Current needs and developments in X-Ray Crystal Spectroscopy for ITER

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ITER-India, IPR, Gandhinagar (Gujrat)

Introduction

ITER measurement requirements
Overview of ITER XRCS systems
- XRCS-Survey spectrometer
- XRCS-Edge spectrometer
Summary

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The XRCS Package

ITER-India has signed procurement arrangements to deliver ‘two’ X-ray Crystal Spectrometers to ITER:

1) XRCS-Edge “imaging 10% of the outer plasma”
   - Ion temperature profile
   - Plasma rotation profile

2) XRCS-Survey “core plasma emission in broad band”
   - Impurity identification
   - Concentration, in-flux

ITER Parameters

MEASUREMENT PARAMETER CONDITION RANGE OF COVERAGE RESOLUTION ACCURACY
1. Plasma Rotation Profile
   - Ne, C rel. conc.
   - Ne, C influx
   - He influx
   - Ne, Ar, Kr rel. conc.
   - Ne, Ar, Kr influx

1. Impurity Species Monitoring
   - Ar, Kr
   - Ne, Ar, Kr
   - Ne, Ar, Kr influx

2. Impurity Density Profile
   - Fractional content, Z=10
   - Fractional content, Z=10

High resolution imaging enables Doppler broadening and Line shifts from the region of interest in plasma

- Thermal broadening of spectra is larger for lighter ions, whereas plasma rotation determination is of high precision for heavy ions.

Impurity Line Doppler effects

The objectives of X-Ray Crystal Spectroscopy on ITER are to,

- Monitor plasma impurities in 0.1 - 10 nm range for the Machine protection and Basic control
- Measure vertical profiles of important plasma parameters for Advance control and Physics study.

Impact of line broadening on line formation

Ar 39.843 3.900e-4 2990 8000
Kr 68.463 2.600e-4 3003 4000
Ne 63.768 2.260e-4 3072 7000
W 63.90 1.796e-4 5958 17000

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Optical Layout for High Resolution

Concept tested on many tokamaks: ALCATOR, TEXTOR, KSTAR etc.

Focus in the plasma for Bragg angle ~48° but for greater angles the sagittal focus is between the meridional focus and the plasma, and the rays will be diverging.

Width in plasma depends on crystal height and Bragg angle.

XRCS-Edge spectrometer

Design option with ‘three’ crystals:
- shutters to select the appropriate lines
- no high precision moving parts!

Three crystals for covering a range of plasma parameters:
54° Ar XVII Ka (3.1219) Quartz 11-20
55° Ar XVIII Lyα (3.3206) Quartz 10-12
53.6° Fe XXV Ka (6.6685) Ge 422
(twice the energy of Ar XVIII Lyα)

Crystals are stacked one above the other
Simultaneous recording of H-like Ar and He-like Fe with energy discriminating advance detector under development.

N- Flux with & without Shielding

Without shield in interspace
With B4C shield in interspace

Relative error

Total n-flux (n/cm²/s)

Performance simulation

For rotation measurements at time resolution 10 ms about 10⁷ count/s are needed.
For temperature measurements, in 100 ms about 100,000 counts/s are sufficient.

Line-of-sight Signals

Results of ADAS and SANCO modeling:

W 40+ to 50+ relevant for the outer plasma.

Chord integral profiles, Ar, Fe, W

Impurity Survey

The Primary role of X-ray Survey system is to monitor, in real time, the impurity content in the ITER plasmas.

Elements which may be abundant in the ITER plasma are:

Wall materials: Be (FW), W (Divertor)
Fusion product: He
Structural materials: Cr, Fe, Ni,..
Other in-vessel materials: Li, O, Mg, Al, Si, Ca, Zr, Mo, Rh,..
Seeded impurities: N (for ELMs control)
Ne, Ar (for Radiative Divertor)

In the worst case, most or all of these species could be abundant in the ITER plasmas and radiate simultaneously (tens of MW).
**XRCS-Survey spectrometer**

First plasma diagnostic

Integrates in EPP-11

Images of H-15 and N-25 are shown: 25, 30 and 35 torr respectively

Vacuum piping

Shielding


**Optical layout for Survey**

- Crystals are curved in 2-D (but not focusing)

**Shadow-XOP Ray-tracing**

- Perpendicular bending of the crystal produces a vertical focusing of the slit image:
  - 2 Pilatus detectors end-to-end (16 cm x 3.5 cm) receives at least 3 spectral channels
- Line width is ~ 50 μm, equivalent to spectral resolution > 1:1000
  - Typical x-ray detector pixels are 50–175 μm

**Crystals, Sensitivity and Resolution**

<table>
<thead>
<tr>
<th>Ch #</th>
<th>Crystal</th>
<th>hkl 2d (Å)</th>
<th>Measurement range (Å)</th>
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<tbody>
<tr>
<td>Ch-1</td>
<td>Ge</td>
<td>422</td>
<td>2.31 – 2.08</td>
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<tr>
<td>Ch-2</td>
<td>Ge</td>
<td>220</td>
<td>4.0 – 3.63</td>
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<tr>
<td>Ch-3</td>
<td>Ge</td>
<td>111</td>
<td>5.52 – 5.92</td>
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<td>Ch-4</td>
<td>ADP</td>
<td>101</td>
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<td>Ch-5</td>
<td>TiO$_2$</td>
<td>200</td>
<td>25.76 – 25.33</td>
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<td>Ch-6</td>
<td>MLM</td>
<td>110</td>
<td>10.89 – 10.00</td>
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<td>Ch-6a</td>
<td>MLM</td>
<td>44.0</td>
<td>18.59 – 30.88</td>
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<tr>
<td>Ch-6b</td>
<td>MLM</td>
<td>320</td>
<td>46.49 – 99.88</td>
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</table>

- All crystals lower and upper cut-offs at the allowed Bragg angles 25–65 deg.
- Overlapping sensitivity coverage between channels
- RP: linear summation (solid) and quadratic summation (dashed)

**MCNP neutronics analysis**

Neutron shield

MCNP neutronics analysis (Improved)

SS + B$_4$C (Diameter ~ 35 cm) (50% + 50%)

Homogenous

MCNP neutronics analysis (Improved)

SS + B$_4$C (Diameter ~ 35 cm) (50% + 50%)

Homogenous

Shut Down Dose Rate (SDDR in μSv/h) calculated at 1 m from closure plate in the PP interspace found low but still higher than its allocated value

**Impurity Spectra**

ADAS and SANCO impurity transport modeling (central chord) for H-mode plasmas

- Database of ~ 5000 spectral lines from potential impurities in plasma
- H- and He-like lines in 1–100 Å

**Predicted Performance**

Survey signal analysis based on modelling data of potential impurity lines in H-mode ITER reference scenario

- The measurements requirements are largely satisfied

**Summary**

- In ITER, intrinsic or extrinsic impurity emissions to perform HR and Survey crystal spectroscopy
  (No problem of light reflections!)
- Detailed design, analysis, and integration with port-plugs ongoing for both XRCS-Survey and XRCS-Edge systems
- Predicted performances have shown design compliance to the measurement requirements

**Outlook**

- X-ray lab sources, components development for prototype R&D, also for environmental testing
Current schedule

<table>
<thead>
<tr>
<th>Milestone</th>
<th>XRC-Survey</th>
<th>XRC-Edge</th>
<th>Status</th>
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<tbody>
<tr>
<td>PA Signature</td>
<td>18-Feb-2013</td>
<td>02-Apr-2012</td>
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<tr>
<td>PDR</td>
<td>09-Nov-2015</td>
<td>29-oct-2017</td>
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<td>26-Oct-2016</td>
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<tr>
<td>Delivery to DA</td>
<td>27-Sep-2019</td>
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<td>Delivery to IO</td>
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Thanks For Your Attention!

Steady State Superconducting Tokamak at IPR, Gandhinagar

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