Multi-Energy X-ray imaging and sensing for diagnostic and control of the burning plasma

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X-rays can make comprehensive BP diagnostic/control tool

• ‘Natural’ thermal emission of the burning plasma (BP)
• X-ray imaging simple, robust and stand-alone diagnostic
• Single-energy traditionally used for MHD
• *Multi-energy for* enhanced diagnostic/control capability
• Less precise than dedicated diagnostics but also less issues
• *Photon counting detectors*: many energies - low speed
• *Filtered detectors*: few energies - high speed
• Filtered detector multi-energy X-ray imaging tested at NSTX
• *Multi- or even dual-energy capability would strongly enhance ITER X-ray cameras*
• X-ray detector challenges in BP: $n, \gamma$ damage and background, *energetic spectrum*
• ‘Optical array’ detectors, ‘bi-cell’ sensors may offer a solution
Multi-energy X-ray diagnostic (ME-XR or ME-SXR)

- Same plasma volume simultaneously imaged in few energy ranges
- Fast and robust monitor of plasma $T_e$, purity, MHD, position
- $\geq 3$ energies can discriminate ‘hot’/’cold’, ‘clean’/’dirty’ plasmas
- More involved measurements with atomic modeling
Fast $T_e$ diagnostic

**ME-SXR $T_e$ vs. Thomson $T_e$ in NSTX**

- Periodic normalization to Thomson Scattering increases accuracy
- ‘Fill-in’ $T_e$ profiles between TS pulses with high time/space resolution
- Could extend time between TS measurements in BP (first mirror, shutter savings)

**ME-SXR $T_e$ during RF heating**

Delgado et al 2008
Impurity content and transport diagnostic

- Neon injection in NSTX (Delgado et al 2009)

- Three filters discriminate L shell / K shell / fully stripped

- High resolution and accurate transport diagnostic (Clayton et al 2011)
Perturbative electron transport measurements

ME-SXR $T_e$ following giant Type-I ELM in NSTX

$\chi_e^{\text{pert}}$ correlation with ELM severity (Tritz et al PoP 2008)

- ‘Giant’ Type I
- Moderate Type I
- Small Type I

$\Delta W_{\text{tot}} \approx 25\%$
$\Delta W_{\text{tot}} \approx 10\%$
$\Delta W_{\text{tot}} \approx 4\%$
Simultaneous core and edge MHD diagnostic

- ME-SXR ‘decouples’ core and edge MHD in plasmas with flat/hollow SXR profiles
- Flat/hollow X-ray profiles likely in radiating-edge and high $q_0$ BP scenarios
Non-magnetic RWM, ELM, L-H sensing

- Slow $T_e$, $n_z$ perturbations from RWMs, 3-D fields difficult to detect with magnetics
- ME-SXR $T_e$ good indicator of approaching ELM, ME-SXR ‘pressure’ of L-H transition
- Toroidally displaced arrays for real-time ELM, RWM, disruption
Radial X-ray camera proposed for ITER (R. Barnsley ITPA 2007)

- Si X-ray detectors have limited lifetime in BP and poor efficiency for hard X-rays
- More efficient and radiation resistant ME-SXR ‘optical arrays’ studied at NSTX
‘Optical arrays’ could make BP compatible ME-XR detectors

- High-Z scintillator + radiation hardened, B-field tolerant image intensifiers
- High optical gain (>10^4) compensates losses; little n/γ noise at $\phi \sim 10^9$/cm²s on NSTX
- Efficient, rad-hard high-Z scintillators used for ITER fast ion, γ cameras; CsI:Tl?
CsI:Tl is radiation hard and neutron insensitive

Radiation damage in CsI:Tl irradiated with 1.3 MeV γ's

Fast neutron sensitivity of CsI:Tl (Am-α source in neutron background)

- <1 kGy γ dose to CsI:Tl scintillator for ex-vessel optical array during ITER lifetime
- Accepting some light output loss CsI:Tl might work also in-vessel (MGy range)
- Neutron insensitivity due to absence of low-Z elements (low n-α cross section)
- The luminescence due to $^{133}$Cs radioactivation does not appear problematic

Hamada et al NIM 2002

Nesenevich et al IET 2012
Thin CsI:Tl layers efficiently absorb X-rays but not γ’s.

**Fraction Q(E) of absorbed photon energy in CsI layer**

- 100 μm thickness
- 10 μm thickness

**Optical signal**

\[ \propto X\text{-ray flux} \cdot Q(X) \cdot E(X) + \gamma \text{ flux} \cdot Q(\gamma) \cdot E(\gamma) \]

- 10¹⁰ ex-vessel
- 10¹¹ in-vessel
- 4 keV
- 4 x 10⁻⁴
- 4 x 10⁻⁵
- 1000 keV

- Negligible ex-vessel γ background (0.1%)
- In-vessel operation might also be possible using very thin scintillator and extra shielding (in-vessel arrays view colder edge plasma and thus need less efficiency for hard X-rays)
MCP intensifiers can work in high B fields

- Scintillator light amplification possible in the BP using field-aligned intensifiers
- MCP-PMTs for current signal?

Chugunov et al. NF 2011
Radiation resistant hydrogenated fibers developed for ITER

- Fiber optic readout feasible ex-vessel and possibly also in-vessel ($\leq 10^{11}$ n,$\gamma$/cm$^2$s)
- Blue radiation induced luminescence could be spectrally discriminated
- Red emitting phosphors for in-vessel optical arrays
- Coupling with reflective optics another possibility
Bi-cell ME-XR sensors for BP position, centroid control

- 'Bi-cell' ME-XR sensors would collect large amounts of radiation (order of 100 µW/cm²) enabling robust signals for plasma control
- Position, centroid, ELM, RWM sensing using the low-E/high-E signals
- Radiation resistant sensors with optical or bolometer detector (NEP~1 µW/cm²)
Summary

• Dual/multi-energy capability would strongly increase the capabilities of
  BP/ITER X-ray cameras

• ‘Optical array’ design may enable ex-vessel and possibly in-vessel ME-XR cameras

• Non-magnetic BP sensing and control using large area bi-cell ME-XR detectors

• No real solutions yet for X-ray detection in ITER; other important ITER diagnostics
  in the same situation. If ITER is the flagship of the US fusion program then US
  must contribute more – and soon - to solving these problems