EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(06)01–10

C.R. Negus, C. Giroud, A.G. Meigs, K-D. Zastrow, D.L. Hillis
and JET-EFDA Contributors

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and JET-EFDA Contributors*

[1]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[2]*Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee 3783, USA.*
** See annex of J. Pamela et al, "Overview of JET Results ",*
(Proc. 20th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in Proceedings of the
16th HTPD Topical Conference on
High Temperature Plasma Diagnostics,
(Williamsburg, Virginia, USA, 7th May - 11th May 2006)

ABSTRACT.

Charge Exchange Spectroscopy is a key diagnostic on the Joint European Torus for radial profiles of ion temperature, toroidal rotation, and impurity densities. This paper describes the current status and the improvements made over the last 5 years. The current system consists of 2 periscopes looking at one of the 2 banks of neutral heating beams, ≈90 optical fibres defining viewing directions, and 7 spectrometers with CCD cameras. The upgrade has involved: replacement of the 2 periscopes and windows; a doubling of the number of optical fibres (plasma viewing directions); new cameras for the existing spectrometers, improvements to the throughput and long-term stability of the 5 existing spectrometers; and the addition of 2 new high-throughput spectrometers with their CCD cameras from ORNL. This work has culminated in improved spatial resolution, increased sensitivity of all the plasma viewing channels (for some by a factor ~3 or more), and enhanced time resolution from 50ms to around 10ms.

1. INTRODUCTION

Charge Exchange Recombination Spectroscopy (CXRS) is the study of visible radiation from highly stripped ions [1, 2]. The process is generated by the interaction of neutral particles with the plasma. Deployment of a series of optical viewing lines intersecting the 20MW heating beams defines a number of plasma volumes and leads to spatial resolution across the toroidal plasma volume.
The CXRS system can be used to determine:

- ion temperature from Doppler broadening of emission lines
- plasma rotation from Doppler shift
- impurity ion densities.

2. SYSTEM

The system (figure 1) consists primarily of 2 horizontally-mounted periscopes, optical fibres and an array of spectrometers for the 430-750 nm region. The periscopes view the neutral heating beams. Each periscope has a small optical head consisting of a mirror and lenses to image the plasma on to an array of optical fibres set in the focal plane.

The intersection of the fibre lines of sight and the neutral beams define a number of plasma probevolumes situated along the neutral beams and fanning out approximately radially from the centre of the toroidal plasma vessel. Each periscope has some off-beam views of the plasma for background signals, figure 2.

The optical signals are transmitted, via optical fibres, out of the radiation environment of the torus hall, to the diagnostic hall where spectrometers with CCD cameras record the spectral information with time and spatial resolution. Each spectrometer-CCD subsystem records 13-20 optical views. In addition to the two periscopes, there are 3 vertical views of the neutral beams and plasma through a top window.

3. ENHANCEMENTS

During the last 5 years, the CXRS system has been upgraded in the following way:

- the optical windows, through which the two periscopes view the plasma, have been replaced to restore the optical transmission from ~60% to 86%
- the two periscopes have been replaced to:
  - double the number of viewing lines from 22 to 44 per periscope by the addition of new hightemperature optical fibres
  - rectify some deterioration in the old periscopes due to their continuous use at high temperature (i.e. between 200 and 320^{o}C)
- the 5 existing ~1m, Czerny-Turner Spectrometers have received:
  - modified input optics to reduce vignetting
  - new optical mount to improve alignment stability over periods ~ 1 year
  - new CCD cameras to enhance the time resolution from ~50ms to ~10 ms
- two new, high-throughput spectrometers have been added with their own high-speed CCD cameras
- new data-aquisition systems have been developed for the 2 new types of CCD cameras.

4. WINDOW AND PERISCOPE

A window tube (one per periscope) is ~2m long with a double, fused-silica window approximately coincident with the protective tiles of the torus vacuum wall. The window is protected by a remotelyoperated shutter, it can operate to 320 °C, and forms part of the toroidal vacuum vessel. The windows interspace is pumped independently of the vessel.

Each periscope resides, at atmospheric pressure, inside a window tube. Each periscope has an optical head consisting of an aluminium-coated nickel mirror, a 3 fused-silica telecentric lens system, and 44 optical fibres (figure 3). Each optical head is mounted on 2 pairs of torsional pivots which allow fine insitu x- and y-pointing adjustments by two stepper-motor-driven rods running the length of each periscope. Each periscope has a motorised, rotational-pointing adjustment, Φ, relative to the window.

The upgrade/replacement of the two periscopes has entailed:

- doubling the number of optical fibres and viewing directions
- re-designed linear bearings for the x-y pointing-control rods to withstand prolonged use at high 200- 320°C
- redesigned fibre holder in the optical head to prevent disintegration at the high temperatures
- curved input face to fibre holder for better probe-volume definition
- redesigned lens holders to prevent lenses cracking under thermal cycling.

5. OPTICAL FIBRES

The fibre-optical looms are in 3 sections: (a) periscope, ~5m; (b) periscope to basement, ~20m; (c) basement to diagnostic hall, ~70m. To prevent loss of fibre transmission during periods of enhanced neutron production, sections (a) and (b) have aluminium-coated fibres that can operate at temperature in the range 200 to 320^{o}C. At elevated temperatures, the transmission of Si/Si fibres is restored between JET pulses (typically 10 minutes) [3]. The fibres of section (a) are inside the periscope and heated by the vessel-wall heating. The fibres of section (b) are heated electrically by mounting the fibres inside heated hoses of ~60mm outside diameter.

The fibres have an attenuation of less than 40 dB / km and a numerical aperture (NA) of 0.22. The fibre NA matches the output NA of the optical head, but is smaller than the input NA of the highthroughput spectrometers and larger than the input NA of the Czerny-Turner spectrometers. Further details on the fibres are given below.

The fibre transmissions have been measured between the torus and diagnostic halls (~90 metres, sections b + c, includes 1 connector loss ≤1dB).

The fibre transmissions have been measured between the torus and diagnostic halls, a distance ~90metres and a fibre connection in the basement. The new fibres showed ~60% transmission, while the existing fibres (measured by a different technique) showed an average transmission of ~30%.

Several types of connectors are in use:

- JET-designed 27-way connectors
- Lemo single-way plugs (JET modified)
- Lemo 12-way connectors
- SMA plugs and ST connectors
- Lemo to SMA adapters (JET designed).

There have been problems in operating commercial connectors at elevated temperatures: either the connectors fall apart or they cannot be separated by forces less than ~1000 Newtons. We are currently experimenting with a JET multiway design to eliminate the latter problem.

The upgrade has consisted of:

- 2 new fibre looms, each of 3 sections, and each of 22 fibres
- new heated hoses
- redesigned fibre adapters/connectors
- new electrically-heated fibre junction boxes in the torus hall
- new fibre junction boxes in the spectrometer enclosures, in the diagnostic hall.

6. SPECTROMETERS

There were 5 Czerny-Turner spectrometers (typically f/10, 1-m instruments, instrument function ~ 3Å, spectral range ~100 Å, 13 fibres per slit). These have been upgraded to:

- increase the light throughput by new improved pre-spectrometer optics by a factor of >3 (fig. 4)
- new camera mounts for better long-term stability (i.e. ~1 year).

In addition, 2 compact, high-throughput, holograph spectrometers have been added. These have 2 slits each with 10 fibres per slit and a filter to separate the 2 spectra per spectrometer [4, 5].

7. CAMERAS

The CCD cameras are all back-illuminated frame-transfer cameras, with either air or water-cooling. Four of the 5 original spectrometers had their ~15 years old Jonathan Wright cameras replaced by Xcam cameras, primarily to increase the time resolution from ~50ms down to 10 ms. The new cameras also have better quantum efficiency above 400nm due to improved CCD technology. Further camera details are listed below.

Supply	Array size	Pixel size µm	Peak Q. E. at 600 nm	A-D conversion	Intergration & readout time for spectral data	Coolant & operating temperature
Wright	385*289 vertically	22.5*22.5	~60%	15 bits	~50 ms	Air / -40° C
X-cam	560*528 vertically	13 * 13	92-95%	14 bits	<10 ms	Water / -30° C
Roper	512*512 vertically	16 * 16	90-92%	16 bits	<10 ms	Air / -30° C

JG05.591-12c

In the case of the high through-put spectrometers, their Roper CCD cameras are coupled to a rotating mechanical chopper that blocks incoming light during the frame transfer time of 1 ms [4, 5].

8. PROBE VOLUMES, ALIGNMENT AND CALIBRATION

The neutral beams are in the region of 2 to 3m from the optical heads of the periscopes. The active plasma volumes, one for each viewing direction are defined by the intersection of the neutral beams and the viewing directions. A typical viewing direction has a beam width ~ 5 cm at the beams which are ~25 cm high by 15cm wide. The plasma probe volumes are therefore inclined cylinders, which are further inclined to the local radius vector. In consequence, there is generally an overlap of adjacent probe volumes radially, figure 6.

The pointing alignment of each periscope is set by back illuminating the optical fibres with a laser. Initially alignment is done in the laboratory, using only a periscope and screen set in the plane of the neutral beams. Final alignment is when the periscope is installed on the machine and heated. Separate cameras are used to view the intersection of the lines of sight on the torus wall. Small corrections can then be made remotely using the motorised x, y, and I movements described previously.

Intensity calibration is by a standard lamp in a hollow ceramic sphere that is placed in front of periscope in the torus hall (when the periscope is removed from window tube). The remaining factor in the intensity calibration is the window transmission. This is determined when the vessel is up to air. A laser beam is sent through the window and back reflected by a corner cube. The returned beam is measured with a power meter, with and without the window in the beam. Resolution and dispersion are determined with small capillary-discharge lamps emitting line radiation.

9. PERFORMANCE

The calibration and dispersion data are in the final stage of analysis. The results from JET restart so far confirm that the sensitivity and time resolution have increased by factors of 5 or more. During a recent shot at JET, exhibiting 20Hz ELM-s, factors of 2, 3 & 20% variations in intensity were observed in the C^{+2}, Be^{+1} & passive C^{+5} emission lines respectively, due to the 5-times increase in camera readout time, while the active C^{+5} intensity remained constant; such oscillations were not possible to see at all with the previous time resolution of 50ms.

ACKNOWLEDGEMENTS

This work was funded jointly by the UK EPSRC and by the European Communities under the contract of Association between EURATOM and UKAEA; and supported by U.S. DOE contract DE-AC05-00OR22725.

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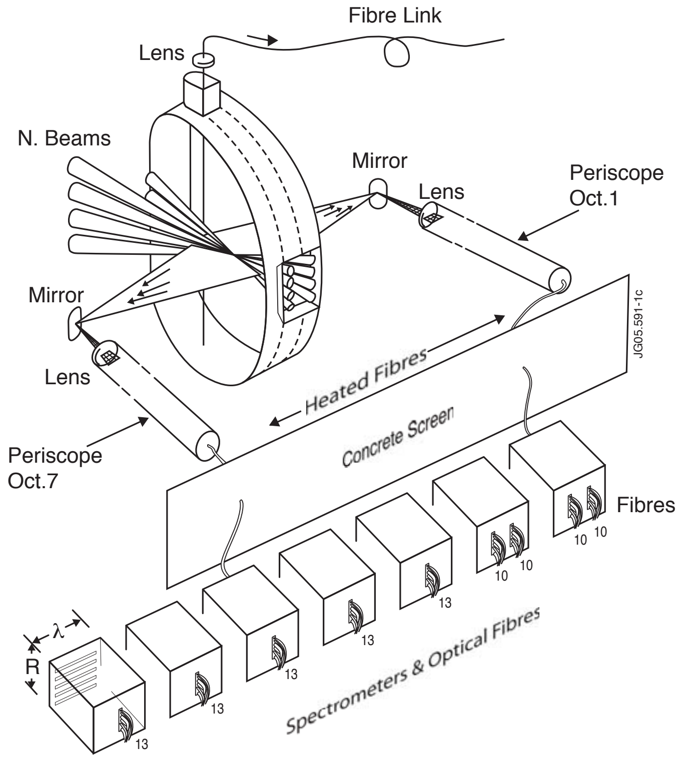

Figure 1: The new JET CXRS System.

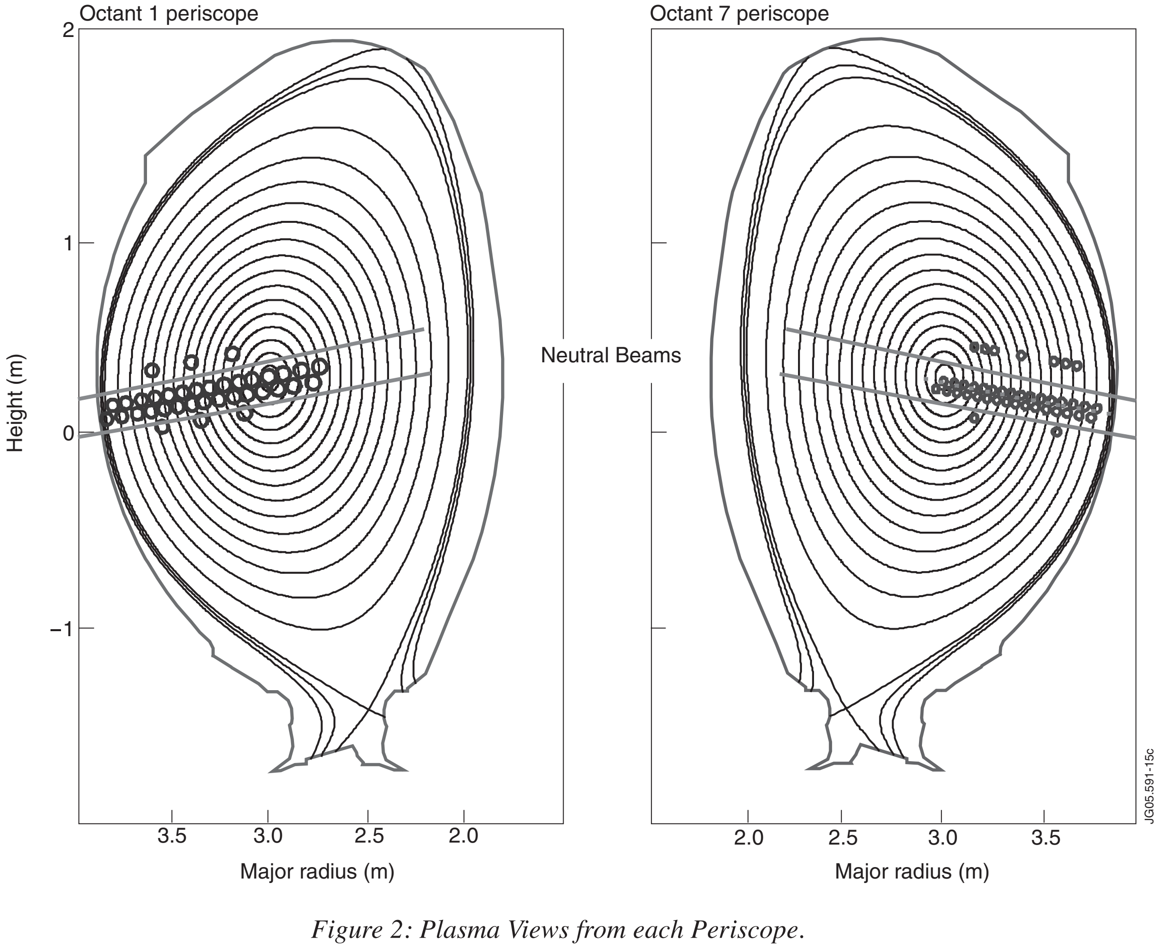

Figure 2: Plasma Views from each Periscope.

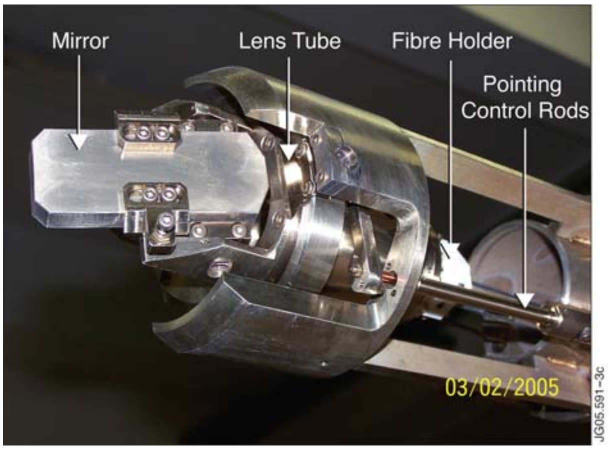

Figure 3: Optical Head of Periscope.

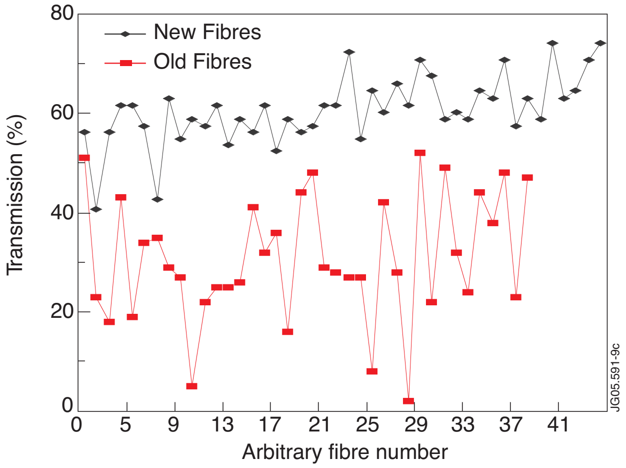

Figure 4: Fibre Transmissions.

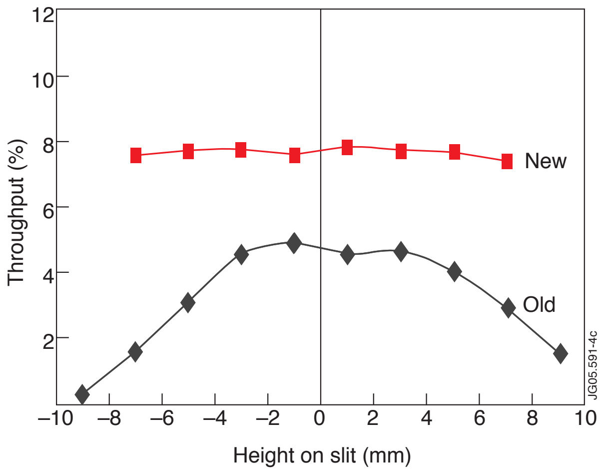

Figure 5: Improved throughput of the existing Czerny-Turner Spectrometers.

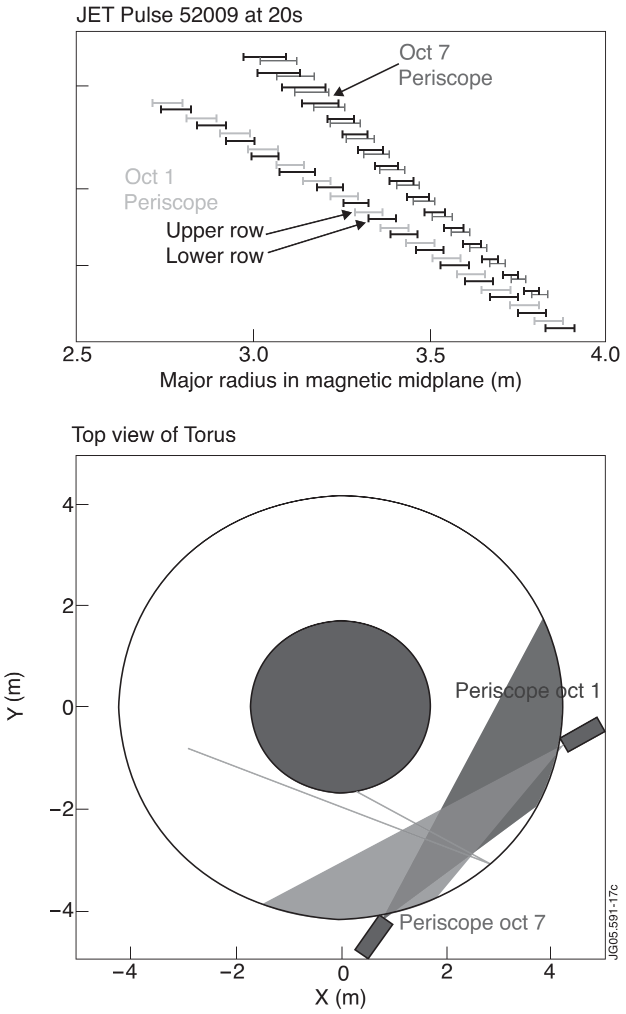

Figure 6: Plasma Probe Volumes and Radial Resolution Overlap.

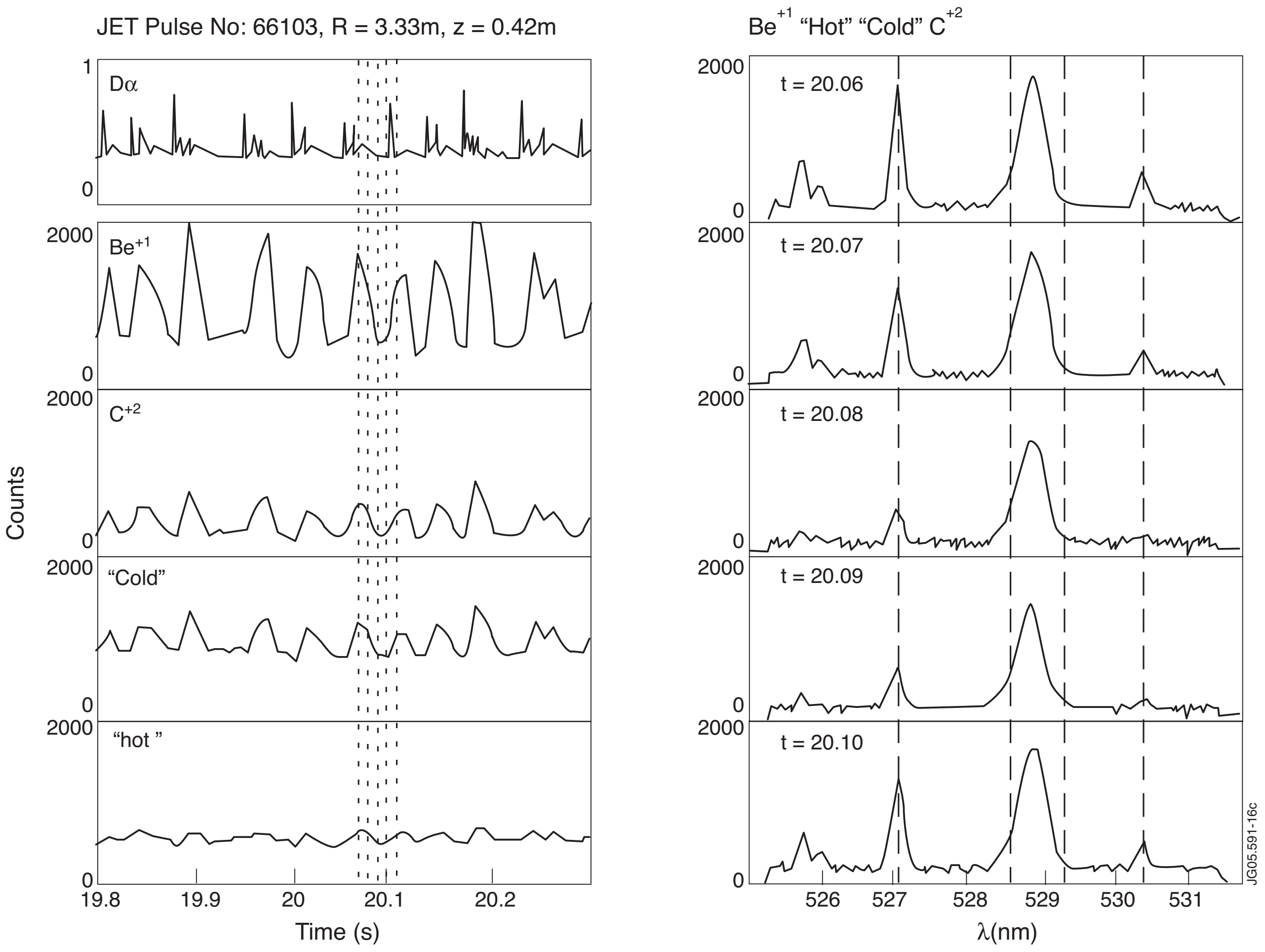

Figure 7: Intensity Oscillations now trackable with 10ms resolution CCD Cameras