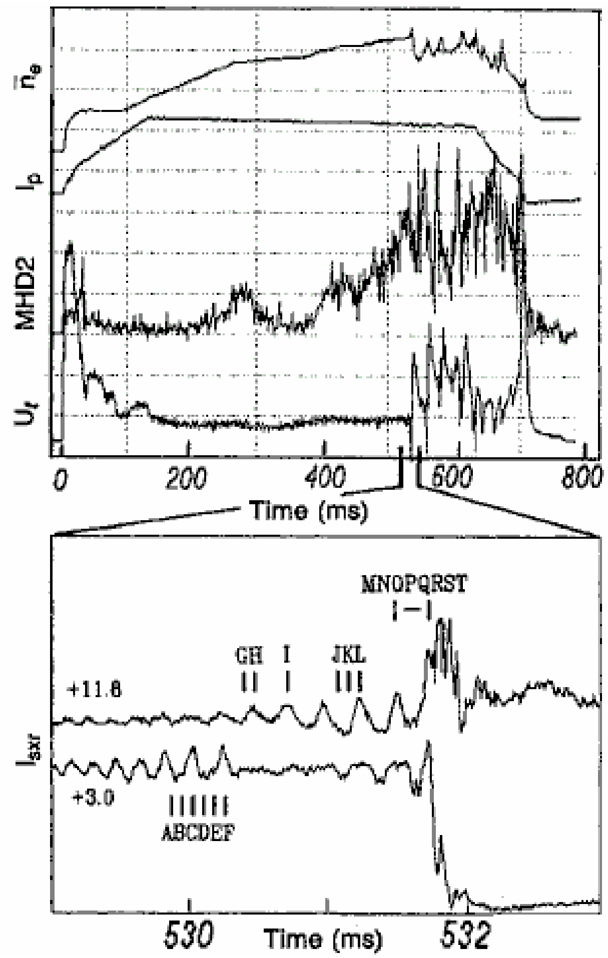
The spikes can be connected with generation of the non-thermal electrons during magnetic reconnection

Contour plot of the maximum non-thermal electron density (N_{r1max}) calculated in plasma with various amplitude of the induced electric field (E_{1max}) and magnetic field perturbations (δB_{1max}).

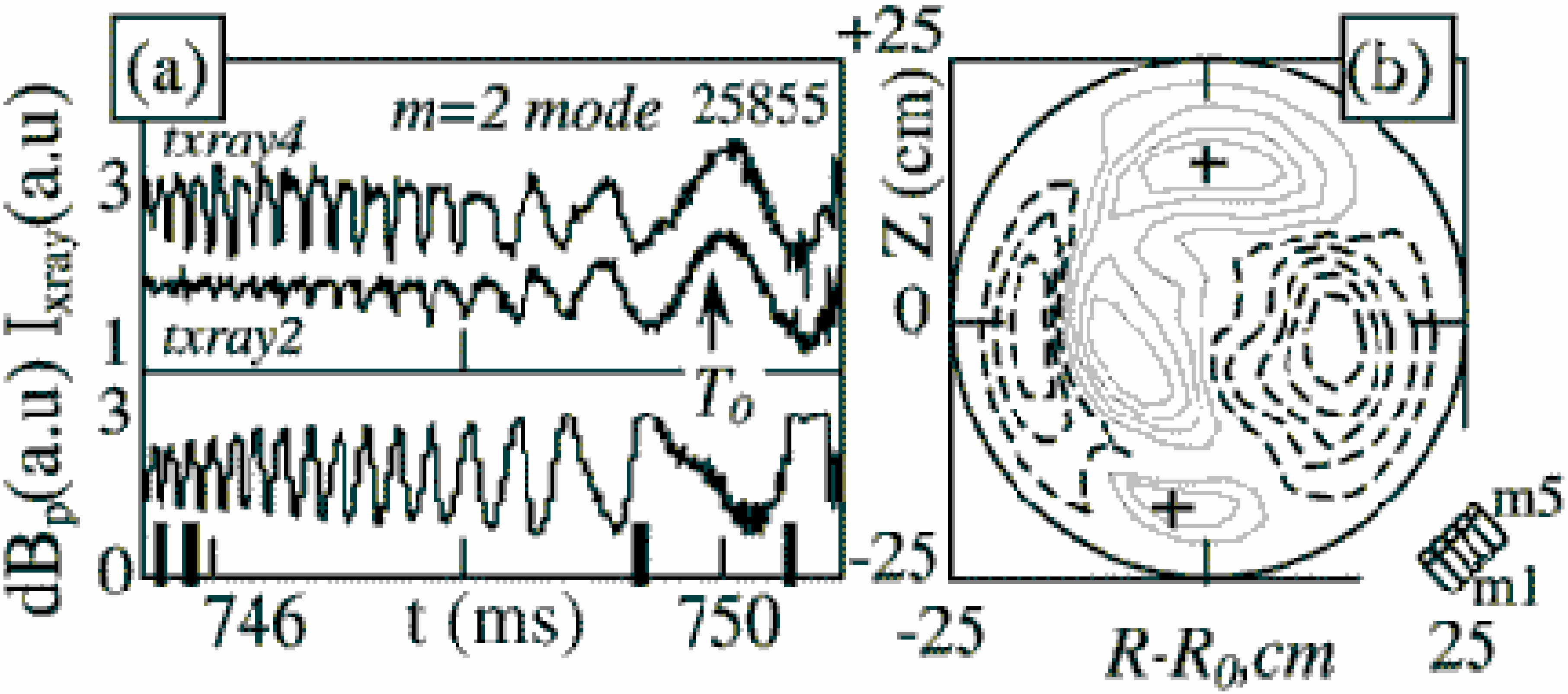


Typical set

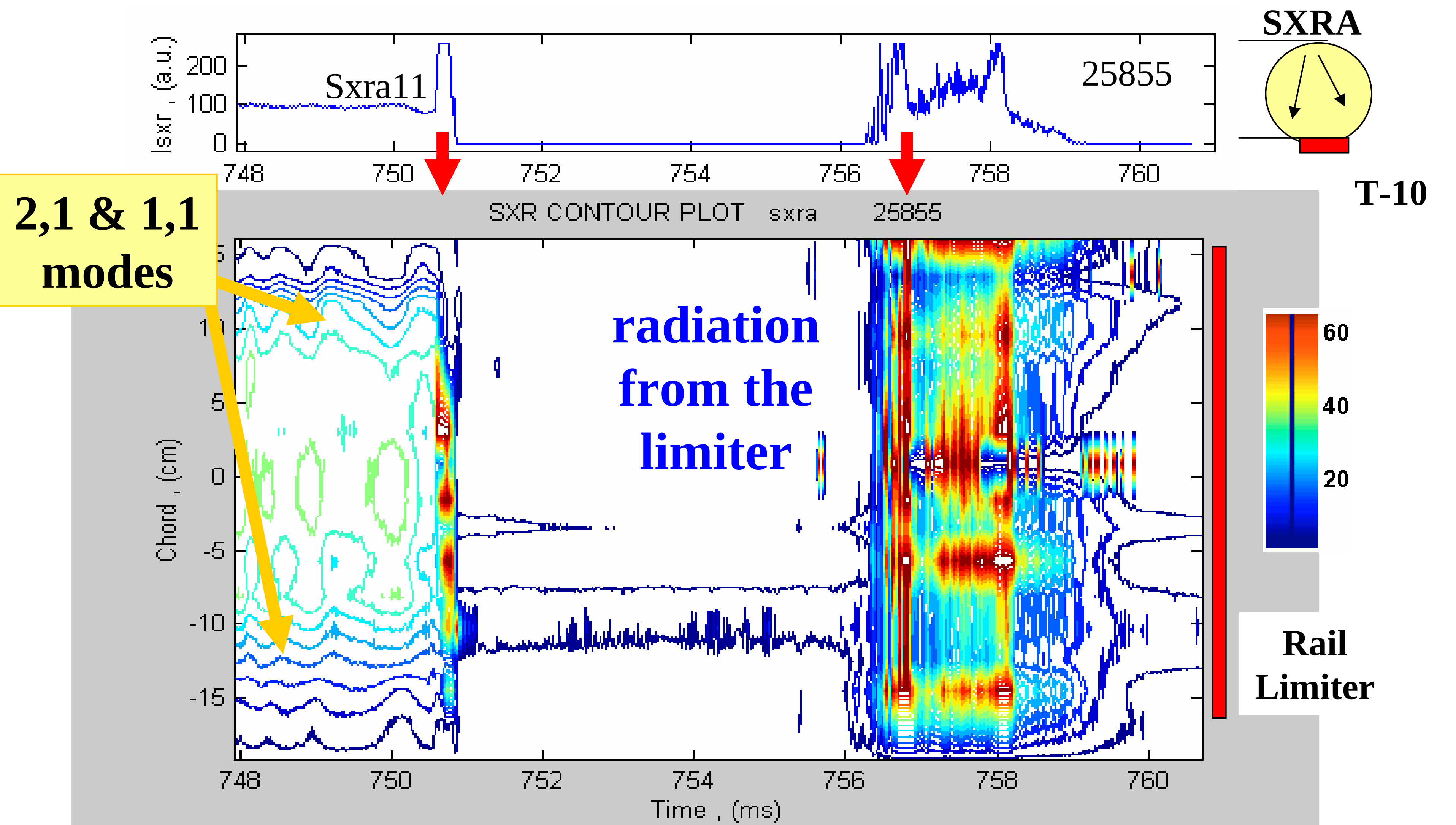
Coupling of the internal m=1,n=1 mode with the m=2,n=1 perturbations is observed just prior to the energy quench



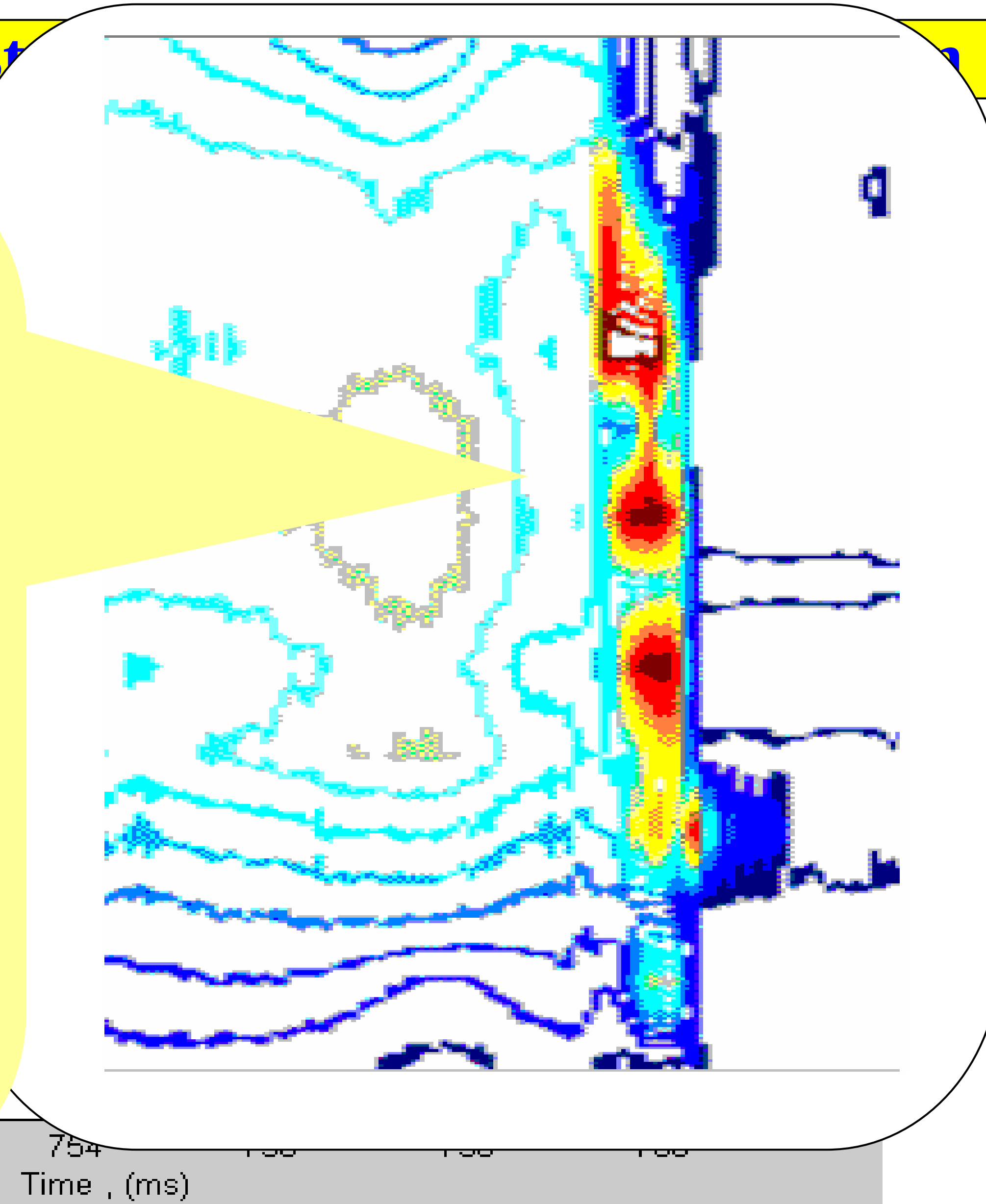
Position of the X-points of magnetic islands are identified from comparison of the x-ray images with data of fast magnetic probes



"Classical" hard x-ray bursts during density limit disruption

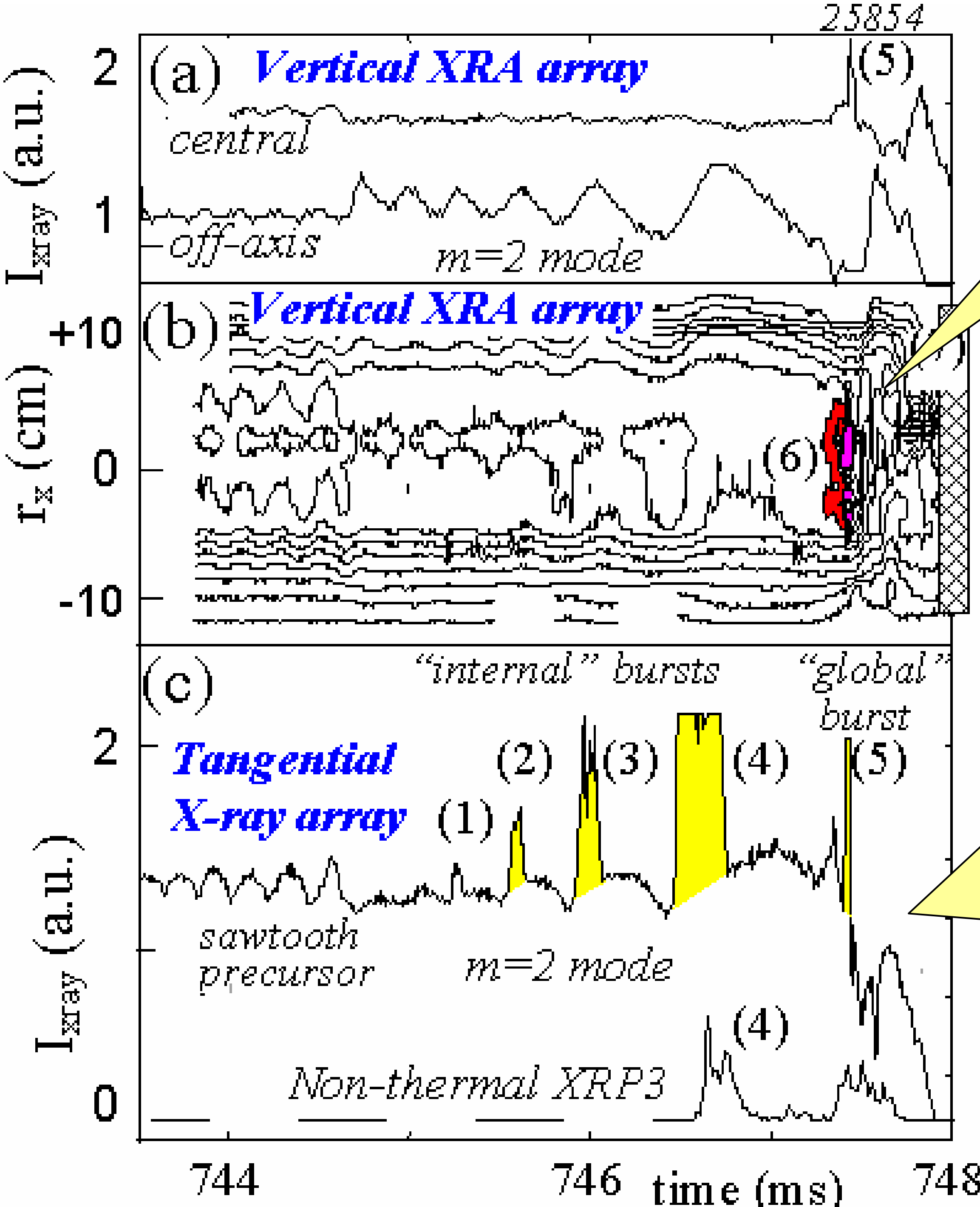


“Classical” hard x-ray burst

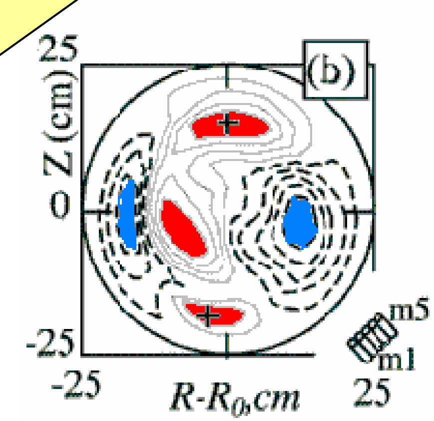


Narrow spots at the limiter can indicate filament-like structure of the beams - possibly connected with MHD modes?

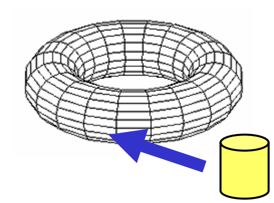
see, also JET disruptions [Gill,2000]



Standard x-ray spike

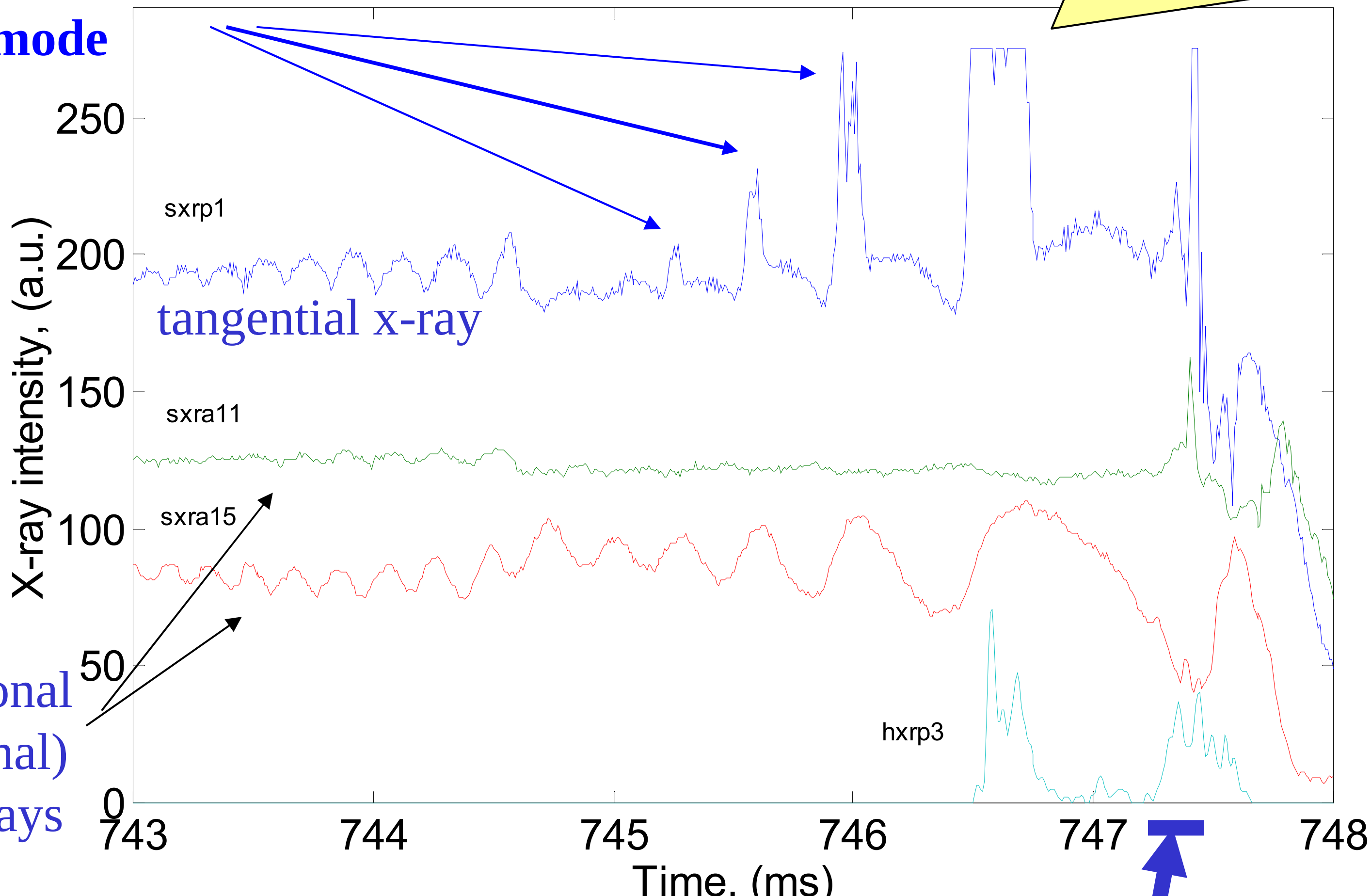


"Internal" x-ray bursts are observed with the tangentially viewing x-ray array



The x-ray bursts are observed at specific phase of the 2/1 MHD mode

The bursts can be connected with non-thermal electrons generated around the m=2 magnetic island



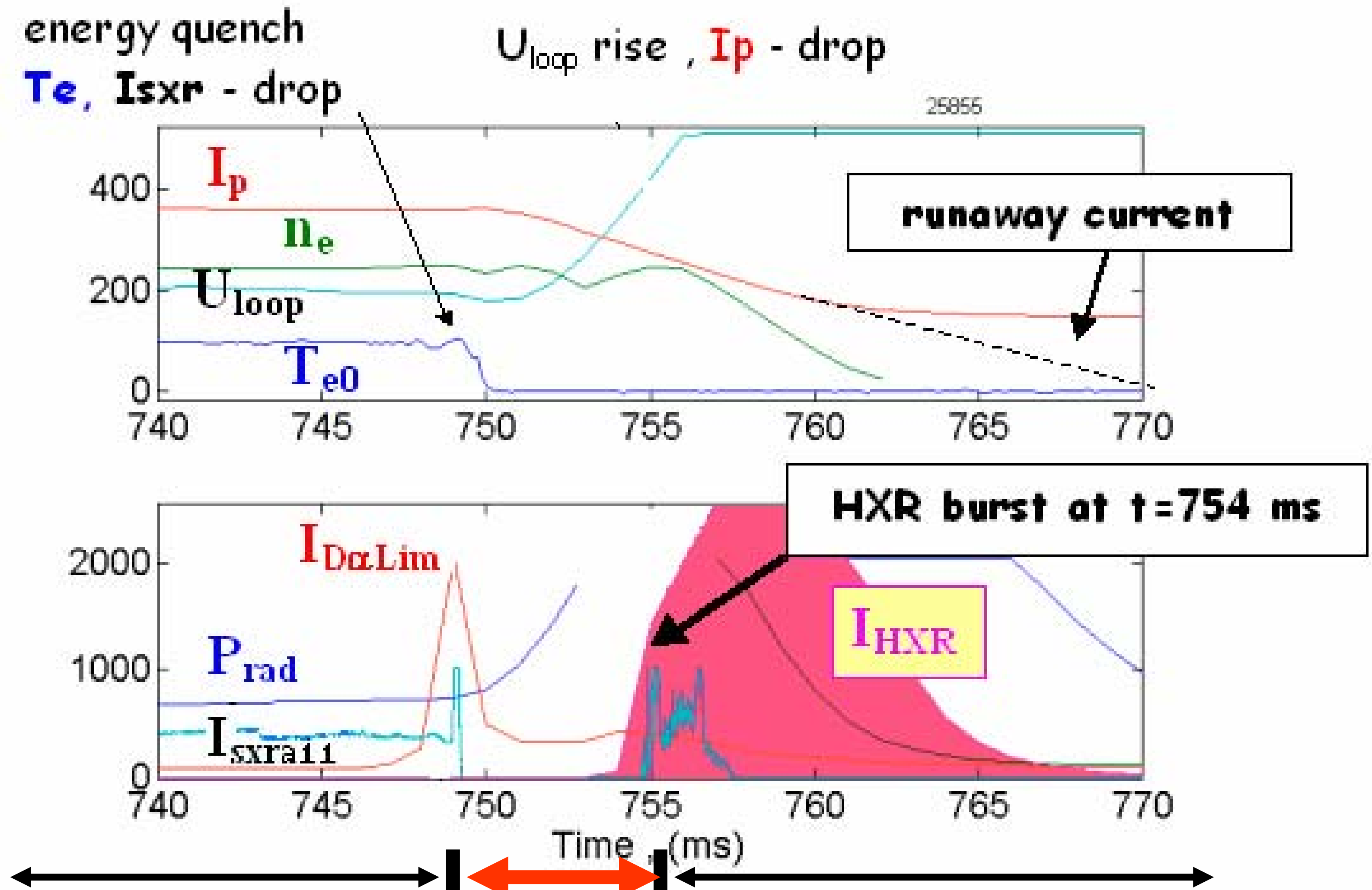
conventional (orthogonal) x-ray arrays

Standard x-ray burst during energy quench is observed with all x-ray arrays

SUMMARY
STAGE- 1

- The pre-disruptive plasma is characterized by joint rotation of the coupled m=1,n=1 and m=2,n=1 MHD perturbations.
- Non-thermal x-ray spikes are observed around X-points of the m=1,n=1 and m=2,n=1 magnetic islands just prior to the energy quench.
- First non-thermal x-ray spike during an energy quench can be connected with interaction of the MHD-induced localized beams with the limiter.

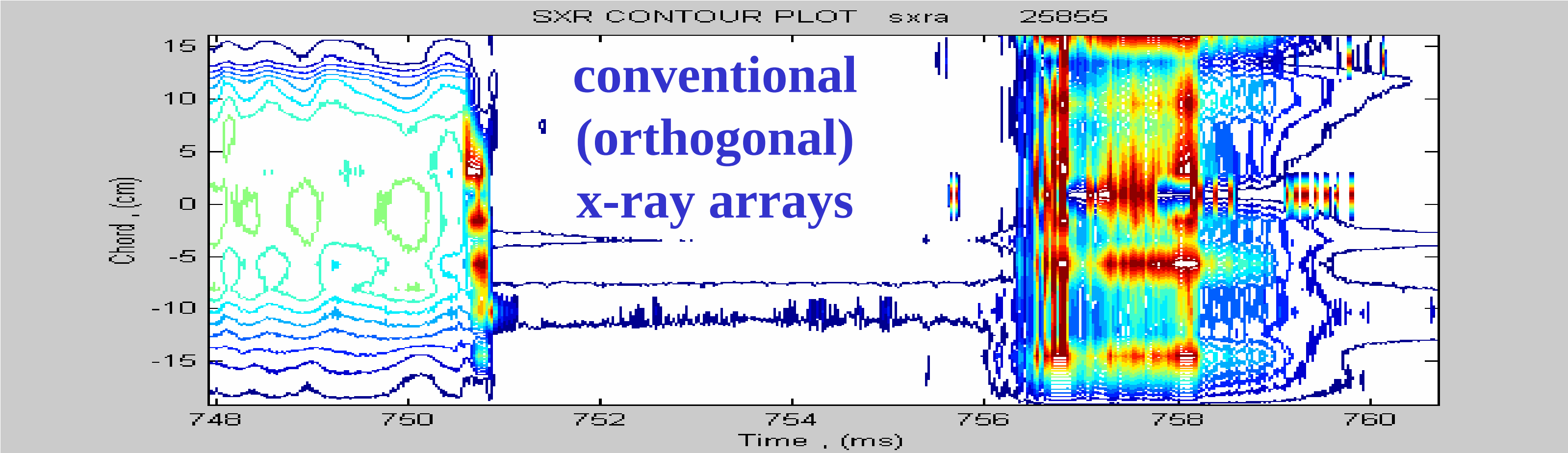
Standard hard x-ray burst are observed 5ms AFTER the energy quench during runaway interaction with the “wall”

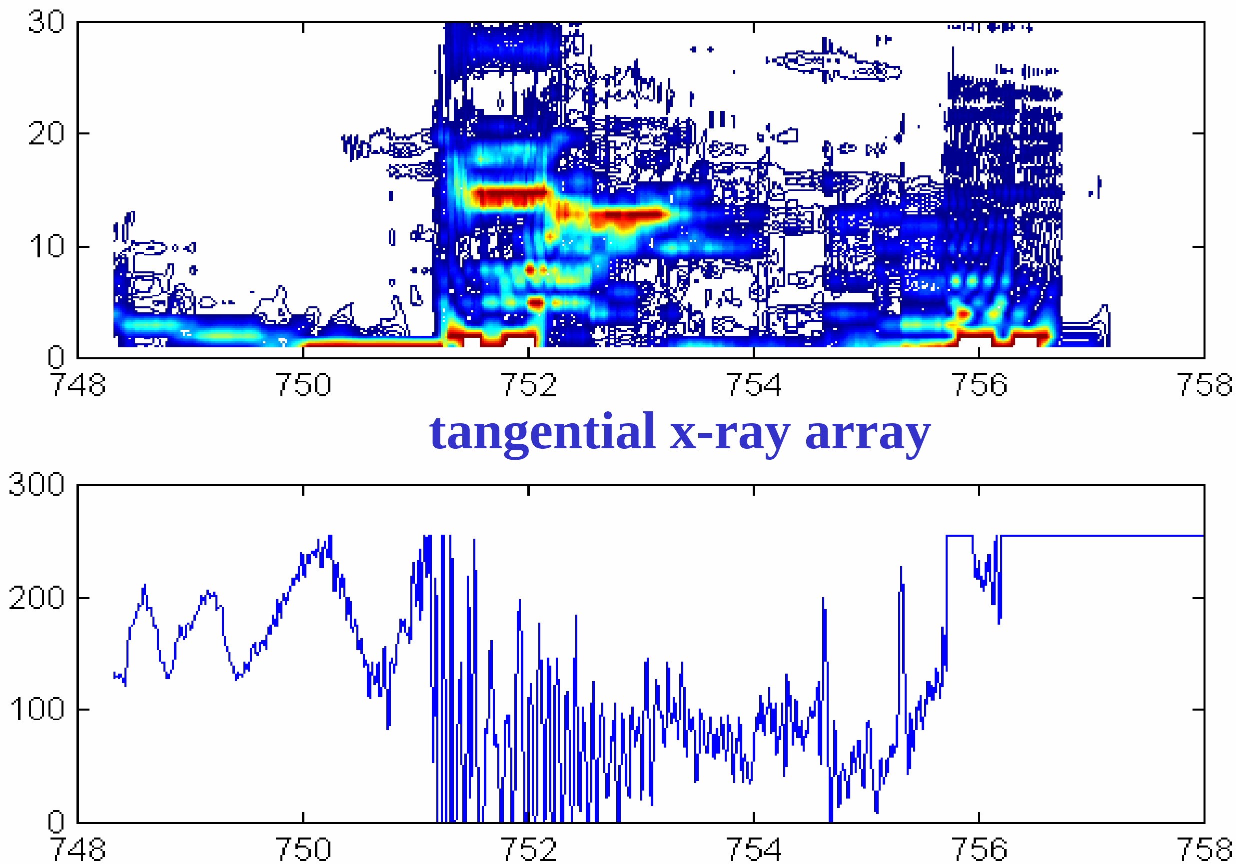


Stage I
pre-disruptive

Stage II energy quench
and runaway formation

Stage III
runaway avalanche





x-ray bursts are observed with the tangentially viewing x-ray array just after an energy quench

Nonthermal x-ray bursts after an energy quench are observed using tangentially viewing x-ray array

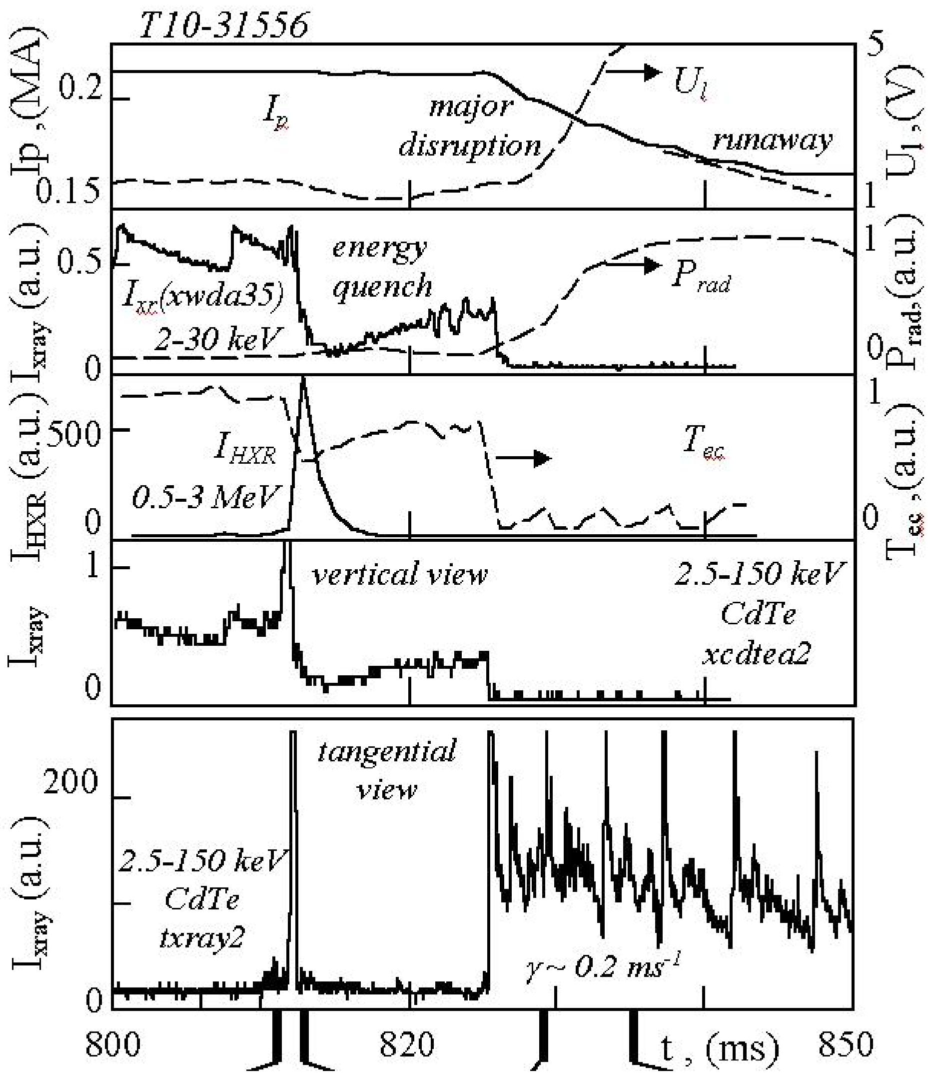
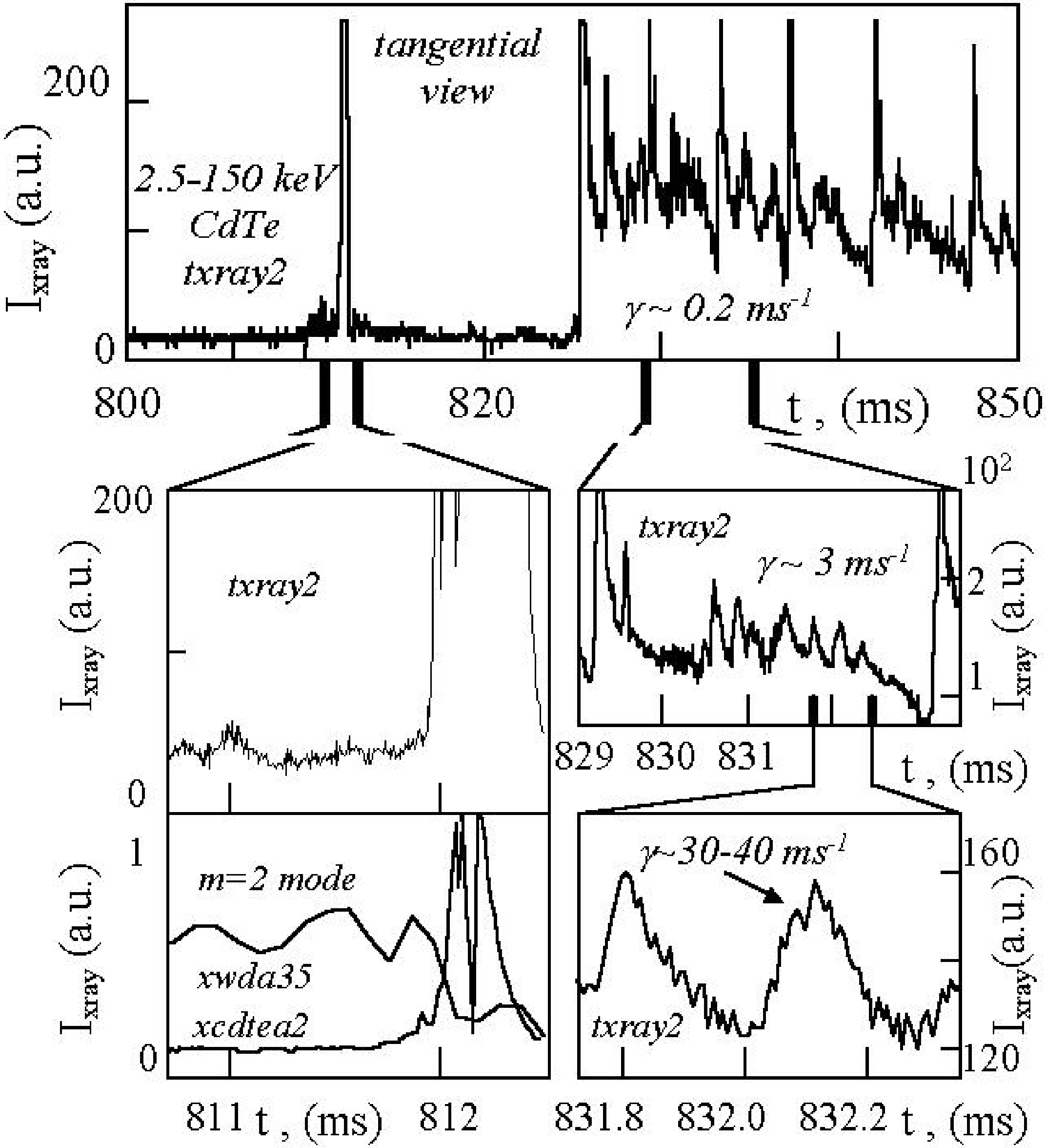


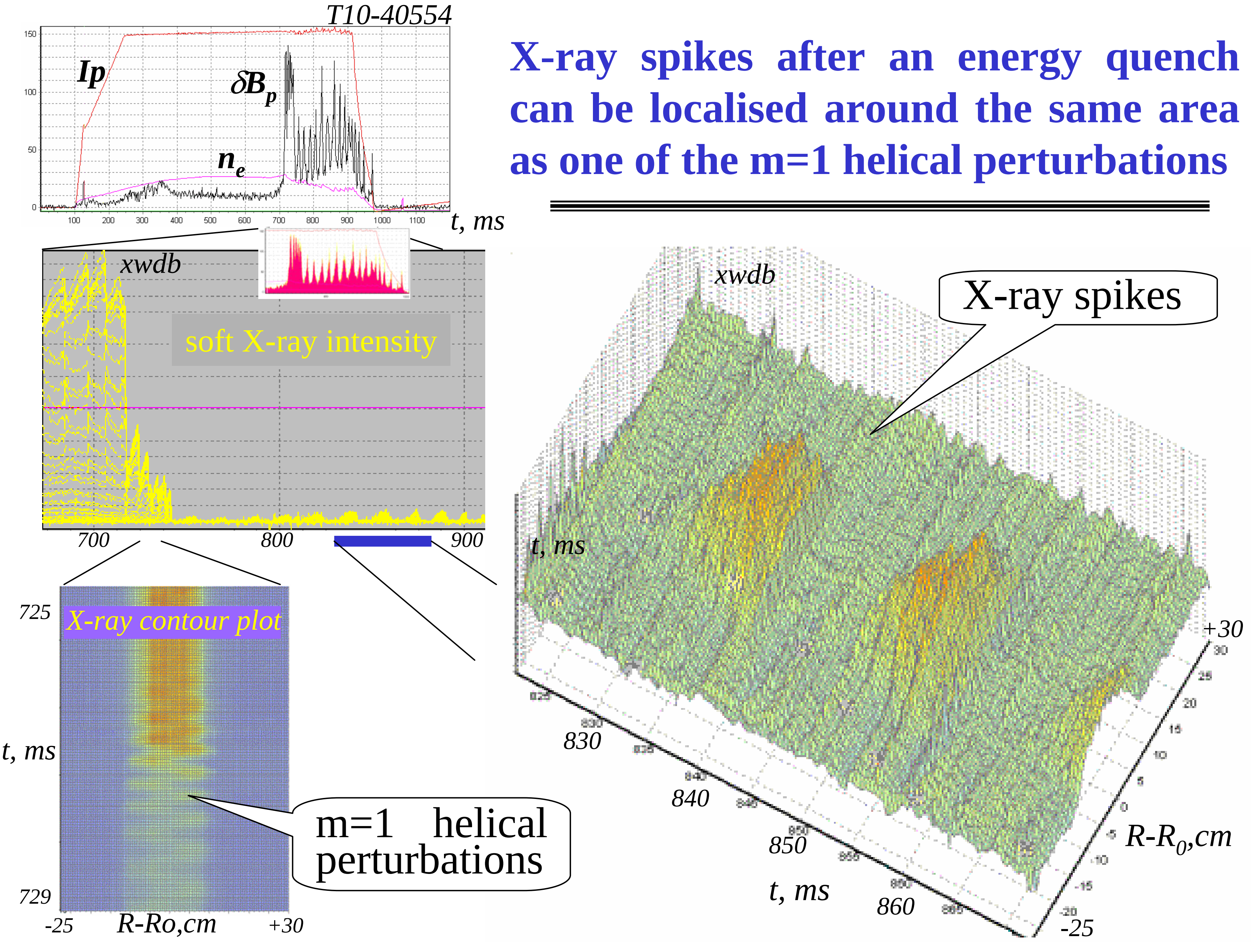
FIG. 12. Time evolution of plasma parameters after an energy quench during density limit disruption in ohmically heated plasma. Here, I_p is plasma current, U_l loop voltage, P_{rad} total radiated power, T_{ec} electron (ECE) temperature, I_{HXR} hard x-ray intensity, *I_x(xwda35)* x-ray intensity measured using XWDA gas detector. Also shown, intensity of the x-ray radiation measured using CdTe detectors with orthogonal (*xcdtea2*) and tangential (*txray2*) view of the plasma column.

Nonthermal x-ray bursts after an energy quench are characterised by multiple frequencies

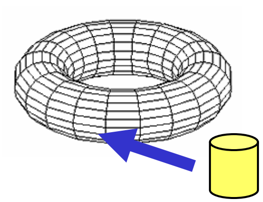


Note, some decrease in the repetition rate in sequence of the bursts

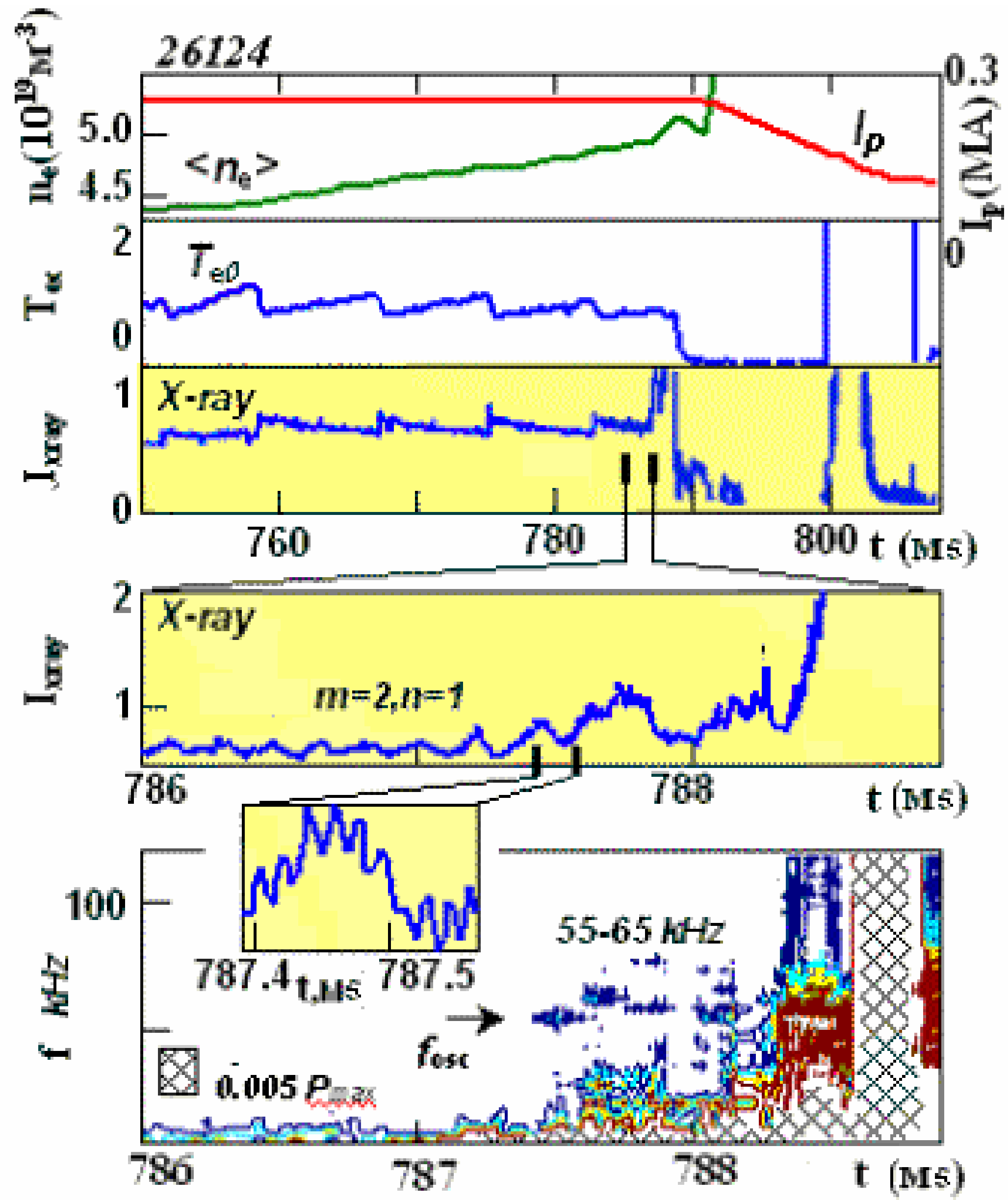
X-ray spikes after an energy quench can be localised around the same area as one of the m=1 helical perturbations



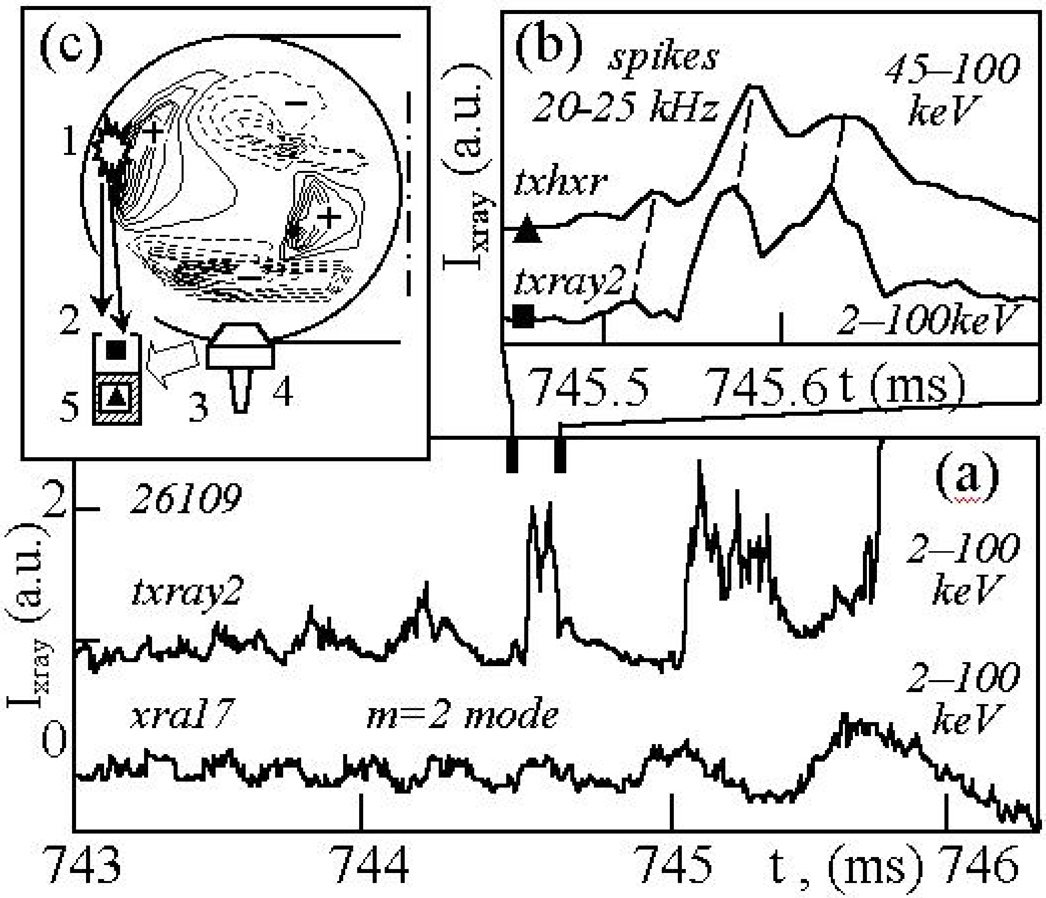
- Small-scale quasi-coherent oscillations (*f~15-80kHz*) are observed prior to the density limit disruption using tangential view x-ray array



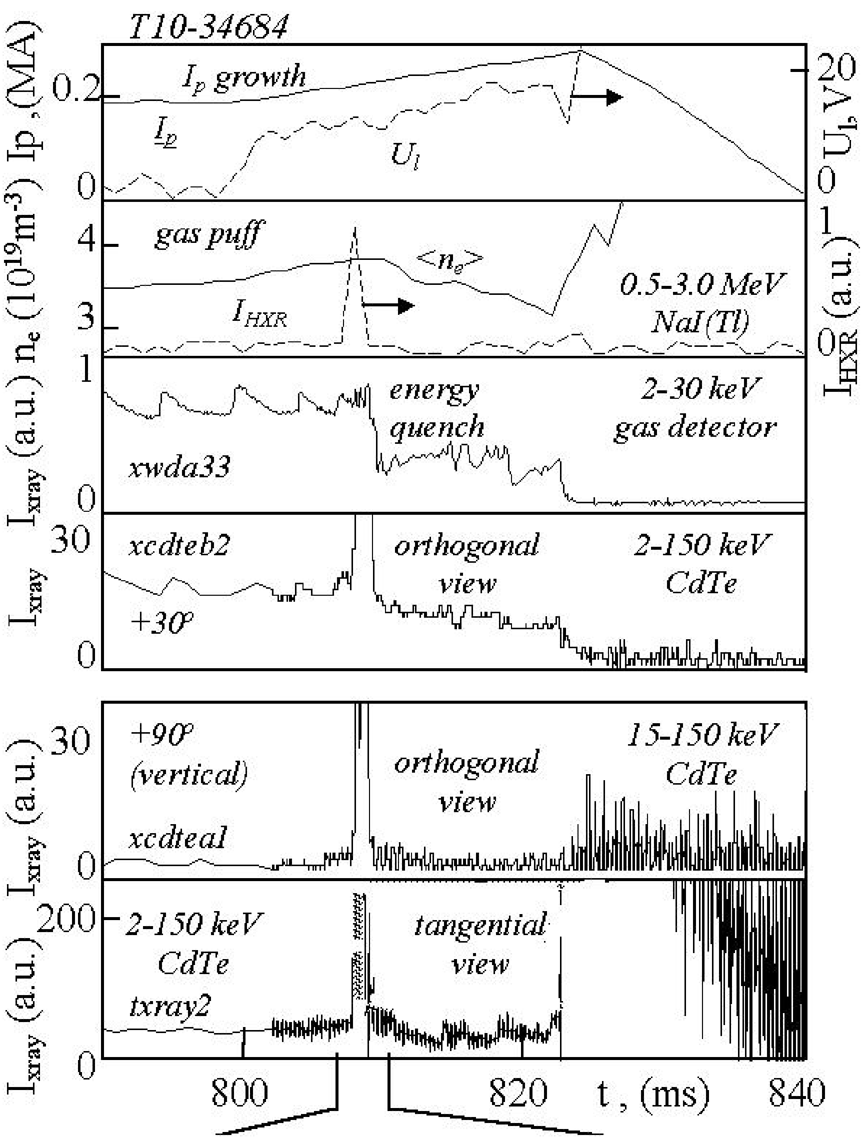
- Analysis indicated possible connection of the oscillations with beams of the non-thermal electrons induce during growth of the MHD modes



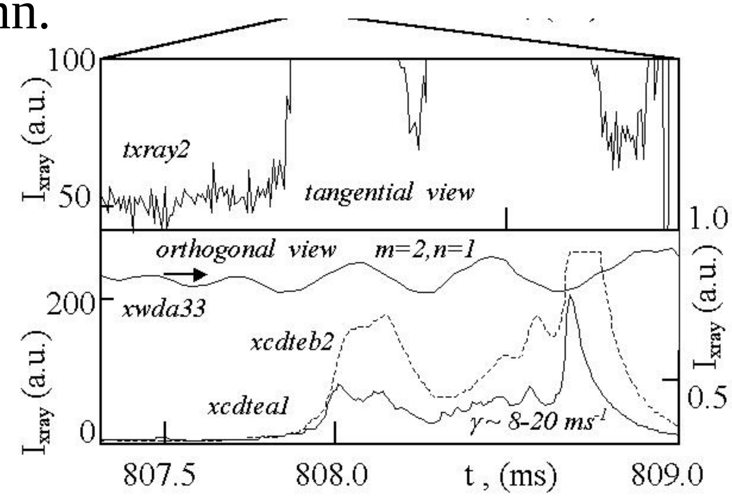
During the energy quench the quasi-coherent perturbations are transformed to intensive bursts of the non-thermal x-ray radiation with amplitude modulation in the same frequency range as one just prior to the disruption.



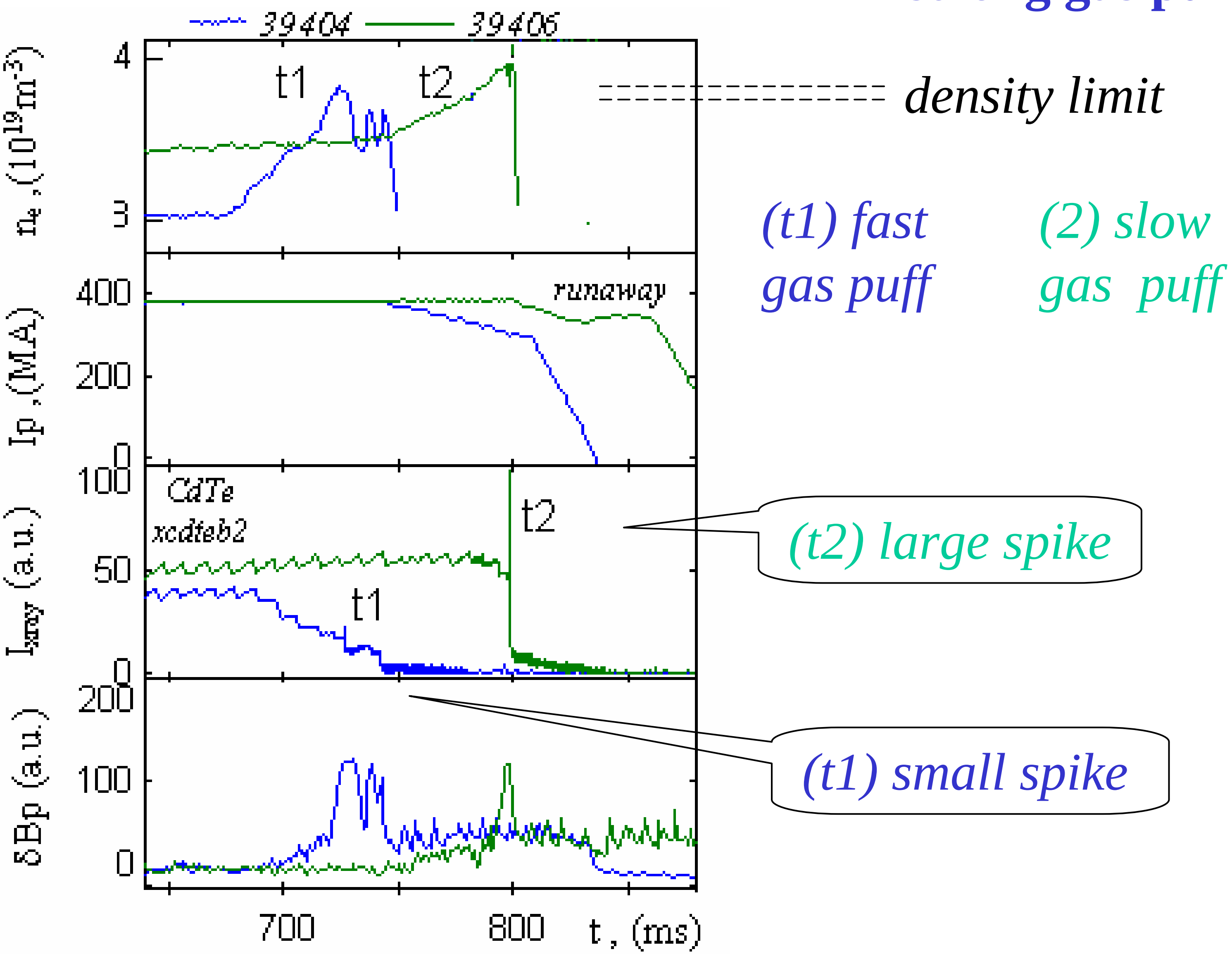
Experiments with the current ramp-up just prior to the disruption: No strong modification in the bursts behaviour



Time evolution of plasma parameters in experiments with ramp-up of plasma current, I_p, just prior the density limit disruption. Here, U_l is loop voltage, $\langle n_e \rangle$ line averaged electron density, I_{HXR} hard x-ray intensity, I_{xray}*(xwda33)* x-ray intensity measured using XWDA gas detector. Also shown, intensity of the x-ray radiation measured using CdTe detectors with orthogonal (*xcdtea1*, *xcdteb2*) and tangential (*txray2*) view of the plasma column.



Amplitude of the non-thermal x-ray spikes at the first minor disruption can be reduced up to 5-15 times in plasma with strong gas puffing



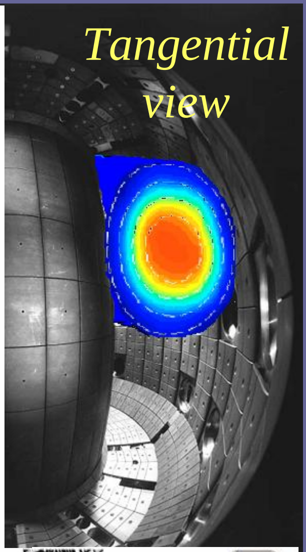
SUMMARY STAGE II

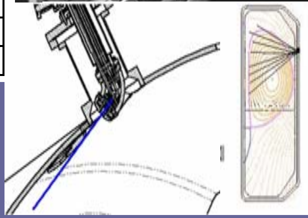
- During the energy quench the quasi-coherent perturbations are transformed to intensive bursts of the non-thermal x-ray radiation with amplitude modulation in the same frequency range as one just prior to the disruption.
- The x-ray bursts observed just after the energy quench are confined within the plasma core.
- Strong increase of the longitudinal electric field prior to the disruption does not change considerably dynamic of the bursts. This indicates indirectly that bursts can not be connected with standard “equilibrium” runaway beams in the plasma core.
- New diagnostics are required for future analysis.

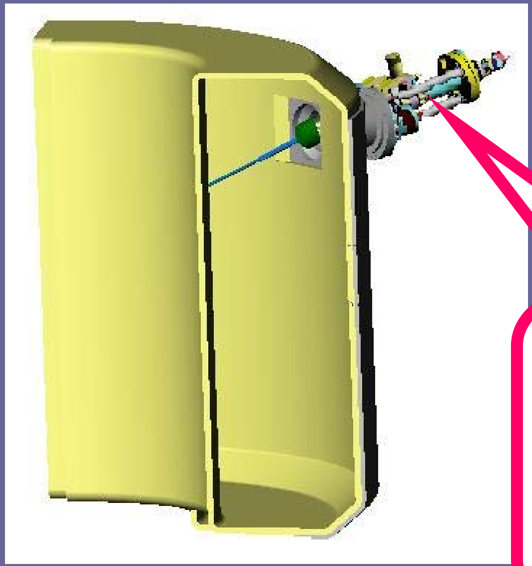
New tangential X-Ray Detector Array Diagnostic system -measurements of the nonthermal x-ray radiation and small-scale MHD modes in the TCV tokamak

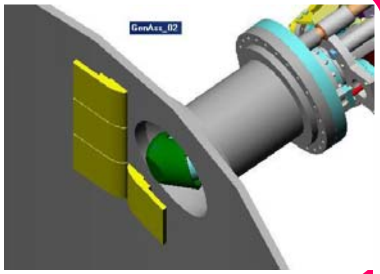
Port	*upper lateral port CF200*
Detectors CdTe sensitive area sensitive region thickness	*5 (+1 screened)* *25 mm² (5x5 mm)* *d = 2 mm*
Energy range of the x-ray fluxes	*E ~ 1.5 - 200 keV*
Spatial resolution	*dr ~ 2cm*
Field of view of the diagnostic (can be changed in subsequent pulses by an automatic orientation system)	*0 to -30° vertical direction* *0 to 72° toroidal direction*
Time resolution	*dt ~ 0.01 msec*
Baking temperature (after extraction of the detector array)	*450°C*
Helium Mass Spectrometer leak tight	*$1x10^{-9}$ atm-cm³/sec*
Electrical isolation	*minimum 6 kV*
Heat flux protection	*Carbon composite*

Tangential view

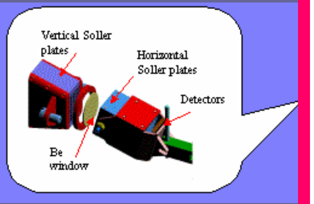


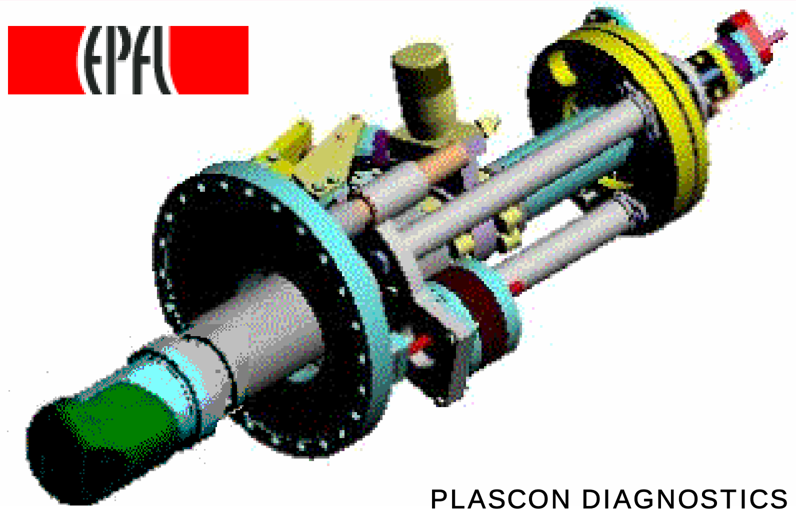






- CdTe detectors (2-200keV)
- Field of view is adjusted using two sets of a movable Soller collimators (0 - 70° toroidal,
- -15° - +15° vertical angle)

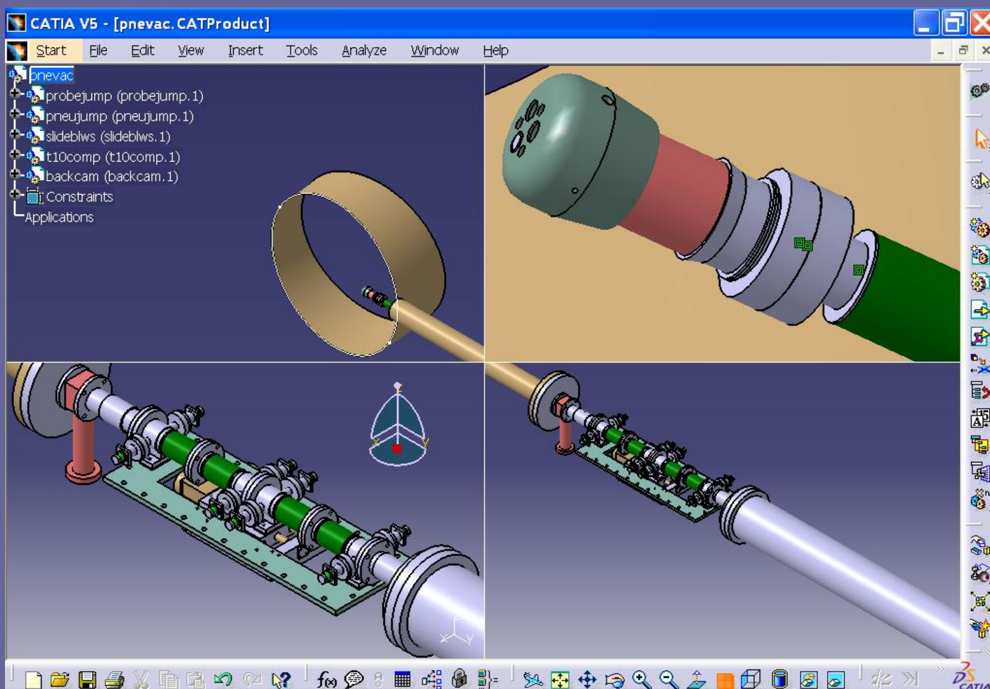


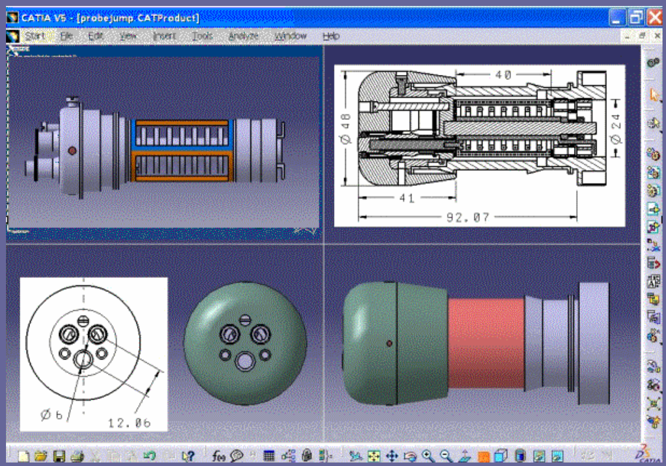


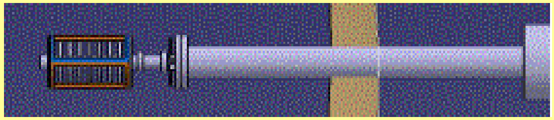
PLASCON DIAGNOSTICS

T-10 XEMERA probe:

1. Tangential X-ray with adjustable line-of-sight
2. Reciprocating Electric (Langmuir) probe
3. Fast reciprocating Magnetic probe







PLASCON DIAGNOSTICS

RUSSIAN RESEARCH CENTRE KURCHATOV INSTITUTE
РОССИЙСКИЙ НАУЧНЫЙ ЦЕНТР "КУРЧАТОВСКИЙ ИНСТИТУТ"

Acknowledgements

The author would like to thank A.Ya. Kislov, G.E. Notkin, Y.D. Pavlov and V.S. Strelkov for support of the experiments and Yu.N. Dnestrovskij, S.V. Mirnov, V.I. Poznyak, K.A. Razumova, I.B. Semenov and V.A. Vershkov for a critical discussion of the experimental results. Measurements of the hard x-ray monitor were kindly provided by A.V. Khramenkov.

Presentation of the paper at the 9th Technical Meeting on Energetic Particles is made possible due to generous support by the International Atomic Energy Agency.