Tangential multi-color "optical" soft X-ray array for fast electron temperature and transport measurements

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American Physical Society (APS),
Division in Plasma Physics (DPP),
October, 24 - 28, 2005
Denver, Colorado, USA

Abstract

- **Fast (≤ 0.1 ms) measurements of the electron temperature profile, heat and particle transport, and MHD activity.**

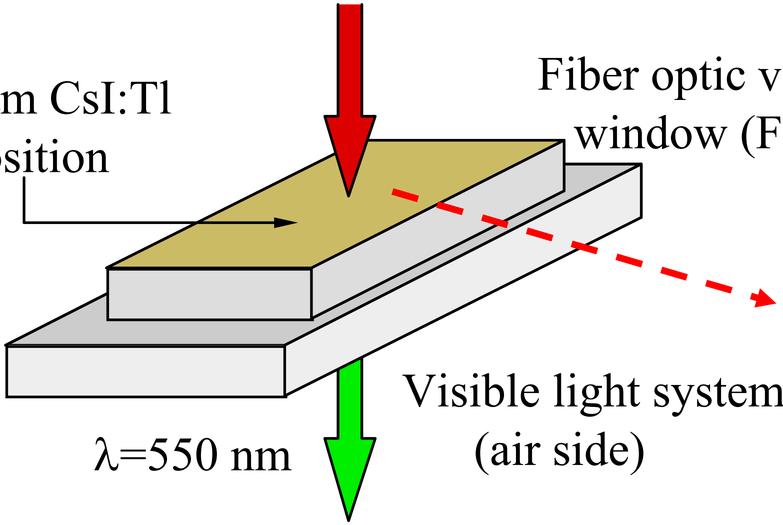
- **Signal-to-noise ratio (SNR) can be superior to that of diode-based arrays.**

- **Tangential 48-channel “optical” soft X-ray array which views the *same plasma volume* at the mid-plane, in three different energy ranges.**

- **Time resolution ranging from a few μs to ~ 1 ms, with spatial coverage from $0 \leq r/a \leq 0.9$.**

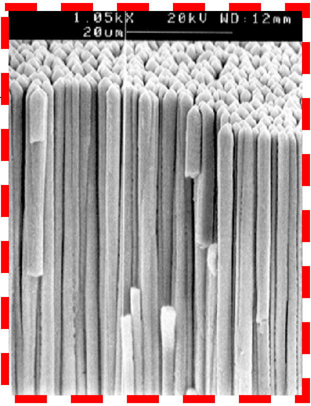
Principles of the "optical" soft x-ray (OSXR) array

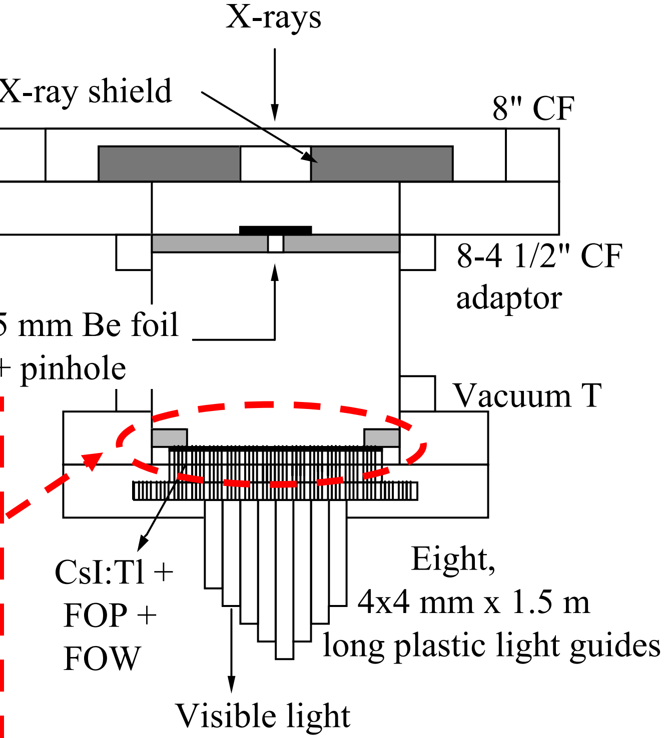
Conversion to visible light



To discrete channels and light (PMT and/or APDs) amplifiers

OSXR array head tested on CDX-U & NSTX spherical tokamaks (2004)





It's a system that uses a **fast** (≈1 µs) and **efficient** scintillator (CsI:Tl) in order to **convert soft x-ray photons** (0.1<E_{ph}<10 keV) to **visible green light (λ≈550 nm).**

Motivation

- **Fast (≤ 100 μs) T_e measurements.**
  (ECE-like diagnostic for STs and Tokamaks)

  → Perturbative electron heat and particle transport (**ELMs, pellets, gas-puff and/or SGI**).

  → MHD related T_e perturbations (**ELMs, MHD-modes, RWMs, FISHBONES/EPMs**).

- **Perturbative impurity transport.**
  (Gas puff (Ne), Impurity pellets (C, B) and/or SGI)

Our previous work with the USXR and the 1-color OSXR systems have shown that the measurements proposed are feasible.

- **Explore the possibilities of the proposed diagnostic in poloidal configuration.**

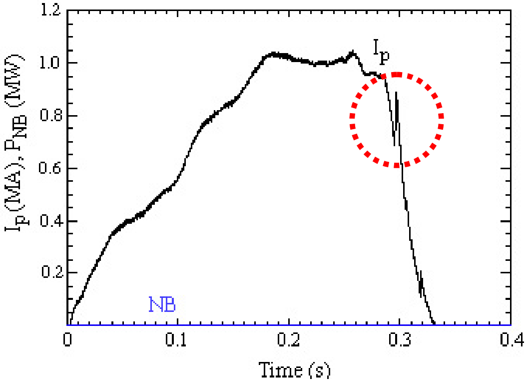
  → Viewing the same plasma volumes at three energy ranges.

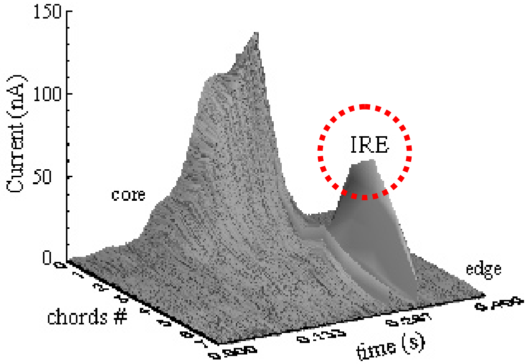
  → Higher SNR in comparison to diode-based arrays.

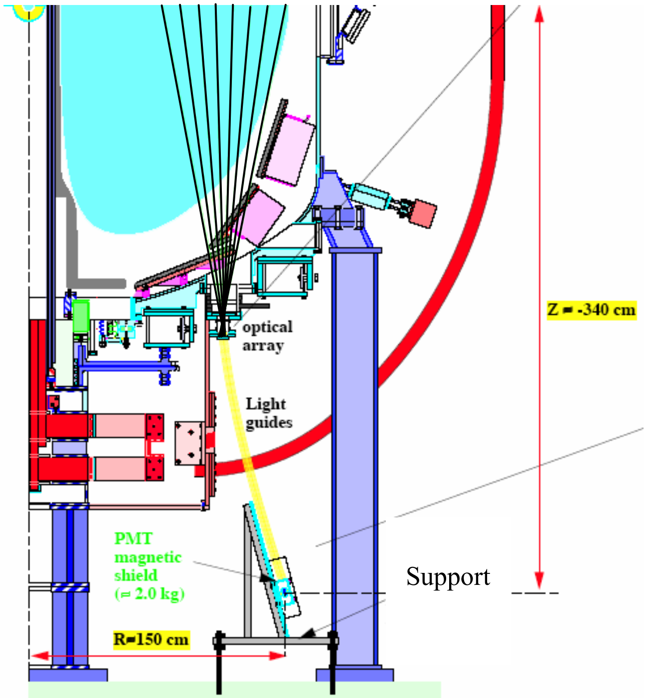
Test of a “single-color” array in NSTX (PPPL), 2004

MHD & noise comparison results with the “OSXR”

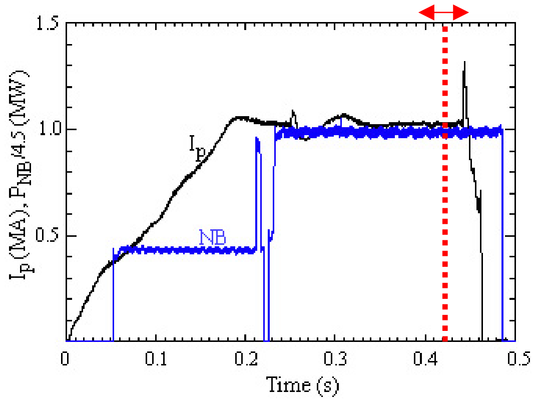
Shot #: 112069 ⇒ Ohmic Shot

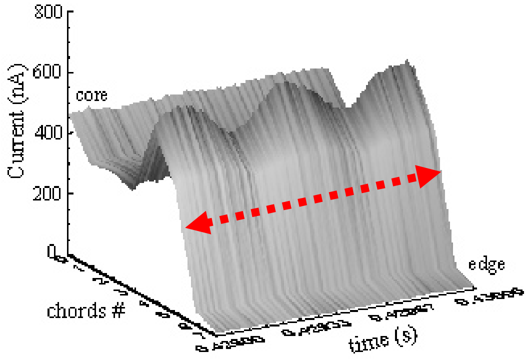






Shot #: 112036 ⇒ H-mode





[1] Luis F. Delgado-Aparicio, *et al*., High Temperature Plasma Diagnostics meeting (San Diego, CA, 2004).
[2] Luis F. Delgado-Aparicio, *et al*., Rev. Sci. Instrum, **75**, 4020, (2004).
[3] Luis F. Delgado-Aparicio, *et al*., APS-DPP-04 meeting (Savannah, GA, 2005)
[4] Luis F. Delgado-Aparicio, *et al*., submitted to Nucl. Instrum. Meth. Phys. Res. A, (2005).

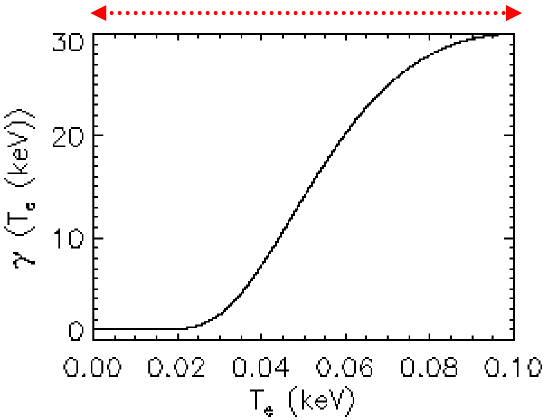
X-ray continuum radiation

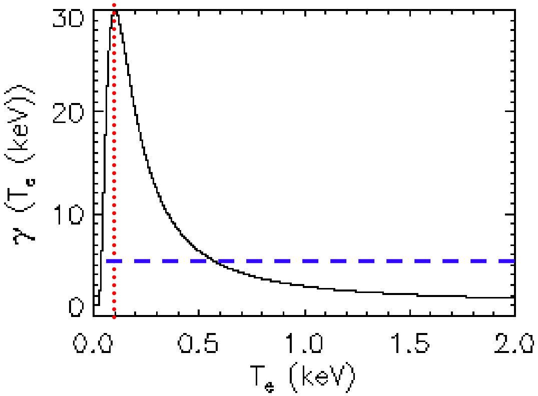
- For a realistic calculation, we consider **plasma continuum radiation**, (i.e. Bremsstrahlung and recombination radiation), described by the radiated X-ray power density (P_x) per unit of X-ray photoenergy ($h\nu$),

$$\frac{dP_x}{dh\nu}\left(cm^{-3}s^{-1}\right)=3\times10^{11}\frac{1}{\sqrt{T_e(\mathrm{keV})}}\gamma(T_e,Z)Z_{eff}\,n_e^2(10^{13}\ \mathrm{cm}^{-3})\exp\left(-\frac{h\nu}{k_BT_e}\right)$$

- The factor **$\gamma(T_e,Z)$** describes the **enhancement of the radiation** over Bremsstrahlung due to free-bound (recombination radiation), assumed to be caused predominantly by highly ionized Carbon. A crude estimate is given by,

$$\gamma(T_e)=1.0+29.0\exp\left\{-\left(2.75-1.1\left[T_e(keV)\right]^{-0.4}\right)^2\right\}$$





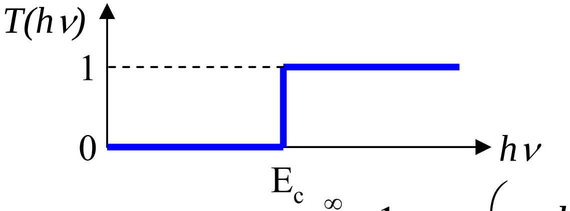
$T_e(r)$ from the X-ray photon emissivity profile: $\varepsilon_{x\text{-}ph}(r)$

Why a tangential view?

Because in order to perform an **emissivity tomographic reconstructions** with a **limited number of chords**, we will have to **rely on magnetic flux surfaces as a constraint** and thus introduce **ERRORS**!

- **Assumption: The Abel-inversion was performed** ⇒ emissivity profile: $\boldsymbol{\varepsilon_{x\text{-}ph}(r)}$.
- **Question: Can we infer T_e?**
- **Approximations:** a) The transmission of the x-ray filter follows a Heavyside function with a E_c given by the -3dB transmission (≈50%).
  b) The intensity of the line emission from impurities (C & O) is not significant in comparison with Bremsstrahlung + recombination (clean plasma).

$$\varepsilon_{x-ph}(r)\left[\frac{1}{\mathrm{cm}^3\mathrm{s}}\right] = \int_{E_{cut}}^{\infty} \frac{1}{h\nu}\frac{dP_x}{dh\nu}\,dh\nu$$

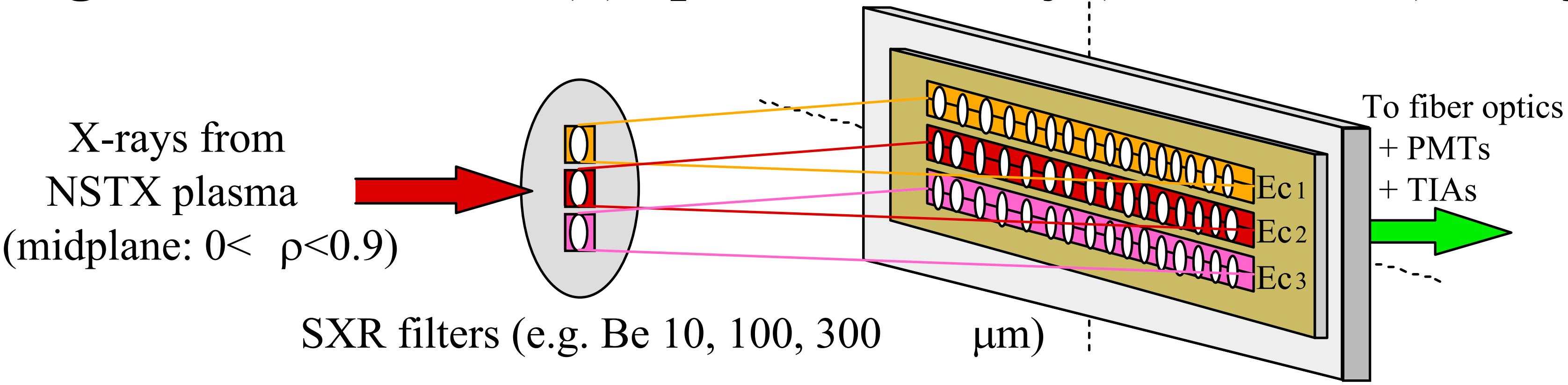


$$= 3\times 10^{11}\frac{1}{\sqrt{T_e(r)[\mathrm{keV}]}}\gamma\left(T_e, Z\right)Z_{eff}(r)n_e^2(r)[10^{13}\ \mathrm{cm}^{-3}]\int_{E_{cut}}^{\infty}\frac{1}{h\nu}\exp\left(-\frac{h\nu}{k_B T_e}\right)dh\nu$$

$$\boxed{\varepsilon_{x-ph}(r)\left[\frac{1}{\mathrm{cm}^3\mathrm{s}}\right] = 3\times 10^{11}\frac{1}{\sqrt{T_e(r)[\mathrm{keV}]}}\gamma\left(T_e(r), Z(r)\right)Z_{eff}(r)n_e^2(r)[10^{13}\ \mathrm{cm}^{-3}]\Gamma\left(0, E_{cut}/k_B T_e(r)\right)}$$

How to design a diagnostic to measure $T_e(r,t)$?

Tangential multi-color (3) optical soft x-ray (tMC-OSXR) array



X-rays from
NSTX plasma
(midplane: 0< ρ<0.9)

SXR filters (e.g. Be 10, 100, 300 μm)

To fiber optics
+ PMTs
+ TIAs

Multi-color technique (“two-foil” method):

- This technique utilize the **multi-color principle**, in which the T_e measurement is obtained by **rationing** the **localized radiation intensities** from two energy ranges, **rather than from an absolute intensity** measurement, as is in the case of a **single color instrument**.

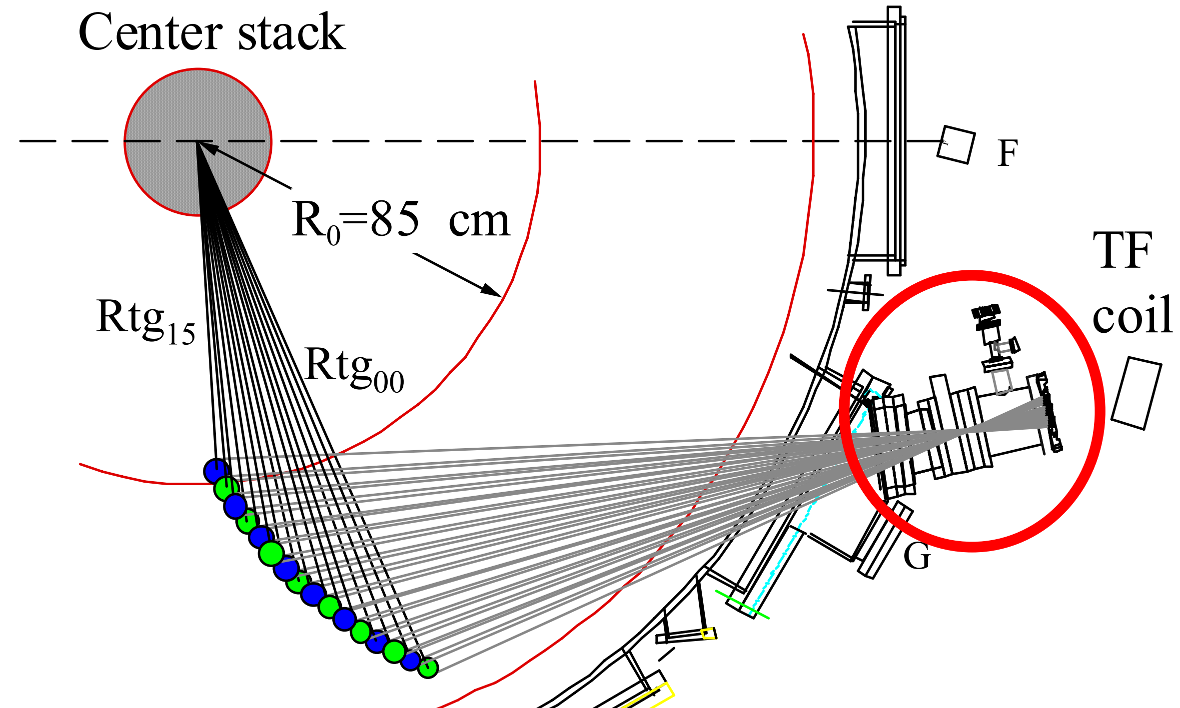
- This design approach naturally eliminates a number of factors that degrade the accuracy of the conventional single color SXR diagnostics for T_e measurements.

$$\boxed{\frac{\varepsilon_{1,x-ph}(r)}{\varepsilon_{2,x-ph}(r)} \approx \frac{\Gamma\left(0, E_{c1}/k_B T_e(r)\right)}{\Gamma\left(0, E_{c2}/k_B T_e(r)\right)}}$$

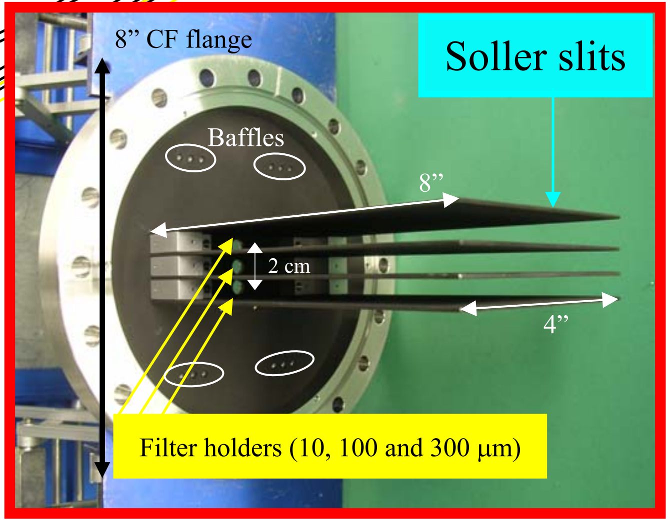
☐ **Absolute** value of the $T_e(r)$ by minimization techniques!

☐ Feedback ↔ $n_e(r,t)\cdot n_Z(r,t)$

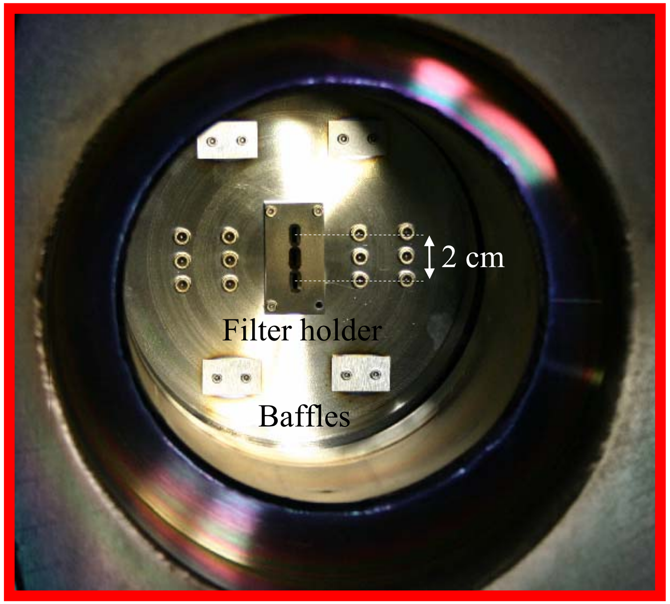
NSTX tangential "optical" soft x-ray (tOSXR) array

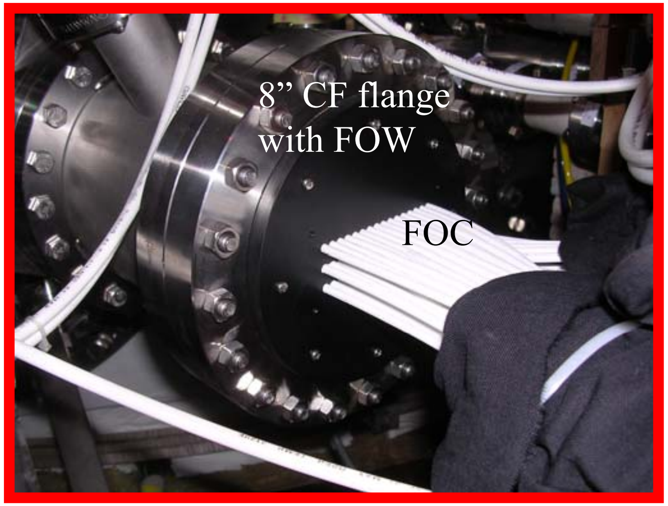


Rtg_{15}=84.093 cm, Rtg_{14}=88.632 cm, Rtg_{13}=93.163 cm, Rtg_{12}=97.632 cm Rtg_{11}=102.19 cm, Rtg_{10}=106.58 cm, **Rtg_{09}=110.95 cm**, Rtg_{08}=115.19 cm Rtg_{07}=119.30 cm, Rtg_{06}=123.49 cm, Rtg_{05}=127.60 cm, Rtg_{04}=131.58 cm Rtg_{03}=135.48 cm, Rtg_{02}=139.30 cm, Rtg_{01}=142.95 cm, **Rtg_{00}=146.57 cm**

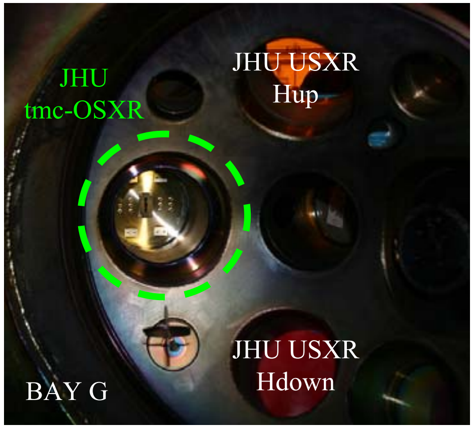


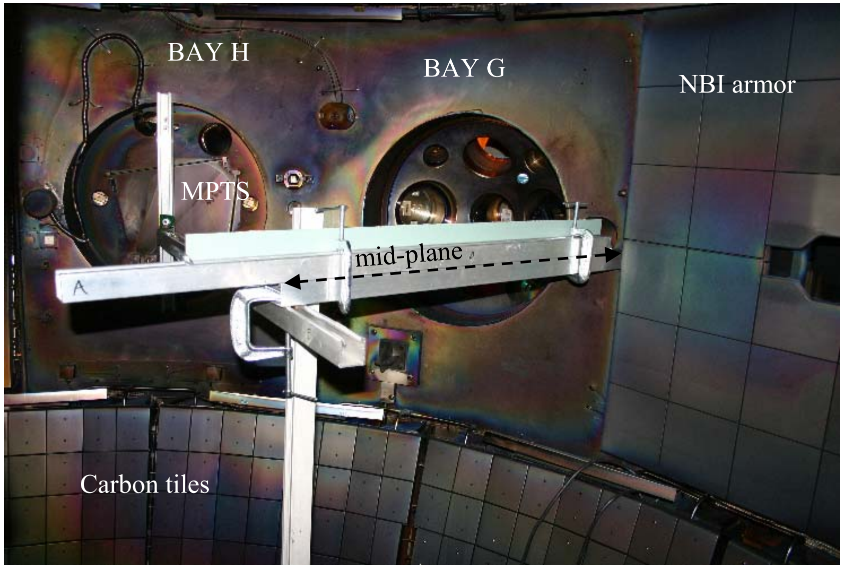
Details of the optical head





Photometric and spatial calibrations inside NSTX



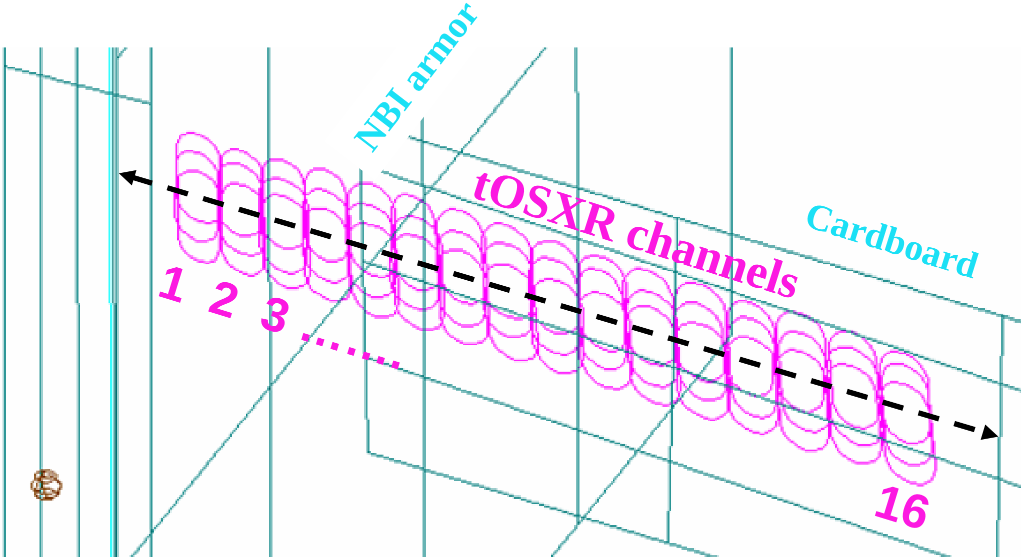


White plate calibration

- The PMT channel to channel sensitivity is measured with a white plate calibration.
- Curved plate covered with Kodak white paint for emission of white Lambertian light.
- Two tungsten lamps

Spatial calibration

An absolute calibrated measurement arm (FARO arm) is used to locate the 48 sightlines using back-projected light from the multi-color OSXR tangential views.



What a tangential line-integrated measurement does?

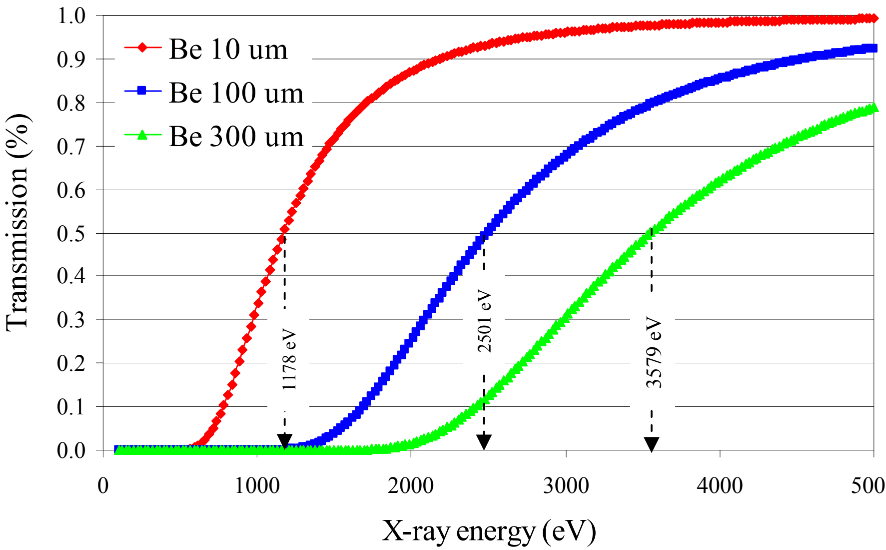
- Experimentally, it is a measurement of the brightness *b_{ph}(photons/s)* or the line-integrated (summation) power *P(Watts)* along sightlines for discrete values of R_{tg}.

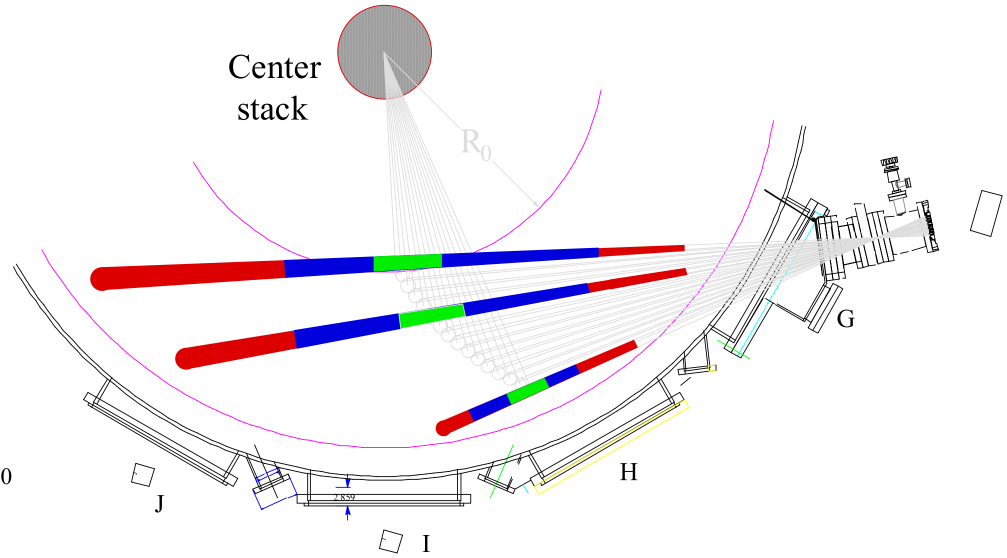
$$b_{ph}(R_{tg}) = \int \varepsilon_{ph}(R)ds$$
$$= 2\int_{R_{tg}}^{R_0+a} \varepsilon_{ph}(R)\frac{1}{\sqrt{R^2-R_{tg}^2}}RdR$$

- The SXR Be foils impose a transmission coefficient *$T(h\nu)$* with a (non-ideal) cutoff energy ($E_{c,50\%}$) determined exclusively by their thickness.

- Since each of the elements of the line-integration is weighted by $\mathbf{n_e^2T_e^{1/2}}$, the summation will be **sensitive** at locations along the sightline on which the power emitted is peaked.

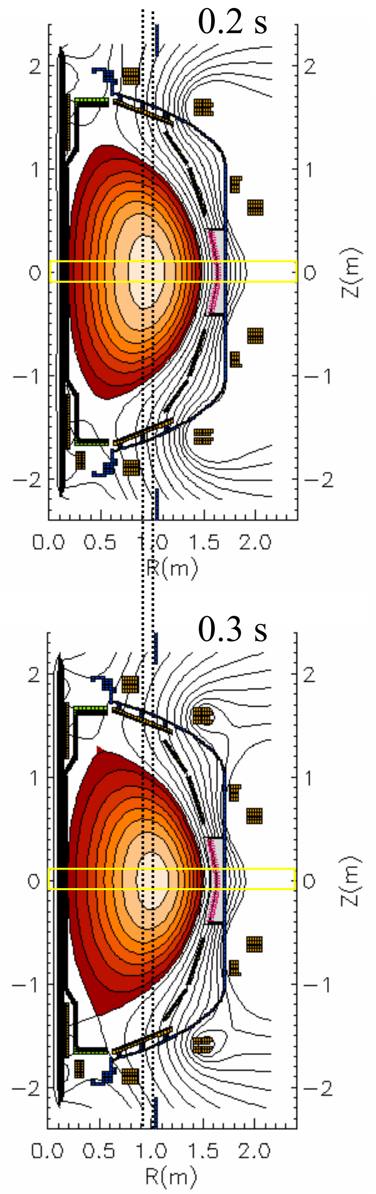
- In the case of peaked profiles those locations with the strongest weight on the line-summation are where the line of sight is tangential to the flux surface.





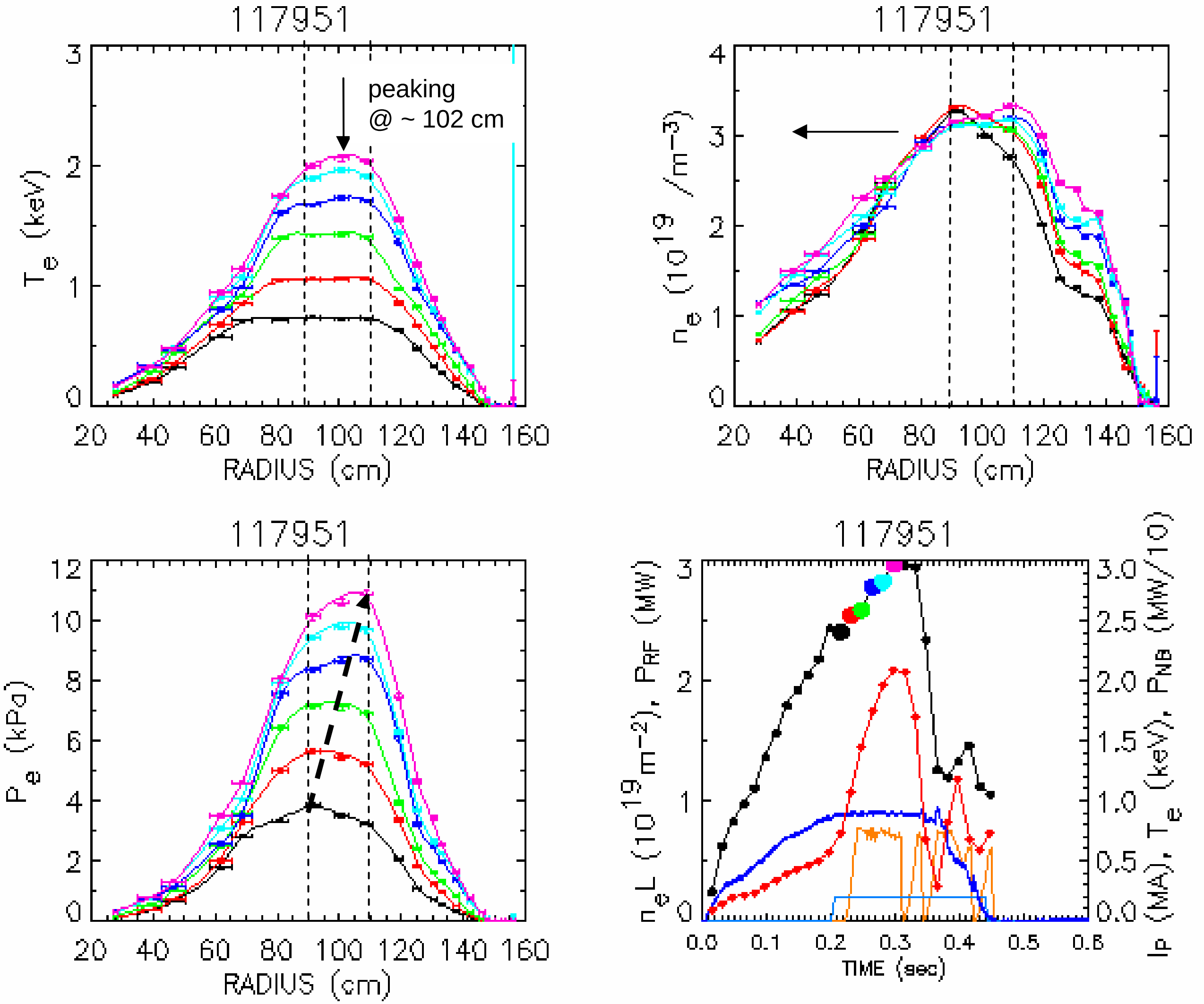
Preliminary results: T_{e0} ~ 2.1 keV L-mode

EFIT02 magnetic flux surfaces reconstruction



MPTS n_e and T_e for $\Delta t \in [0.2,0.3] \Rightarrow$

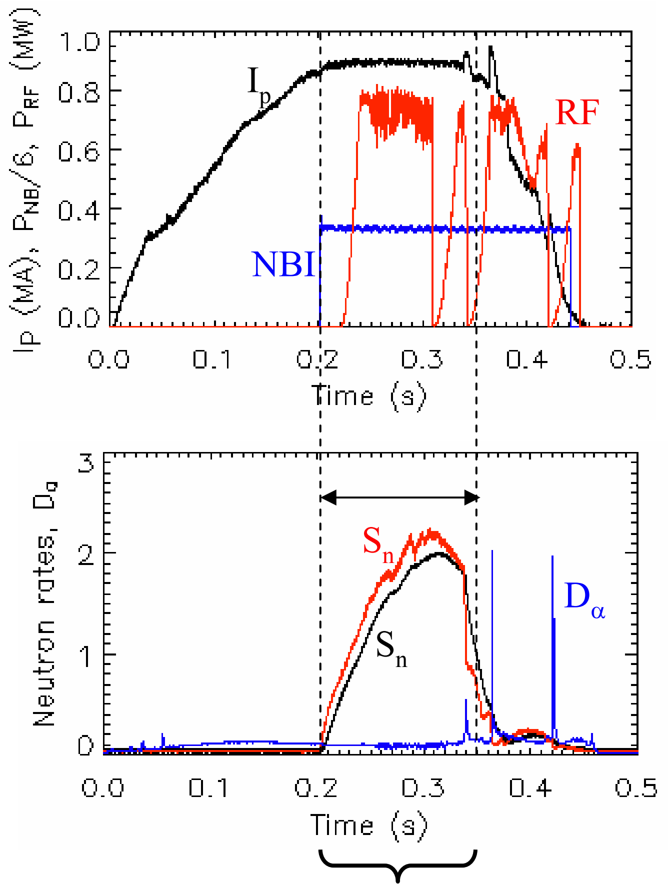
$\Delta\tau_{MPTS}$ ~ 16 ms



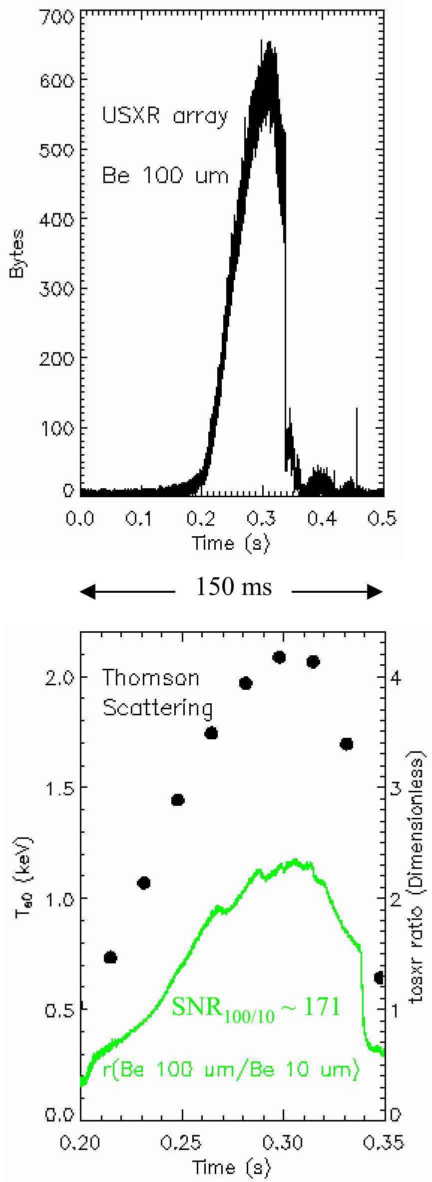
t=215 ms, t=231 ms, t=248 ms, t=265 ms, t=281 ms, t=298 ms

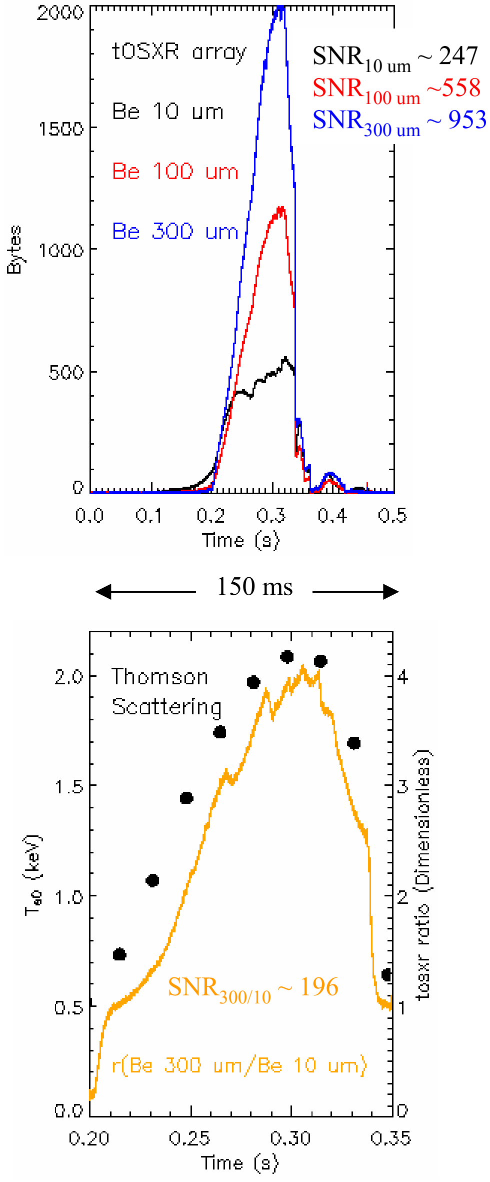
T_{e0} from tangential line-integrated multi-color ratio

NSTX shot # 117951



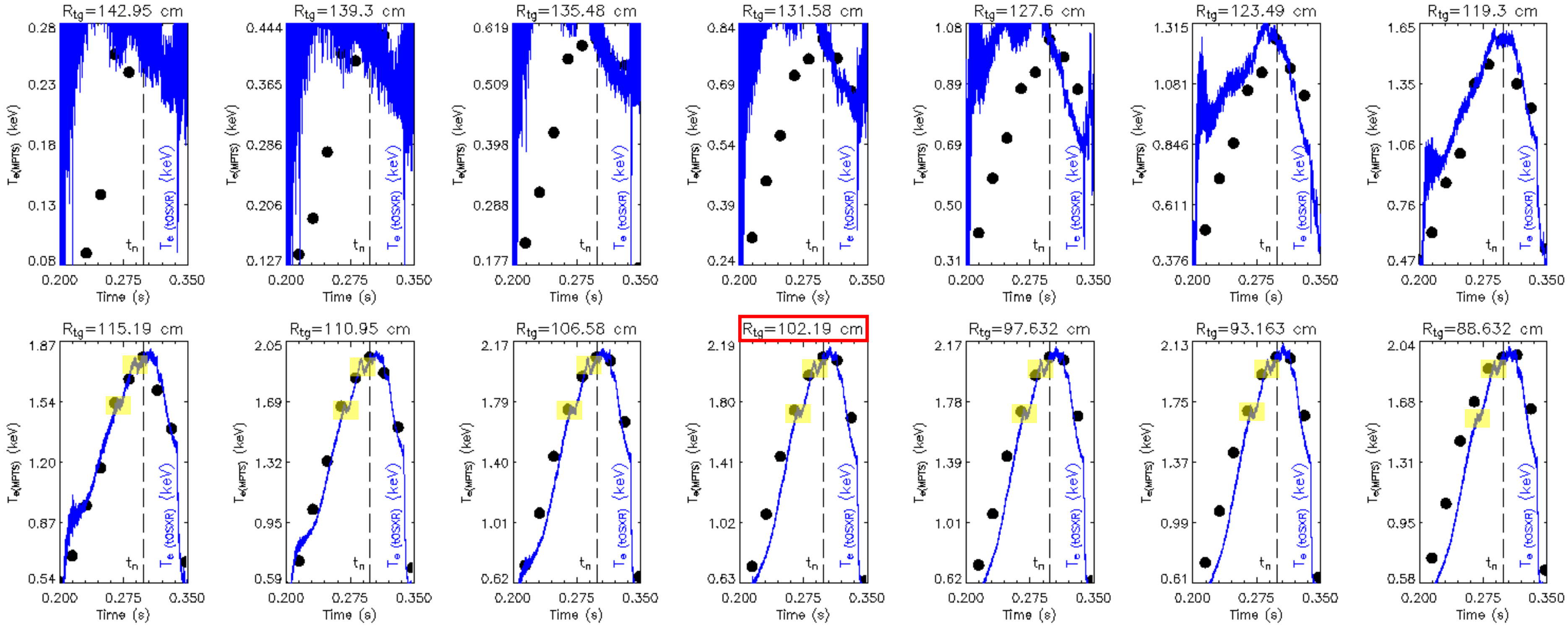
What happen with S_n & T_e for $t \in [0.2,0.35]$?





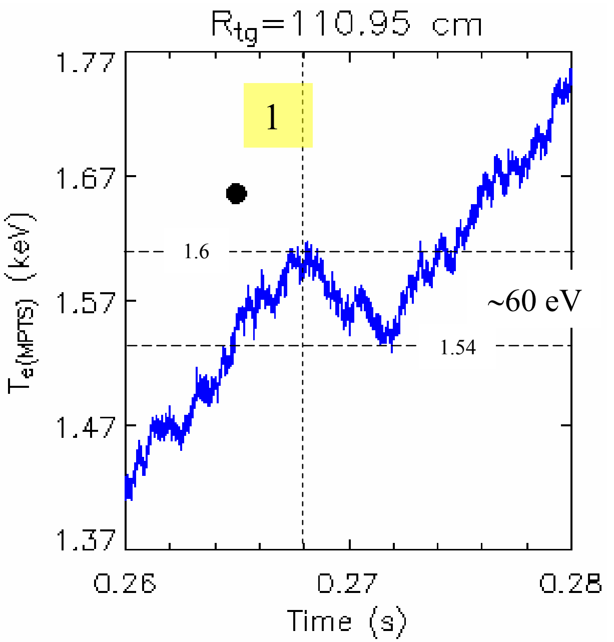
$T_e(r,t)$ from tangential line-integrated multi-color ratio

- tOSXR ratio of 300 μm versus 10 μm Be foils: $\rho_{300/10}(R_{tg},t)=S_{300}(R_{tg},t)/S_{10}(R_{tg},t)$
- Look for splined data from MPTS @ $R=R_{tg} \pm 0.3$ cm (●)
- Forward technique: Fix a time (t_n) @ which is desired to normalize the tOSXR ratios to the T_e from MPTS ⇒ **propagate**!

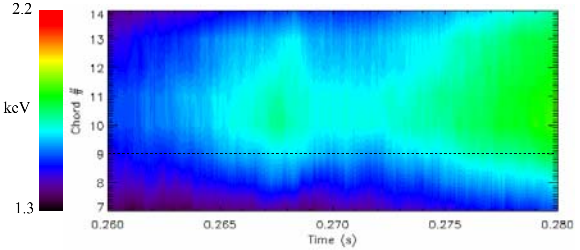


- Since these are profiles derived from line-integrated signals, the accuracy of this first approximation technique for outer radii (R>120 cm) is under discussion.
- Why the drops in T_e (🟨)?
- **Abel inversion is needed!**

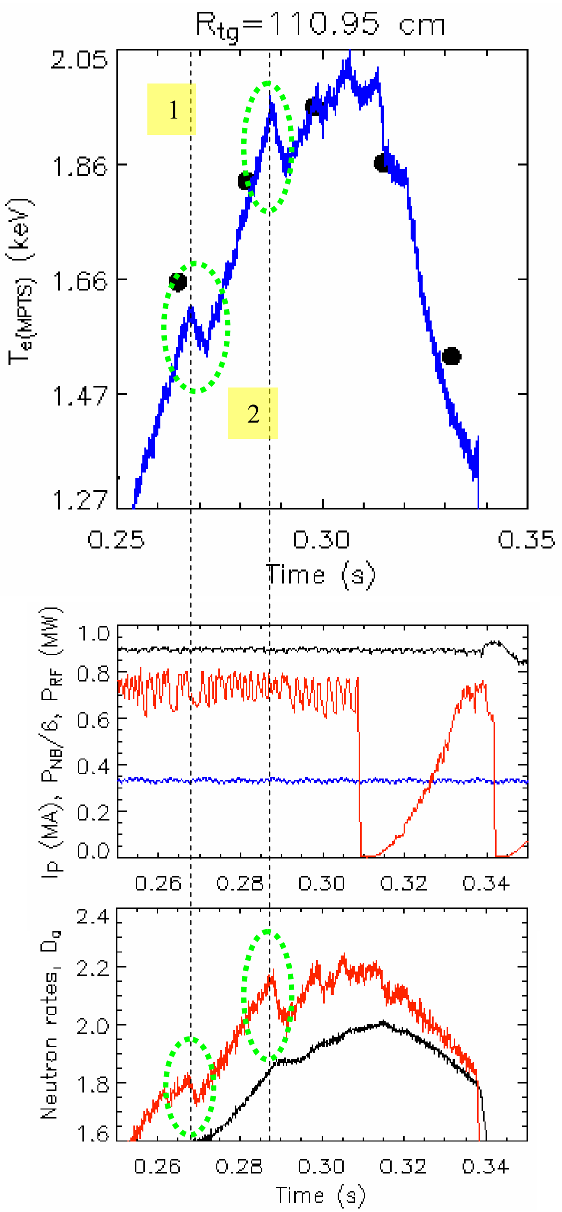
Is the (NBI-plasma) neutron rate (S_n) T_e dependent ?

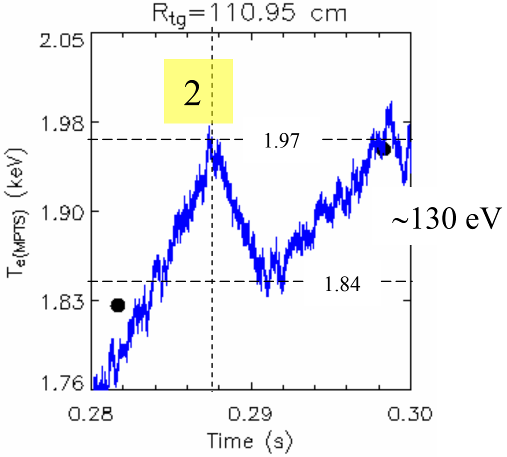


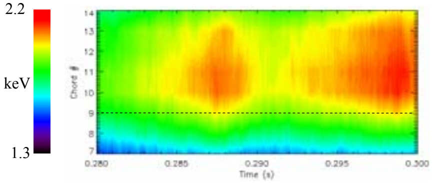
$T_e(r,t)_{tOSXR}$ space-time profile



Are the neutron yield (S_n) and the electron temperature (T_e) related ?





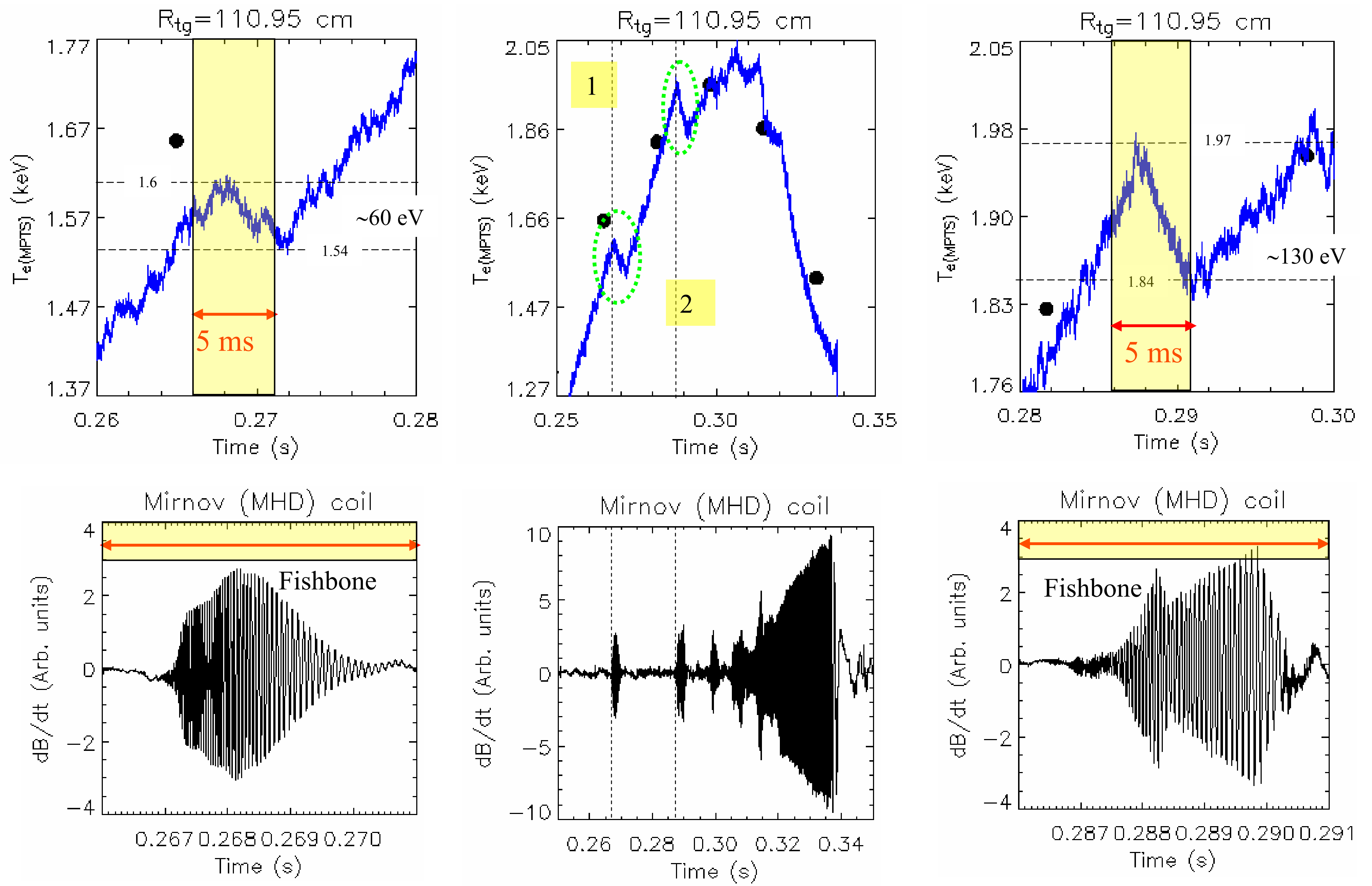


Experimental evidence

$$\frac{S_n}{S_{n0}} \approx \left(\frac{T_e}{T_{e_0}}\right)^{3/2}$$ ✓

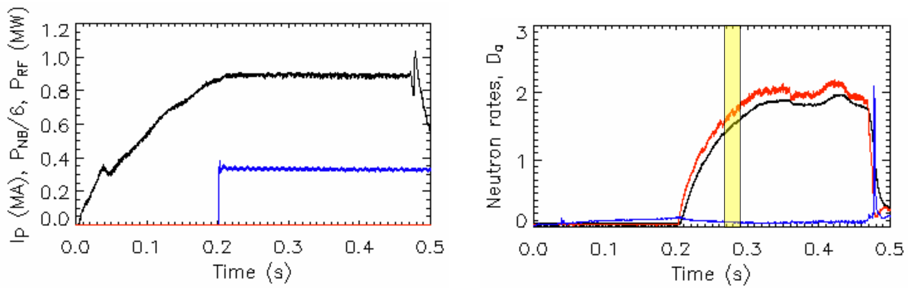
The fast beam-ions density (n_b) directly depends on the slowing-down time **$\tau_{sd}\sim T_e^{3/2}/n_e$**
($S_n/V\sim n_i\cdot n_b\cdot<\sigma v>$; $n_b\sim<\Gamma_b>\cdot\tau_{sd}$)
$\Rightarrow S_n\sim T_e^{3/2}$

$T_e(r)$ **drops**: what is preventing the T_e from peaking?

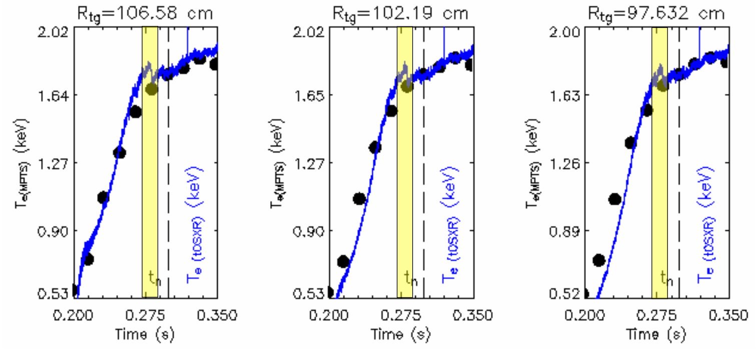


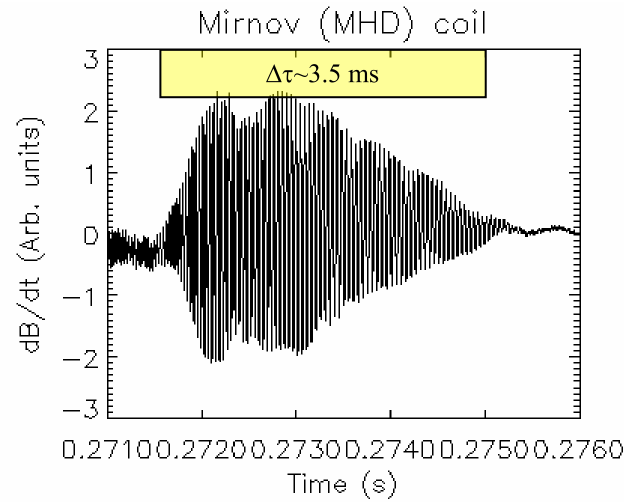
Fishbones limiting T_{e0} during NBI + HHFW

NSTX 117945

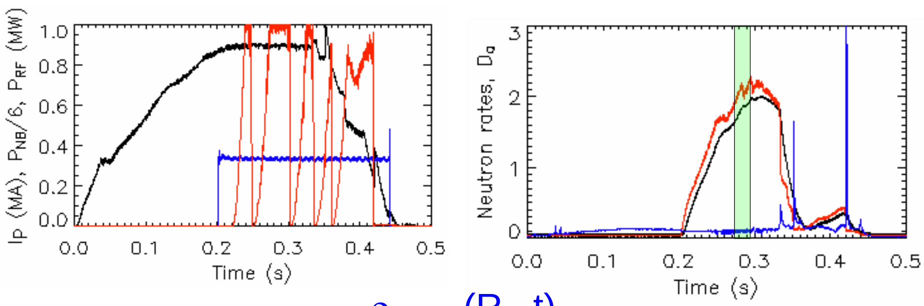


$\rho_{100/10}(R_{tg},t)$

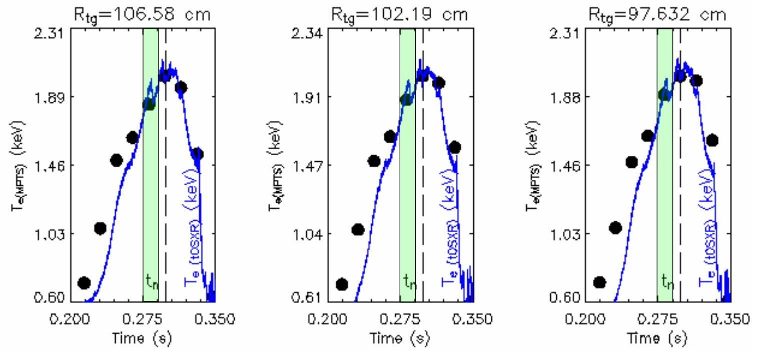


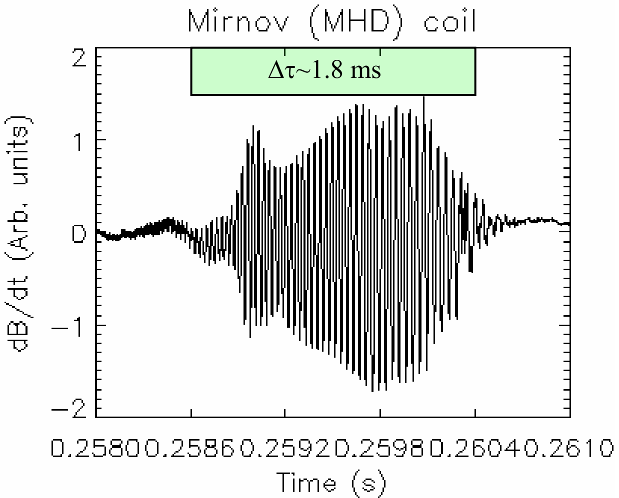


NSTX 117950

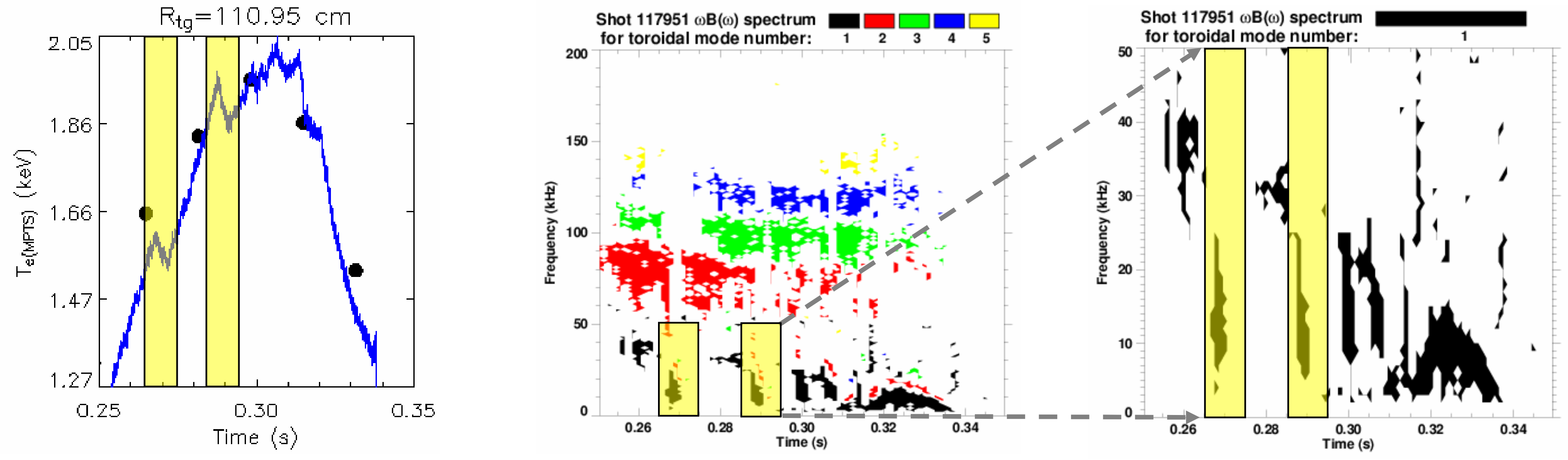


$\rho_{300/10}(R_{tg},t)$





MHD fishbones (n=1) ALSO affect $T_e(r)$ during $\Delta\tau_{fish}<\tau_{sd}$



Summary:

1. **Strong changes in the background plasma:**
   - a) $S_n/V \sim n_i \cdot n_b \cdot \langle \sigma v \rangle$; $n_b \sim \Gamma_b \cdot \tau_{sd}$; $\tau_{sd} \sim T_e^{3/2}/n_e$; $\mathbf{\Delta T_e \sim 50 - 150}$ **eV**.
   - b) Changes in $\mathbf{n_e}$ and the central safety factor $\mathbf{q_0}$

2. **Fishbones prevent the peaking of the electron temperature profile.**

3. $\mathbf{S_n \sim T_e^{3/2}}$ **NBI scaling.**

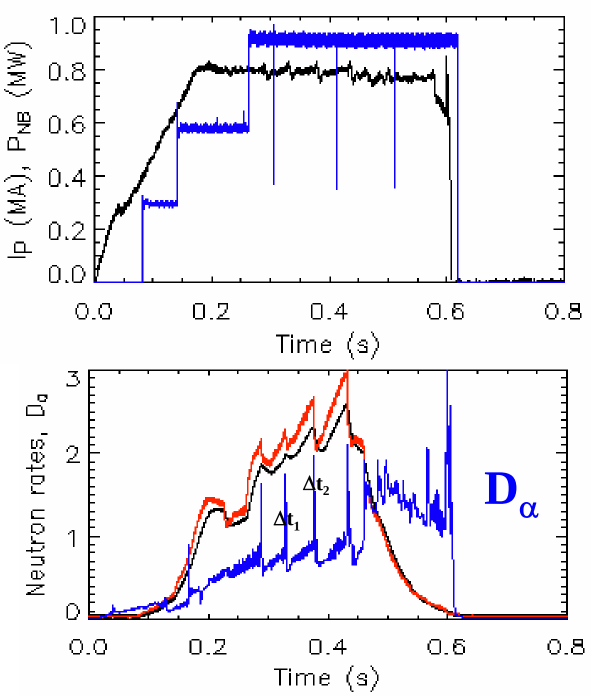
[5] M. F. F. Nave, *et al.*, *Fishbone activity in JET*, NF, **31**, 697, (1991).
[6] B. Wolle, *et al.*, *T_e determination from neutron rate measurements for NBI-heated high density TEXTOR plasmas*, PPCF, **39**, 541, (1997).
[7] T. Kass, *et al.*, *The Fishbone instability in ASDEX Upgrade*, NF, **38**, 807, (1998).
[8] S. Günter, *et al.*, *The influence of Fishbones in the background plasma*, NF, **39**, 1535, (1999).

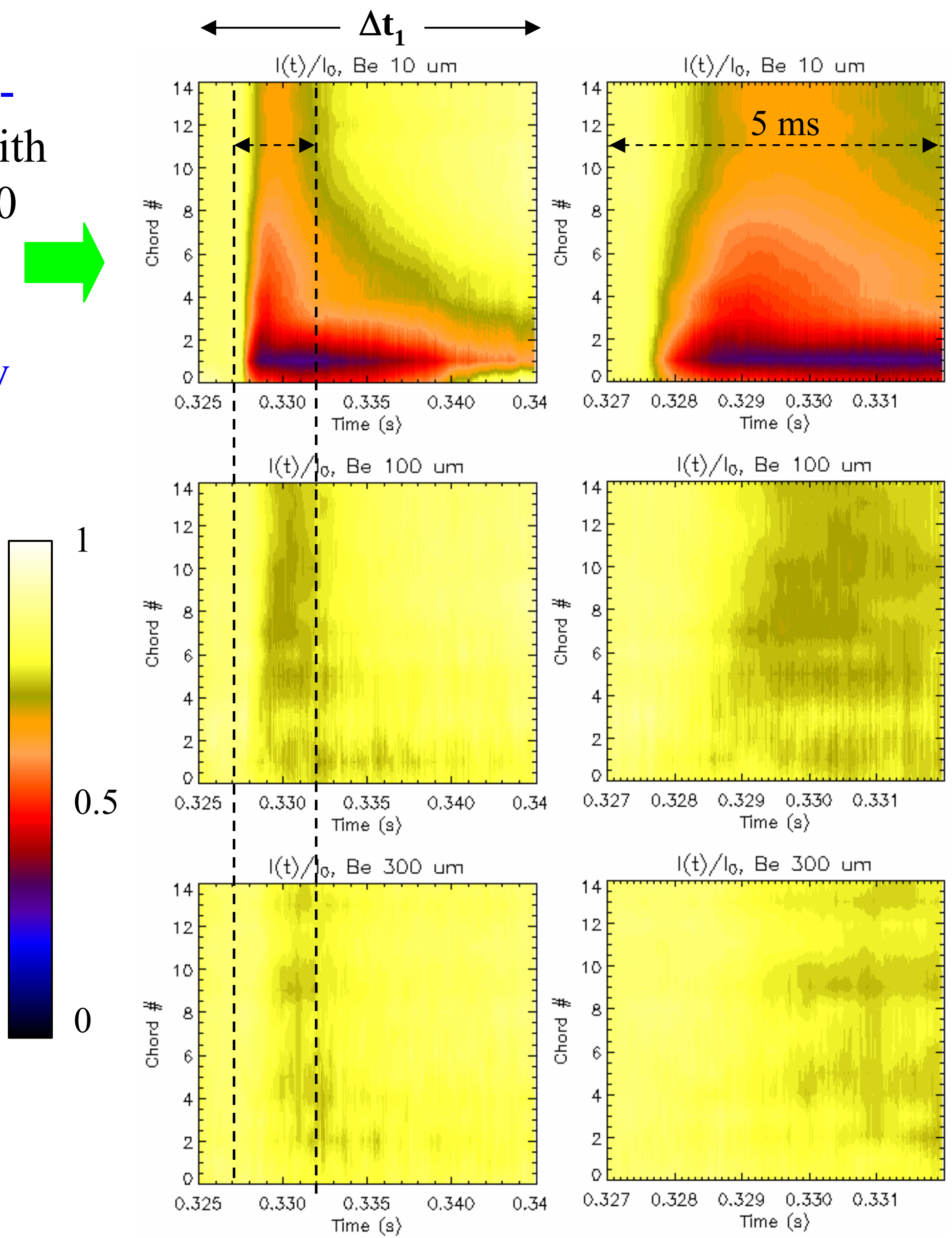
Preliminary results: Type I ELMs study at I_p~800 kA

- Normalized contour plots of tangentially-line-integrated soft x-ray signals, filtered with Be foils with thicknesses of 10, 100 and 300 µm, respectively.

- Shown here is the effect on the soft x-ray intensity of an edge-localized-mode (ELM) occurring at ~ 327 ms

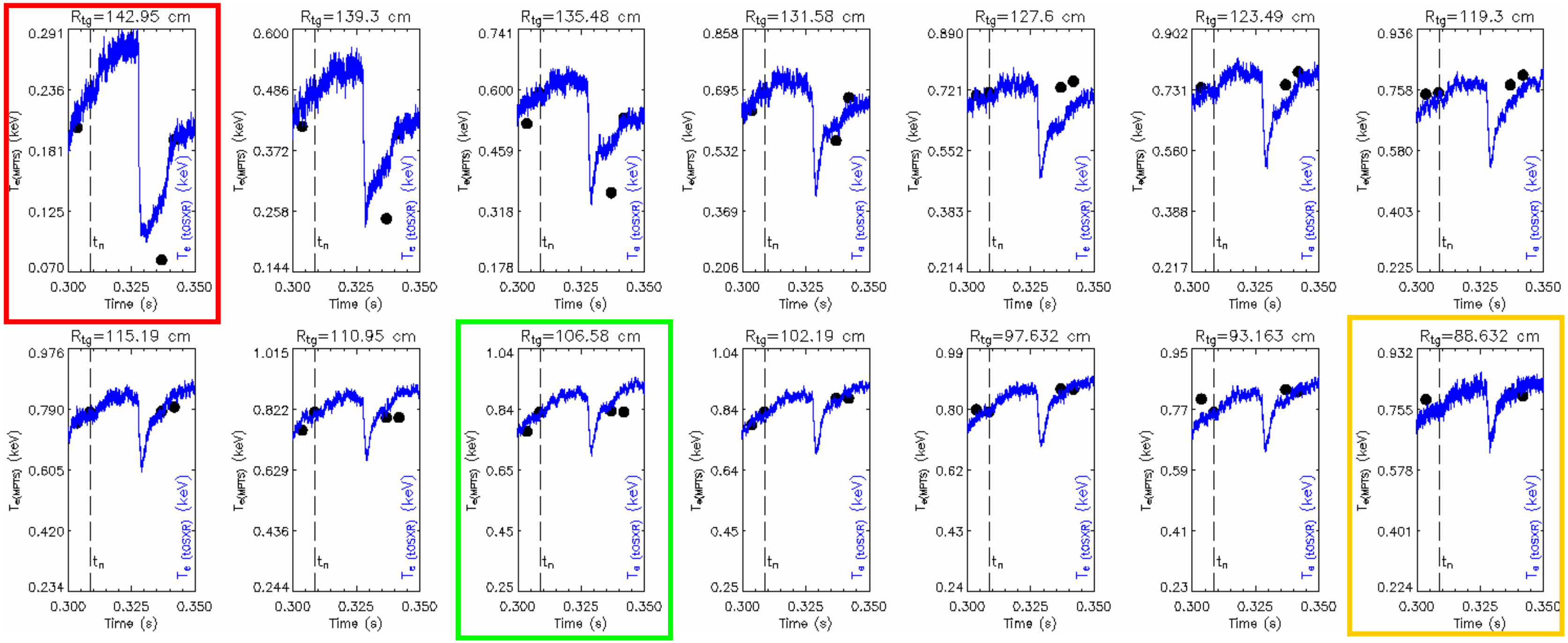
NSTX shot # 117903



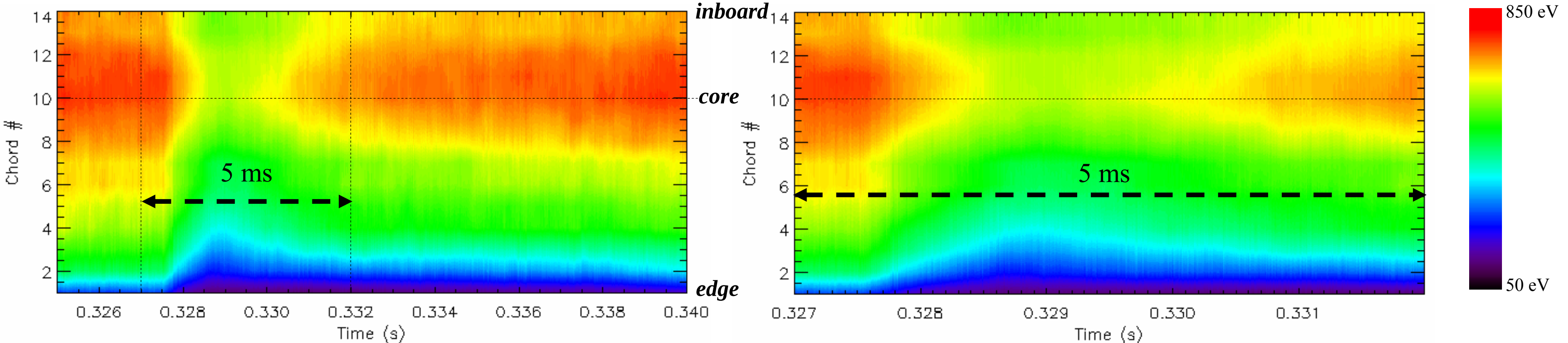


Type I ELM preliminary $T_e(r,t)$ profiles: Δt_1

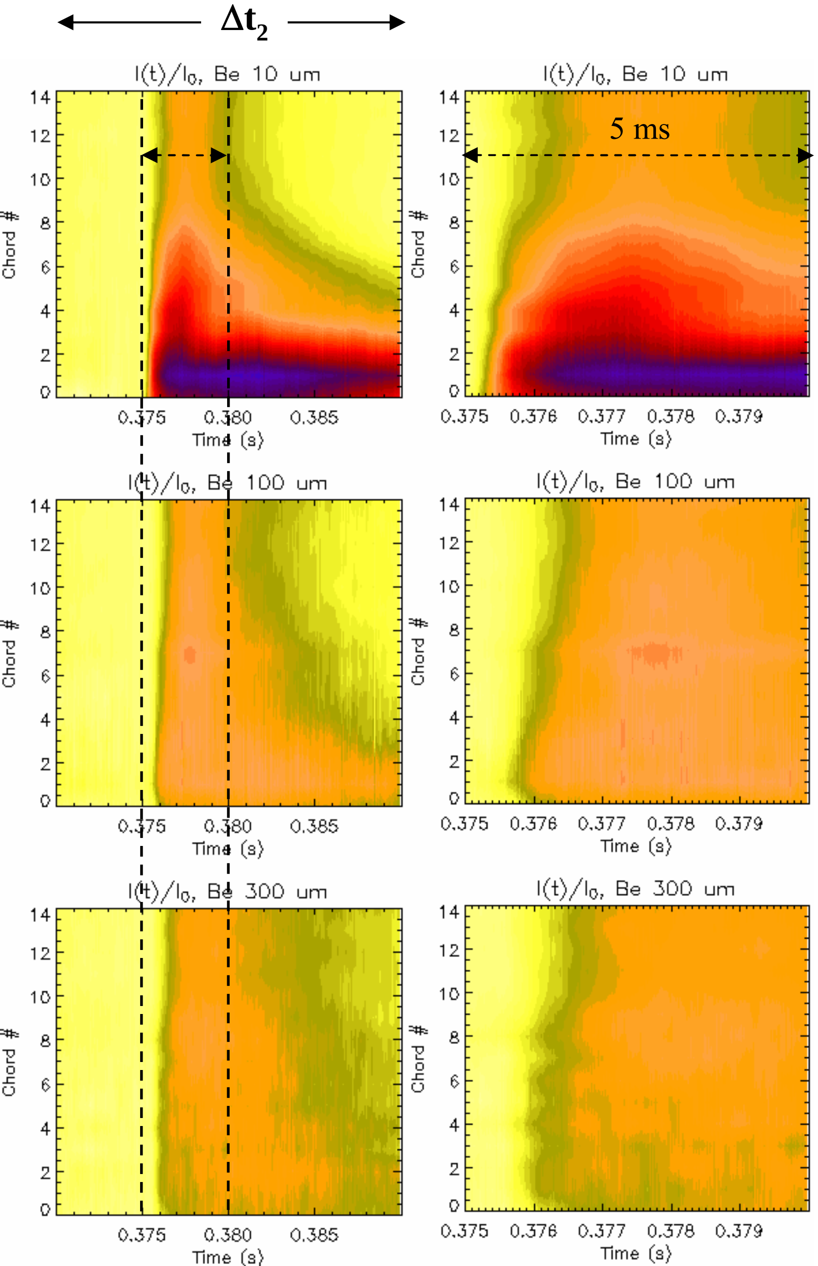
NSTX shot # 117903,
$t \in [0.3, 0.35]$



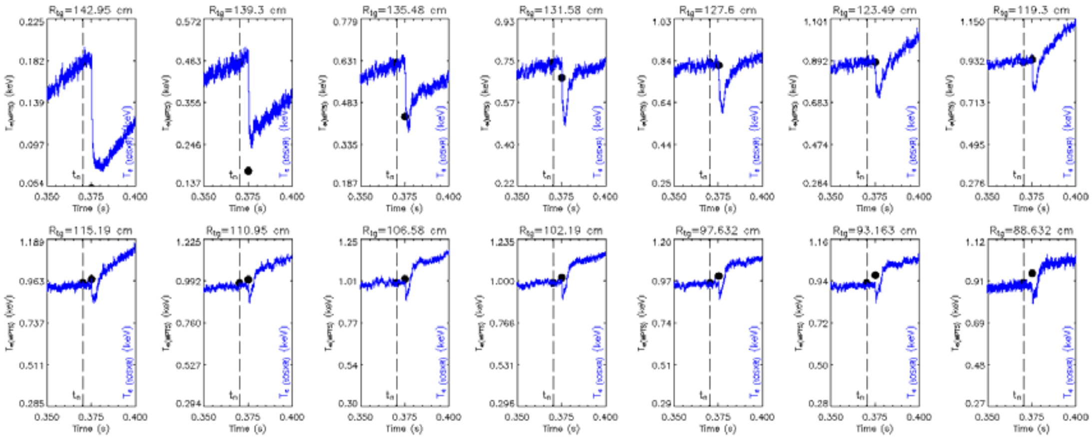
Approximate $T_e(r,t)$ profiles from the multi-color ratio normalized to MPTS



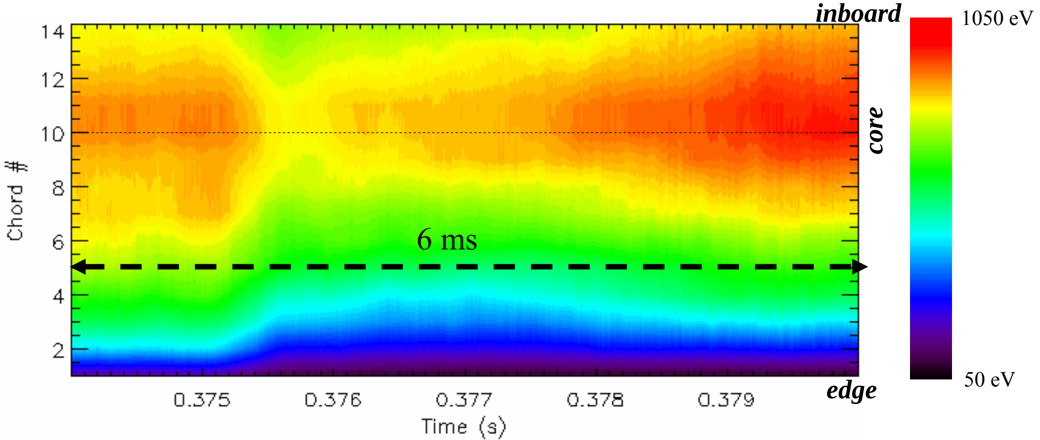
Type I ELM OSXR and $T_e(r,t)$ profiles: Δt_2



NSTX shot # 117903, t∈[0.35,0.4]
(Be10/Be300)



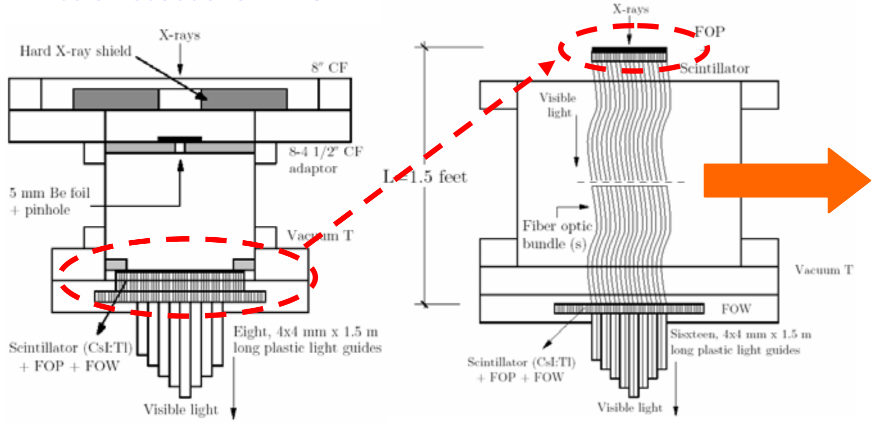
Approximate $T_e(r,t)$ profiles normalized to MPTS



Future: re-entrant "multi-color" poloidal OSXR system?

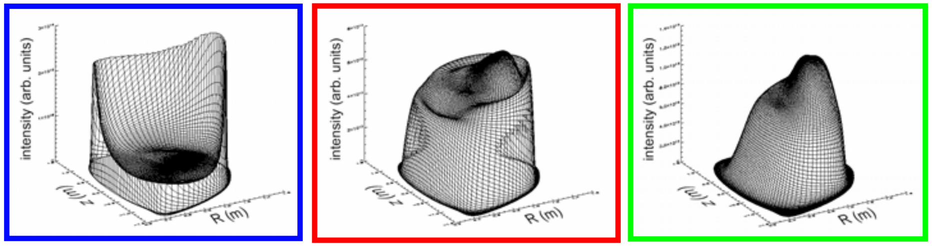
OSXR array head tested on NSTX

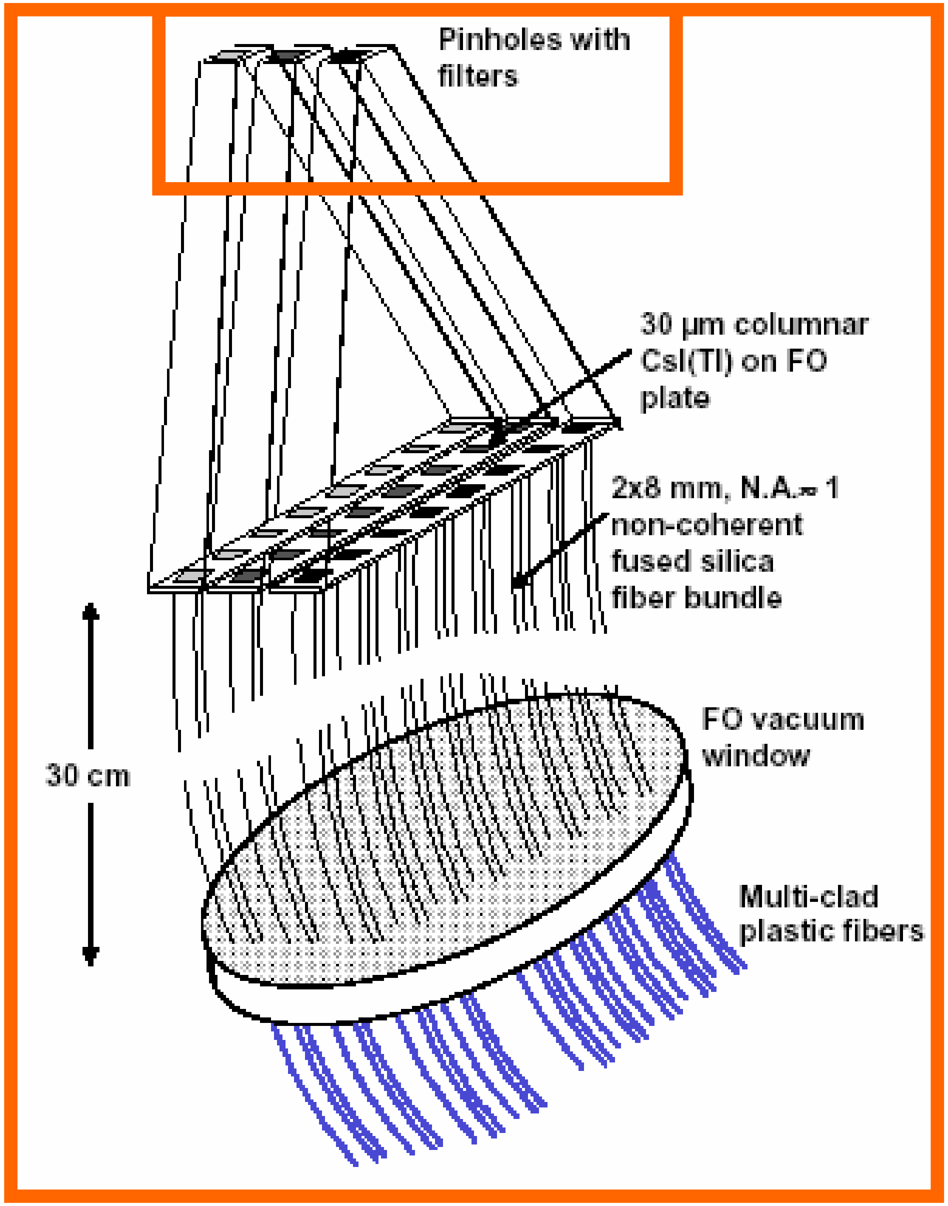
NSTX (07) & NCSX



It's a system based on the OSXR concept with an **optimized plasma access and the capability of recording MHD phenomena from the core to the periphery *SIMULTANEOUSLY*!**

⬇





Further work

- Compare forward modeling to **Abel inversions**!
- **Modify the filter holder** to enable photometric (X-ray and visible light) calibration in absence of the Be foils. Use SXR extended source.
- Use **500 μm Be foil for increase contrast**.
- Use transimpedance **amplifiers (bandwidth: DC-40 kHz)** module behind PMT.

Conclusions

1. We have designed, build, installed and tested the prototype version of a tangential multi-color optical SXR array for fast electron temperature measurements.
2. Line integrated signals enabled the measurement of fast electron temperature profiles in good agreement with the (slow) Thomson Scattering measurements.
3. However in the cases of strong inhomogeneities in the local plasma characteristics the limitation of the use of line integrated signals become apparent.

Acknowledgments

- **The Johns Hopkins University**: Gaib Morris, Scott Spangler, Steve Patterson, Russ Pelton and Joe Ondorff.

- **Princeton Plasma Physics Laboratory**: Mike Bell, Bill Blanchard, Thomas Czeizinger, John Desandro, Russ Feder, Jerry Gething, Scott Gifford, James Kukon, Doug Labrie, Steve Langish, Jim Taylor, Sylvester Vinson, Doug Voorhes and Joe Winston (NSTX).

- This work was supported by The Department of Energy (DOE) grant No. DE-FG02-86ER52314ATDOE

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