Enhanced CXRS measurements on JET

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ABSTRACT

During the shutdown of 2004/5 the Joint European Torus (JET) charge exchange recombination spectroscopy (CXRS) system underwent a major upgrade. As part of the upgrade the two new spectrometers were added to the suite of CXRS diagnostics. The new spectrometers complement and enhance the existing CXRS measurement capabilities on JET. These high-throughput, transmission grating instruments allow measurements down to 5 ms resolution. One instrument is optimized for the 529.1 nm C v line, while the other instrument is optimized for the 468.58 nm and 468.6 Hz e lines. This allows for the assessment of CXRS measurements in a carbon-free machine compared to measurements from the existing, upgraded systems, and will include analysis using the new CXSfit routine, developed to supplement KS4fit.

OUTLINE

• Overview of CXRS systems on JET
• ORNL supplied CXRS systems
• Noise Characterization
• Calibration
  • Dispersion
  • Instrument Function
  • Relative and Absolute Intensity
• Measurements
  • CXSfit and KS4fit
• Summary
• Future work

CXRS SYSTEMS ON JET

• JET Charge Exchange Recombination Spectroscopy (CXRS) consists of:
  • Two horizontally mounted periscopes (octants 1 and 7) viewing the heating neutral beams (octant 8, primarily PINI's 6 and 7)
  • Three vertical views of NBI PINI's and background plasma
  • 44 spatial views/periscope covering from outboard mid-plane to beyond the magnetic axis
  • CxSfit and KS4fit
• Measurements providing coverage of spectral range from 430 to 750 nm
• 5 Czerny-Turner
• 7 instruments providing coverage of spectral range from 430 to 750 nm
• 5 Czerny-Turner, ±1 m adjustable wavelength instruments utilizing Jonathan Wright and XCAM CCD cameras
• 2 short focal length, Kaiser-Optical Hollowspec instruments at fixed wavelength with Roper Cascade 512b CCD cameras.

ORNL SUPPLIED CXRS SYSTEMS ON JET

• Two Kaiser Optical Systems, Hollowspec spectrometers (KS5D and KS5E) (3)
  • Short focal length for high light throughput
  • 85 mm entrance lens, 58 mm exit lens
  • Demagnification of entrance slits (2 curved, filtered separator) to fit on CCD chip
  • Interchangeable gratings at fixed central wavelength: 5277 Å (KS5D), 4889 Å (KS5E)

ORNL SUPPLIED CXRS SYSTEMS ON JET (continued)

• With Roper Scientific Cascade 512b CCD cameras (4)
  • Thinned, back-illuminated 512x512 pixel (16x16 µm pixel)
  • Binned to reduce read-out noise and increase framing rate
• Frame transfer from “Sensor Area” requires ~1.25 ms
• “Overlap Mode” data is read-out from the shaded area while a new exposure is collected
  • Read-out time requires ~3.6 ms (depending on binning strategies)
  • On-chip gain can be applied bit-wise as data is read-out

Figure 1: Fig. 1 and Table 1 from Ref. [1] showing details of the JET CXRS system. Also shown is a photograph with the arrangement of the KS5C, KS5D, and KS5E subsystems.

Figure 4: Statistics on the measured synchronization of the KS5D chopper during a JET pulse. A chopper tab shadows the CCD for the time period indicated by the two black lines, while the CCD frame transfer occurs during the time period indicated by the two red lines.

NOISE CHARACTERIZATION [6, 7]

• Unbinned CCD:
  • Signal: \( S = n_\text{bias} + n_\text{reset} + n_\text{elec} \)
  • Photo-electrons: \( S_{\text{elec}} = \text{data or “leakage” light} \)
  • Dark current: \( S_{\text{dark}} = C_{\text{dark}} \cdot t \)
  • C_{\text{dark}} = “Output Gain Conversion” constant ~7 electrons/count
  • C_{\text{reset}} = “C_{\text{reset}}”inch and cooling dependent constant ~5.5 electrons/pixel/sec
  • Bias: \( S_{\text{bias}} = \text{due to electrons injected to CCD} \)
  • Noise: \( N = \sqrt{N_{\text{elec}}^2 + N_{\text{reset}}^2 + N_{\text{dark}}^2} \)
  • Poisson statistics: \( N_{\text{elec}} = \sqrt{\text{bias}} \cdot N_{\text{elec}} = \sqrt{S_{\text{elec}}} \)
  • “XTC” noise, independent of exposure: \( N_{\text{XTC}} \)
  • Capacitance of pixels and readout register may be different, resulting in different \( N_{\text{elec}} \) and \( N_{\text{reset}} \)
  • \( N_{\text{noise}} = \text{noise floor,} \) typically ~70 electrons RMS

• Binned (on-chip):
  • Signal: \( S = 2S = n_\text{bias} + n_\text{reset} + n_\text{elec} \)
  • Noise: \( S_{\text{noise}} = \sqrt{N_{\text{elec}}^2 + N_{\text{reset}}^2 + N_{\text{dark}}^2} \)
  • Pro: Reduces contribution of “reset noise.”
  • Pro: Increases CCD framing rate, due to reduced readout time.
  • Cons: Loss of information contained in individual pixels.

Figure 5: Measured relative “noise” level (%) of various processes affecting the KS5D system as a function of exposure time. Here the chip is binned vertically by ~50 pixels. “Leakage” light from the chopper LED is the dominant noise source at 1%. “Reset,” “bias,” “fixed pattern,” and “dark current” noise each contribute < 1%. Timing uncertainty due to synchronization contributes ~0.1%.
CALIBRATION: DISPERSION

- Consequences of short-focal-length Hollowspec instruments
- Curved entrance slits necessary to effect straight images in exit plane
- Non-constant dispersion across the image plane
- Dispersion can be calculated from first principles
- Calibration necessary to determine “as built” dispersion
- 2 entrance slits: spectra separated via optical band-pass filter
- 10 fibers/stack: total of 20 spatial chords on a single instrument

CALIBRATION:

• Absolute Intensity Calibration
  - Calibration lamps (cold) have negligible spectral line width
  - Because the dispersion is non-constant, the instrumental broadening of spectral lines due primarily to finite entrance-slit width
  - Width of the slit image predominately due to magnification of the instrument:
    - Optical: \( M = \text{f}_\text{exit}/\text{f}_\text{entrance} \)
    - Hollowspec: \( M = \text{f}_\text{exit}/\text{f}_\text{entrance} = 88 \text{ mm} / 85 \text{ mm} = 0.68 \)
    - Hollowspec: \( \text{f}_\text{exit} = 150 \mu \text{m} \rightarrow \text{slit width} = 102.4 \mu \text{m} \rightarrow 6.4 \) pixels
    - KSSE: slit width = 250 \( \mu \)m \rightarrow slit width = 170.6 \( \mu \)m \rightarrow 10.7 pixels
  - Because the dispersion is non-constant, the instrumental line width (\( \lambda \)) depends on location on the CCD chip (i.e. pixel)

Fitting routines have been written for assessment purposes, and indicate that the instruments are performing as expected.

CALIBRATION: INSTRUMENT FUNCTION

- Instrumental broadening of spectral lines due primarily to finite entrance-slit width
- An ideal, infinitesimally narrow (cold) spectral light source produces an image of the entrance slit on the exit plane: slit image
- Width of the slit image predominately due to magnification of the instrument:

\[
M = \frac{f_{\text{exit}}}{f_{\text{entrance}}} = 1
\]

- Hollowspec: \( M = \frac{f_{\text{exit}}}{f_{\text{entrance}}} = 58 \text{ mm} / 85 \text{ mm} = 0.68 \)
- KSSE: slit width = 150 \( \mu \)m \rightarrow slit image width = 102.4 \( \mu \)m \rightarrow 6.4 pixels

- Flexible data input/output (machine independent)
- Quasi-graphical, command line interface
- Save sets re-run for each shot
- Fitting routines have been written for assessment purposes, and indicate that the instruments are performing as expected.

Figure 8: (a) Fit (in green) to spectra from KS5D during JET pulse 67635 at 59°: left (black) and right (red) side spectra. (b) Fit He i spectra from KS5E during the same pulse at the same time. Compressing Gaussian fits are shown for the left (blue) and right (mauve) side spectra. (c) Time evolution of JET pulse 67635 showing neutral beam power. Left: measured line-averaged electron density, and the central C vi ion temperature.

SUMMARY

- Two new, short focal length, Hollowspec instruments for CXRS measurements have been implemented on JET.
- These high light throughput instruments allow CXRS measurements to be made at 10 ms resolution.
- These dedicated C vi and He ii CXRS instruments provide greater flexibility to the JET CXRS suite of diagnostics, allowing the J. tunable Czerny-Turner instruments to be utilized more fully.

FUTURE WORK

- Track and wavelength dependence of instrument function needs to be fully implemented.
- Comparisons between KS5C and KS5D data.
- Comparisons between CXSfit and KS4fit analysis of KS5D data.
- Implementation of KS5C in CXSfit.
- “Realtime” implementation of KS5D data control.
- CHEAPing of data from CXSfit.
- Preparations for 5 ms framing period operation.

REPRINTS

Electronic copy available at:
http://sprunt.physics.wisc.edu/biewer/APS06poster.pdf

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REFERENCES

[9] Codes under development, for information contact A. Whiteford (allan@phys.strath.ac.uk).