Charge Exchange Recombination Detection of Low-Z and Medium-Z Impurities in the Extreme UV Using a Digital Lock-in Technique

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More sensitive detection of charge exchange recombination lines from low-Z elements, and first-time detection from the medium-Z elements nickel and copper, has been achieved in DIII-D plasmas with a digital lock-in technique. That portion of the extreme UV (EUV) spectrum varying synchronously in time with the square-wave modulation of a high energy, neutral heating beam is extracted by forming a scalar product of a correlation function with the data record of each pixel in the linear array detector. The usual, dense array of collisionally excited, metallic lines from the tokamak plasma are strongly suppressed, leaving only a sparse spectrum of lines dominated by charge exchange recombination transitions from fully stripped, low-Z elements. In plasmas with high metal content, charge exchange recombination lines from the Li-like ions of nickel and copper have been positively identified.

Overview

- A digital lock-in technique has been employed to extract beam-correlated CER emission from EUV spectra.
- In low-Z elements, the CER emission from H-like ions can be followed to high n-values in the n-2, n-3 and n-4 Rydberg line series.
- For medium-Z metals, CER transitions have been detected in the EUV from the Li-like charge states of nickel and copper.
- With the broad □-coverage of DIII-D's EUV survey spectrometer, impurity concentrations of low-Z and medium-Z elements may be monitored simultaneously.

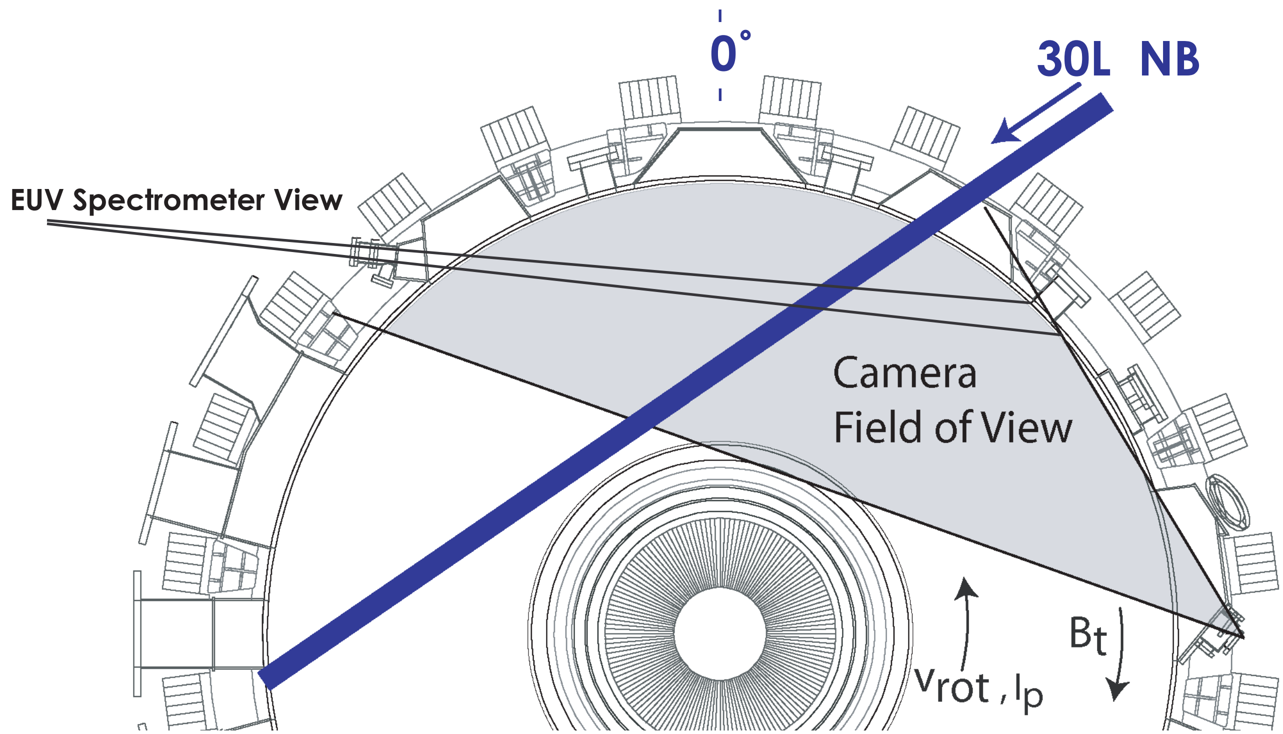
How technique works

- Square-wave modulation of heating beams on DIII-D provides a means to distinguish CER emission from that due to collisional processes
- Differencing of consecutive ON/OFF beam phases has been successfully employed in the visible for CER spectroscopy and CER imaging
- Digital lock-in to a long train of modulation pulses improves rejection of uncorrelated, quasi-steady-state emission
- The lock-in method works best in the EUV, where direct-view light is not contaminated with wall-reflected light from secondary sources

Experimental Setup

EUV Survey Spectrometer views 30-Left Neutral Beam from Opposite Direction as Intensified Fast-framing Camera

- **Beam enters plasma through 30˚ port at the vessel midplane; thickness of the blue bar corresponds to 1/e width of Gaussian beam**
- **The camera view extends from center column on left, to outer wall on right**
- **EUV spectrometer intersects the beam at R = 1.88 m (▯ ~ 0.3)**



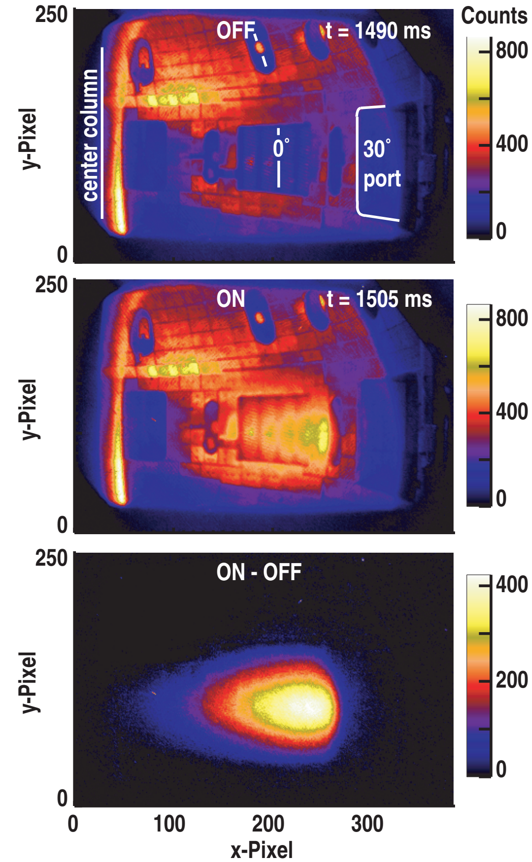
Differencing of Dα images from beam ON and OFF phases reveals trajectory of high-energy neutral atoms in D beam

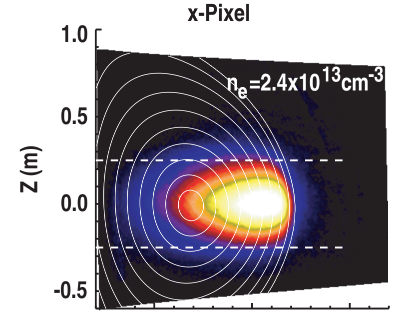
- **The midplane port boxes appear dark during the OFF phase. Note that filter passes C II line, as well as Dα.**

- **Dα beam emission is comparable in intensity with cold Dα and C II**

- **ON/OFF difference yields clean image of 30 Left, in absence of modulation on other beam sources**

- **Beam penetrates to magnetic axis in image containing flux contours that have been mapped to the points of intersection of camera sightlines with the beam**

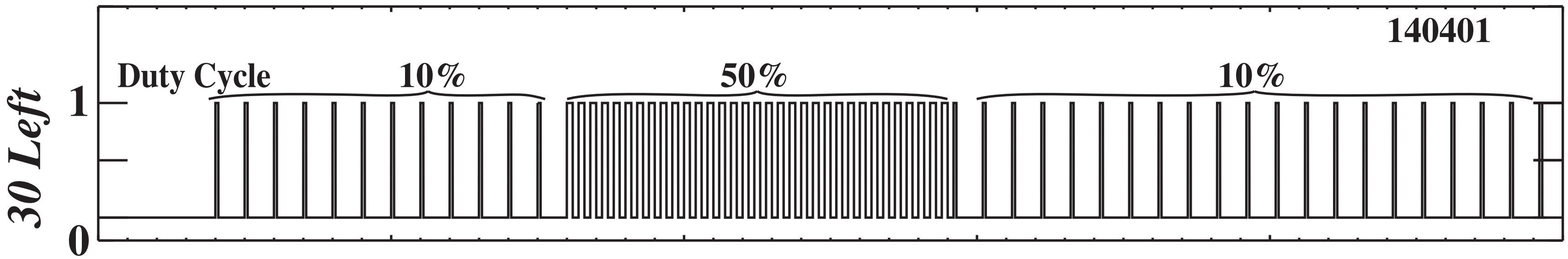




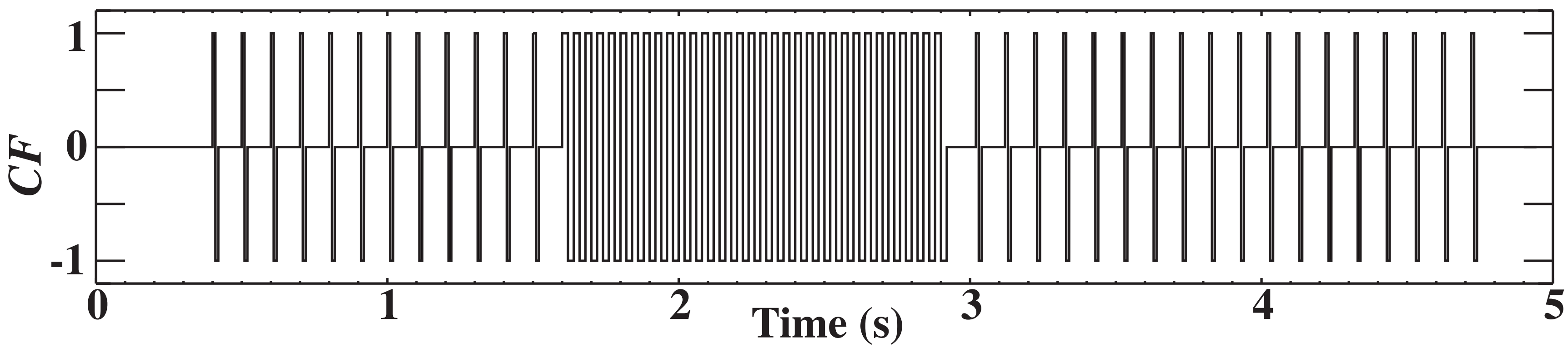
Beam-Correlation Function

The Correlation Function, *CF*, integrates to zero over each modulation cycle within a beam pulse train

- Period and duty cycle are determined for each pulse train, from the programmed command signal for modulation of the *30-Left* beam

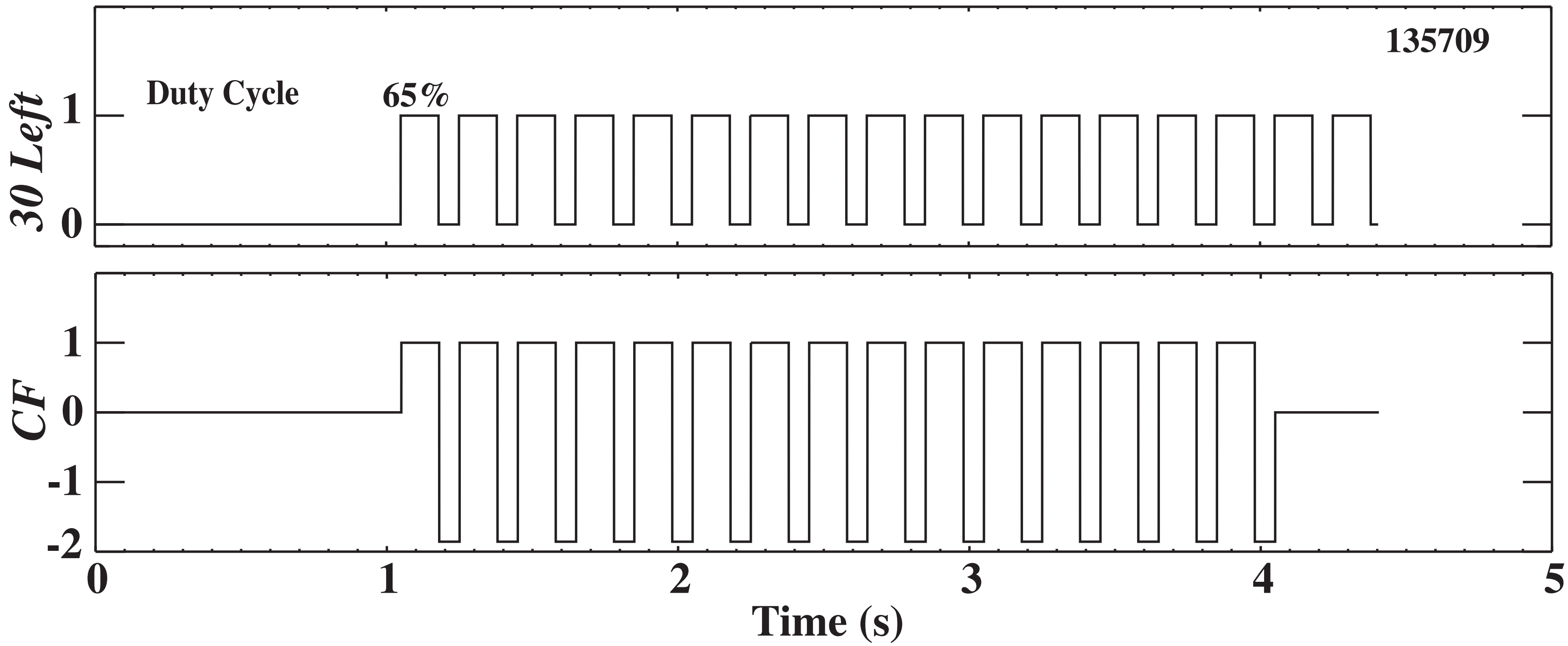


- If duty cycle ≤ 50%, the – phase in *CF* waveform is given the same length as the + phase, and an equal amplitude.



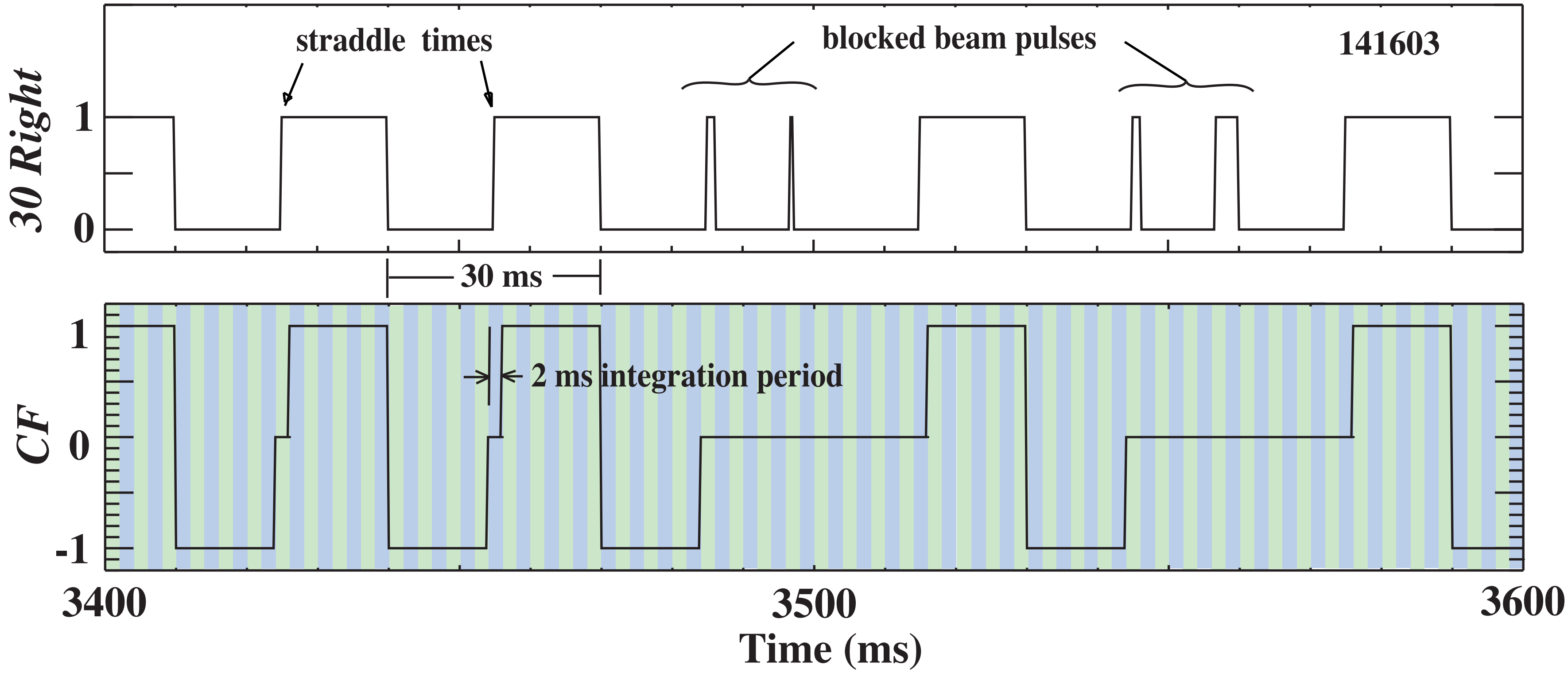
- The scalar product $CF(t) \cdot I_j(t)$ is calculated for each pixel *j*, where the vector $I_j(t)$ is the intensity time history at λ_j
- Only light which varies synchronously with the modulation of the beam is retained in the scalar product

When duty cycle > 50%, the negative phase of the $CF(t)$ waveform is given an absolute value greater than 1



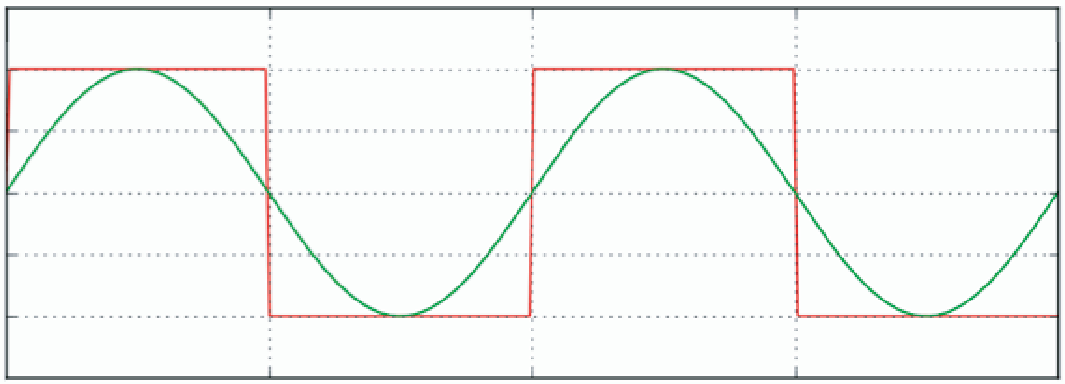
"Blocked" beam pulses require special handling; likewise, straddles of the data integration period.

- When arcing occurs between grids in the beam source, V^{accel} is crowbarred off for 10 ms. *CF* is set to zero over that modulation cycle.
- When SPRED integration periods straddle beam-ON and beam-OFF phases, *CF* is set to zero for that single integration period.

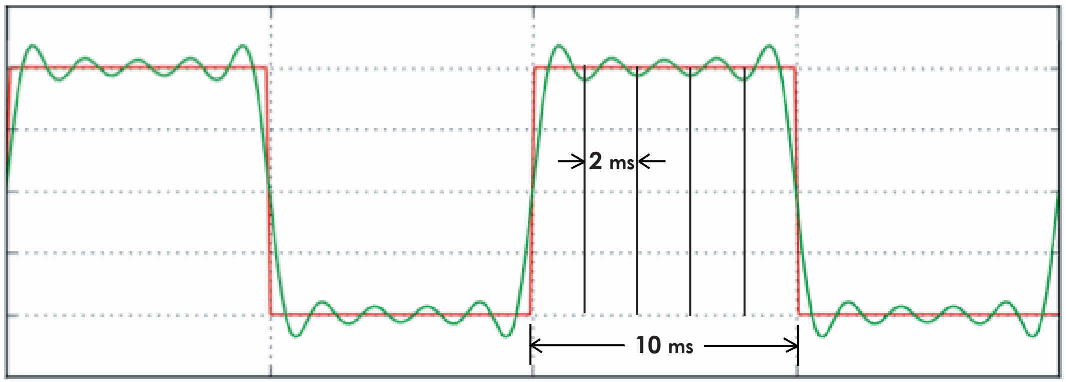


Best noise suppression is achieved by making the data acq. period as short as the turn-on time of the neutral beam pulse.

- Fourier analysis at the beam modulation frequency provides a poor match to the square wave character of prompt CER emission



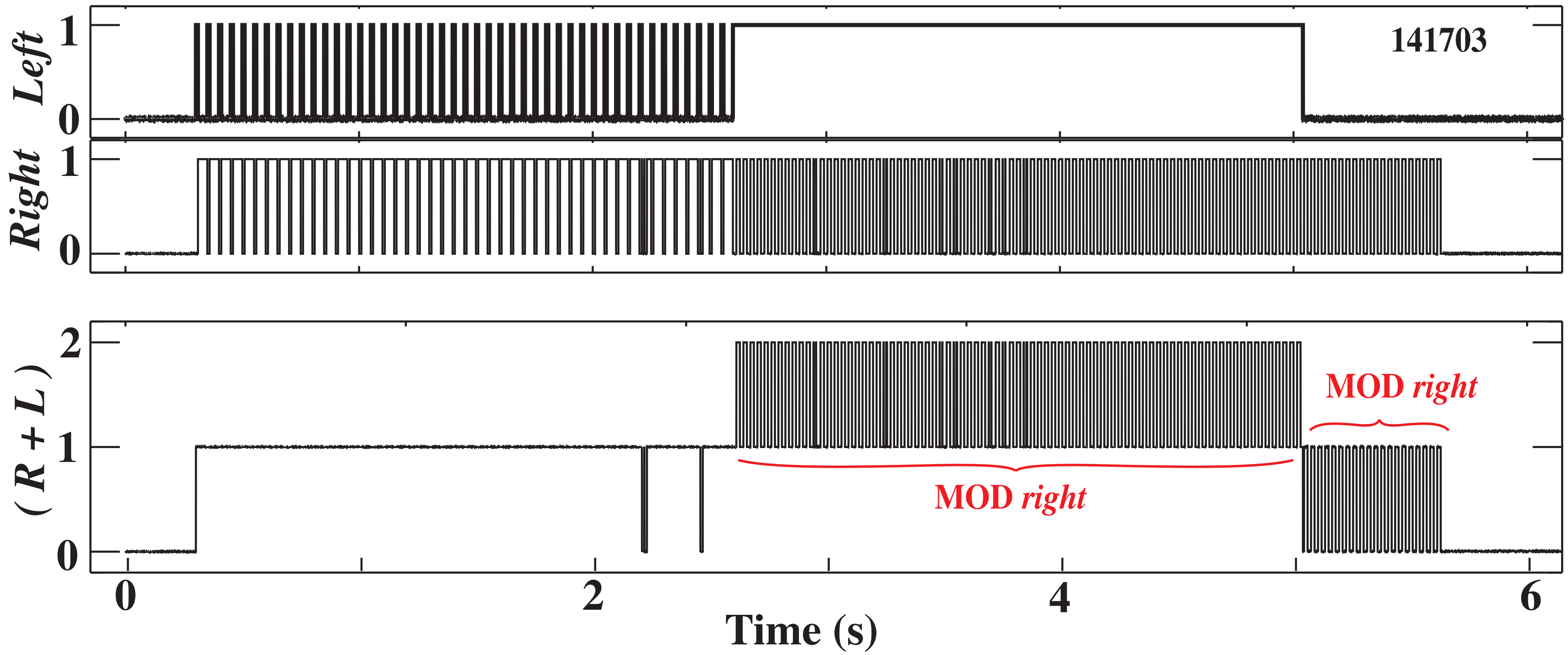
- For the 500 Hz data sampling and 50 Hz beam modulation frequencies on DIII-D, use of a correlation function is equivalent to Fourier analysis at the pulse pulse repetition frequency and four harmonics of it, simultaneously.



With both left and right sources operational, software must identify periods when only one source is modulated

- Typically, both left and right sources are modulated. Digital lock-in is feasible only when second source is full ON, or full OFF.

- Difficult cases are handled by specification of a time window.



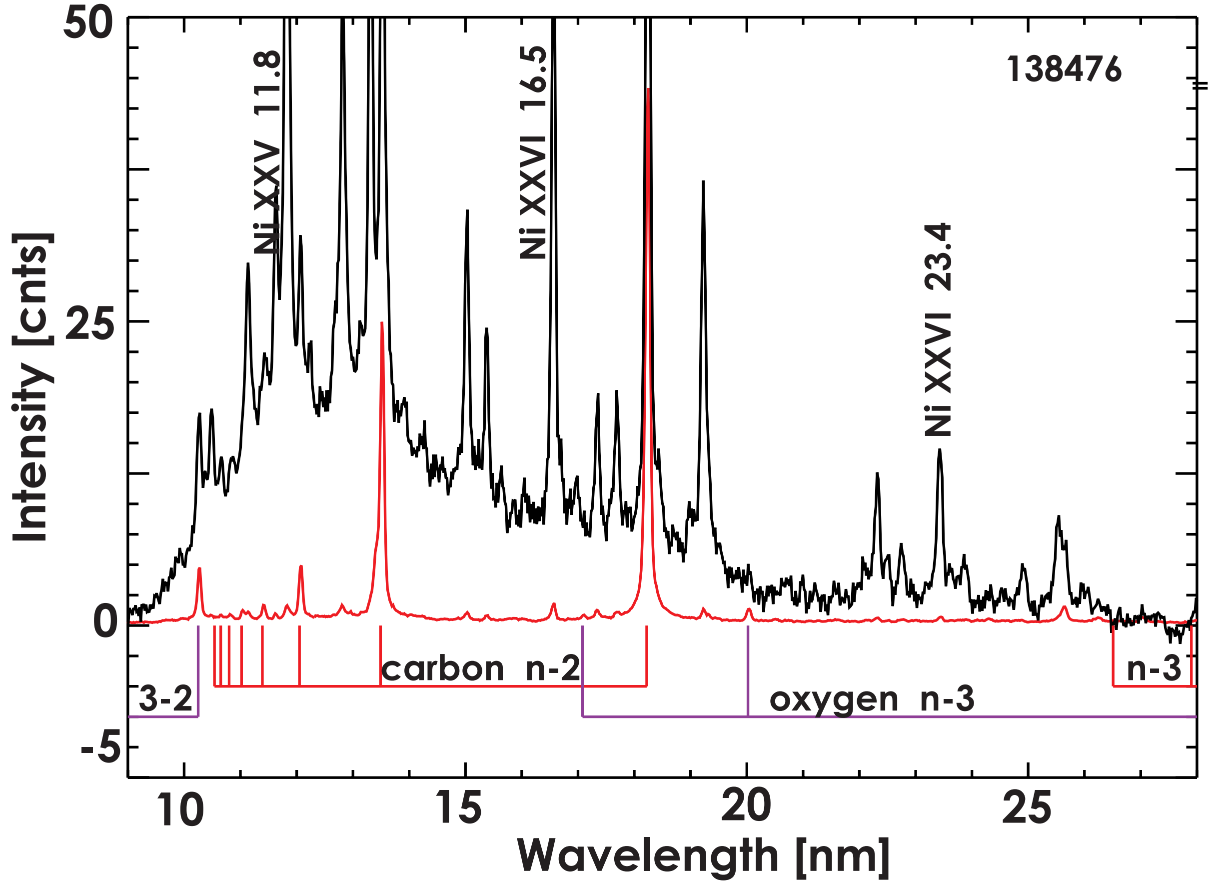
Low-Z Elements

A typical EUV spectrum, crowded with metal lines, is reduced by digital lock-in to a sparse spectrum of isolated CER lines

- The full spectrum at 2.0 s is shown in black, the digital lock-in spectrum in red. The latter is time-averaged over the interval 1.9 – 2.1 s

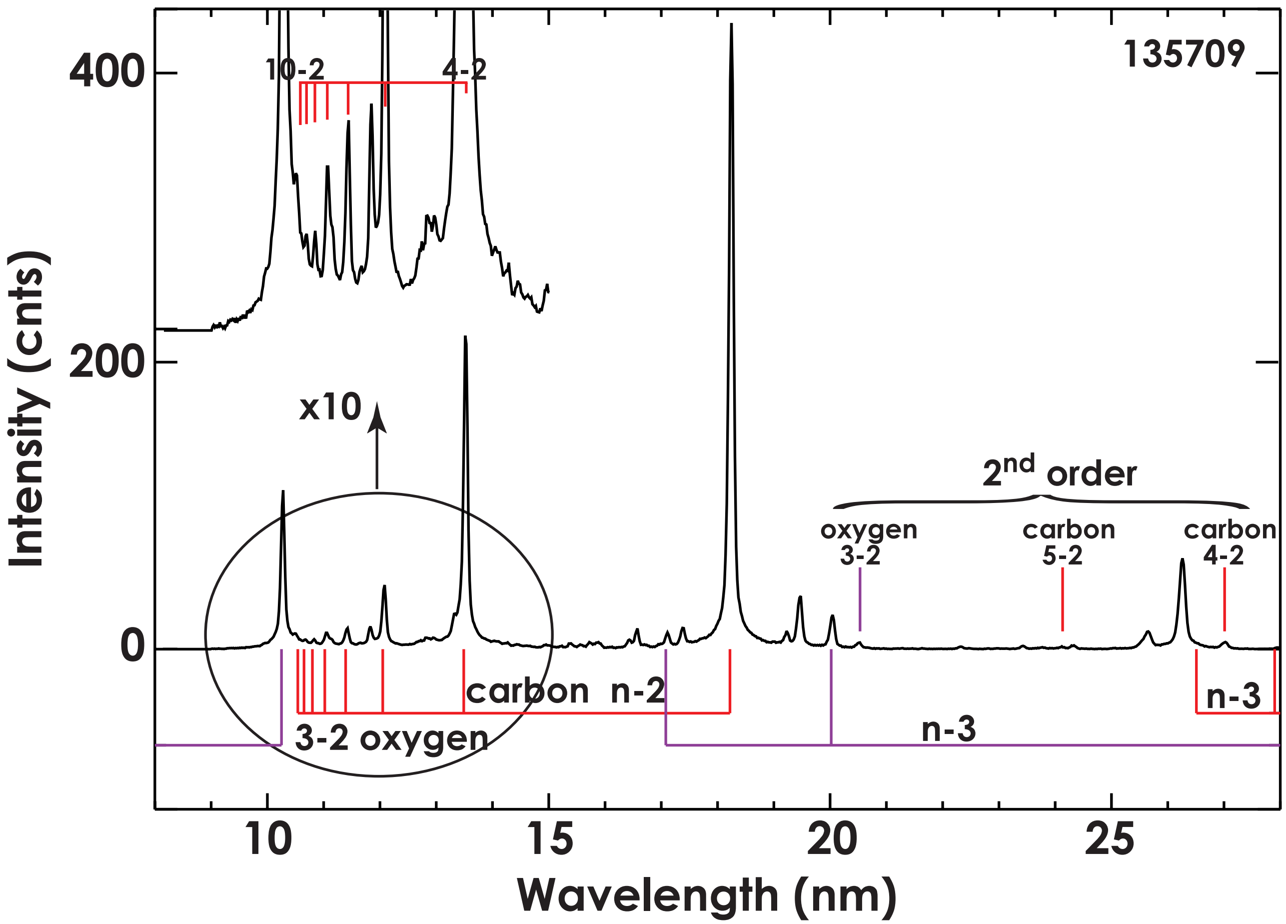
- Li- and Be-like nickel are labeled in spectroscopic notation to orient the viewer

- The CER spectrum consists of well-isolated lines that are readily identifiable



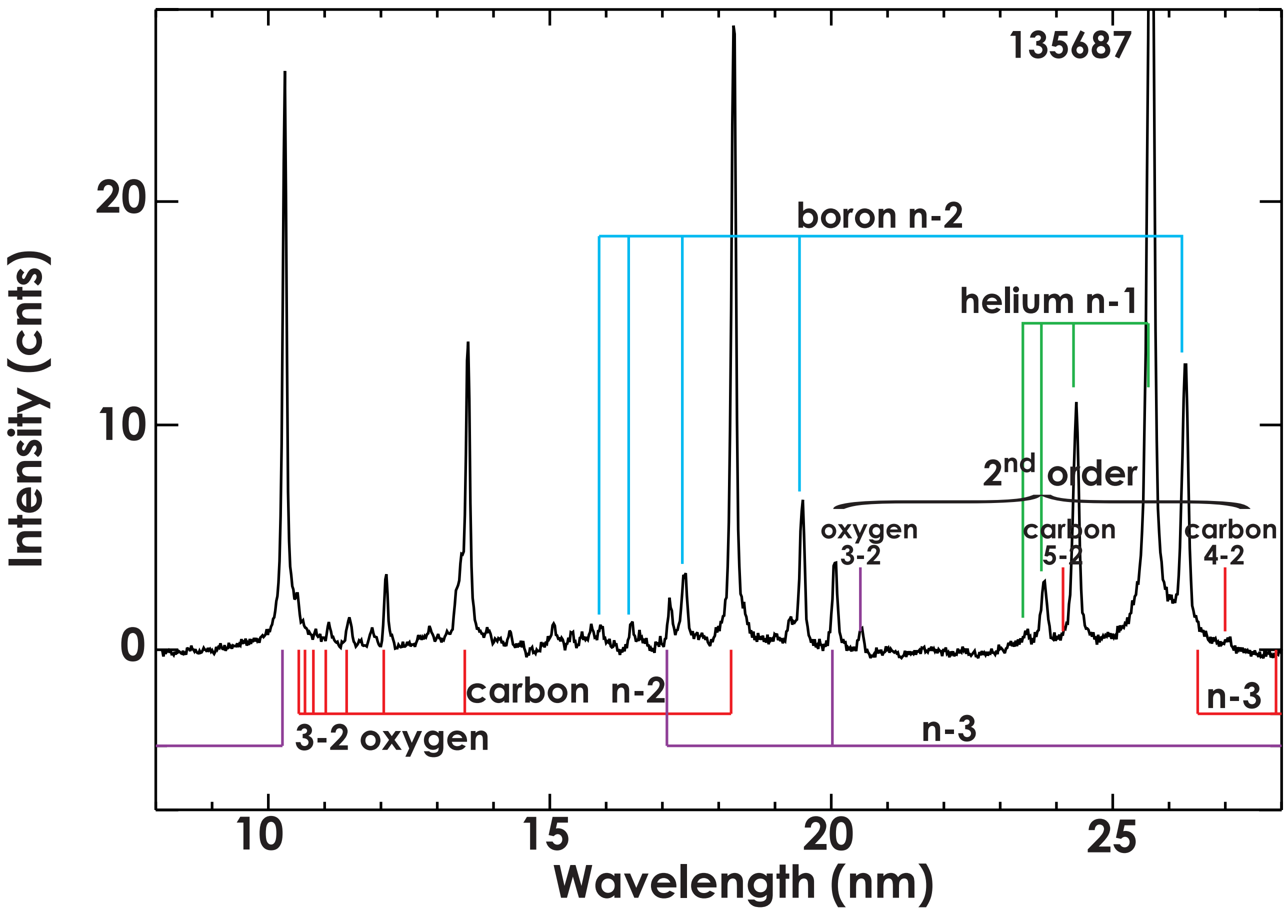
Long Rydberg series of lines are visible in lock-in spectra time-averaged over a full discharge

- Carbon is the main impurity in DIII-D. Its n-2 and n-3 series are visible in the 9-28 nm range spanned by the 2100 G/mm grating of the dual-range SPRED. Oxygen is next brightest; boron is detectable, but weak.



Immediately following boronization, boron and helium are readily visible, but carbon is dimmer than usual.

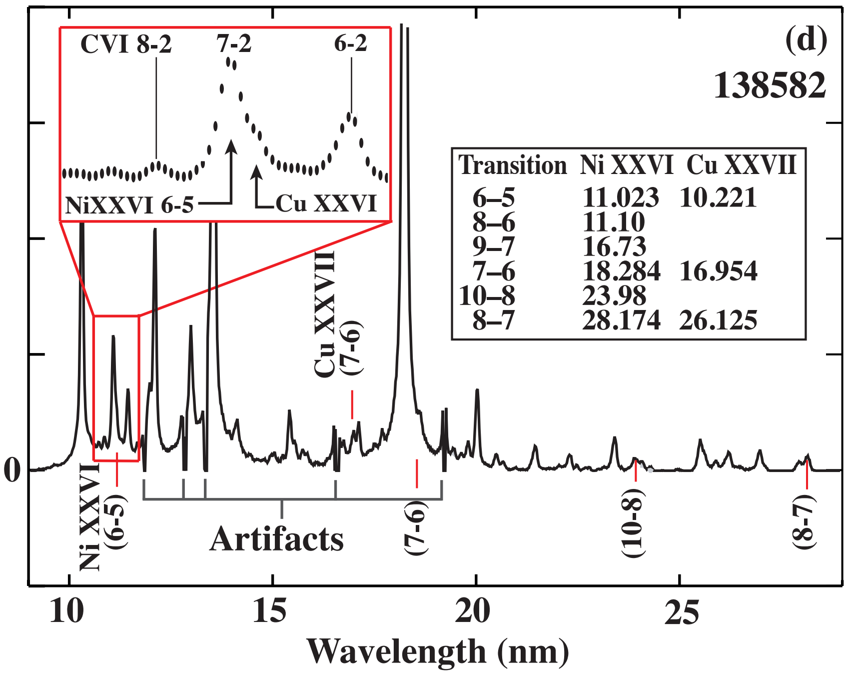
- On the clean-up day after boronization, 135687 was the first discharge and 136709 the last. Over those 23 shots, helium fell rapidly, carbon recovered and oxygen declined modestly, all relative to boron.



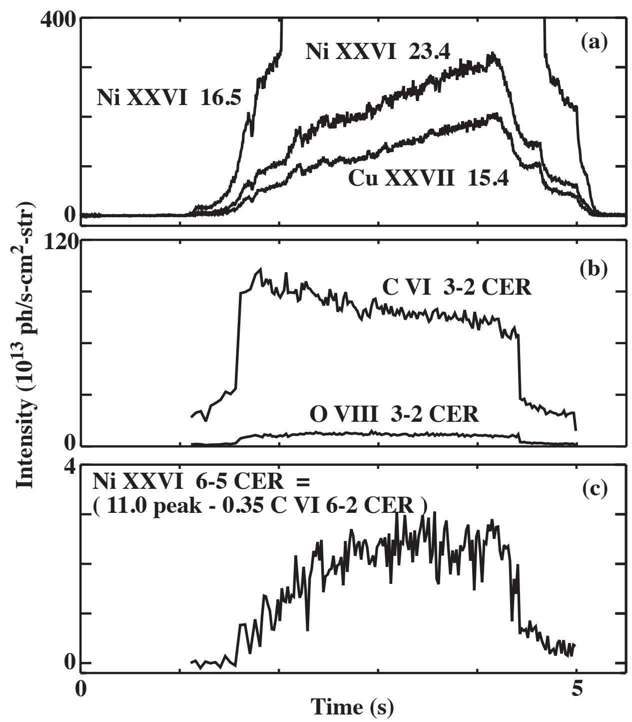
Medium-Z Elements

DIII-D discharges with high core metal concentrations provide a rich hunting ground for CER lines In Li-like ions

- **Many beam-modulated features are visible in between the peaks already identified with CER lines of low-Z elements.**
- **The table gives predicted wavelengths for Ni XXVI and and Cu XXVII transitions based on relativistic calculations in H-like ions‡ of equivalent net charge, assuming no ℓ mixing.** ‡G Erickson, J. Phys. Chem. Ref. Data, 6, 831, 1977
- **The [6-5, 7-6, 8-7, 10-8] transitions in Ni and 7-6 in Cu are detectable in the lock-in spectrum. The brightest of these, the Ni 6-5, is coincident with C 7-2.**

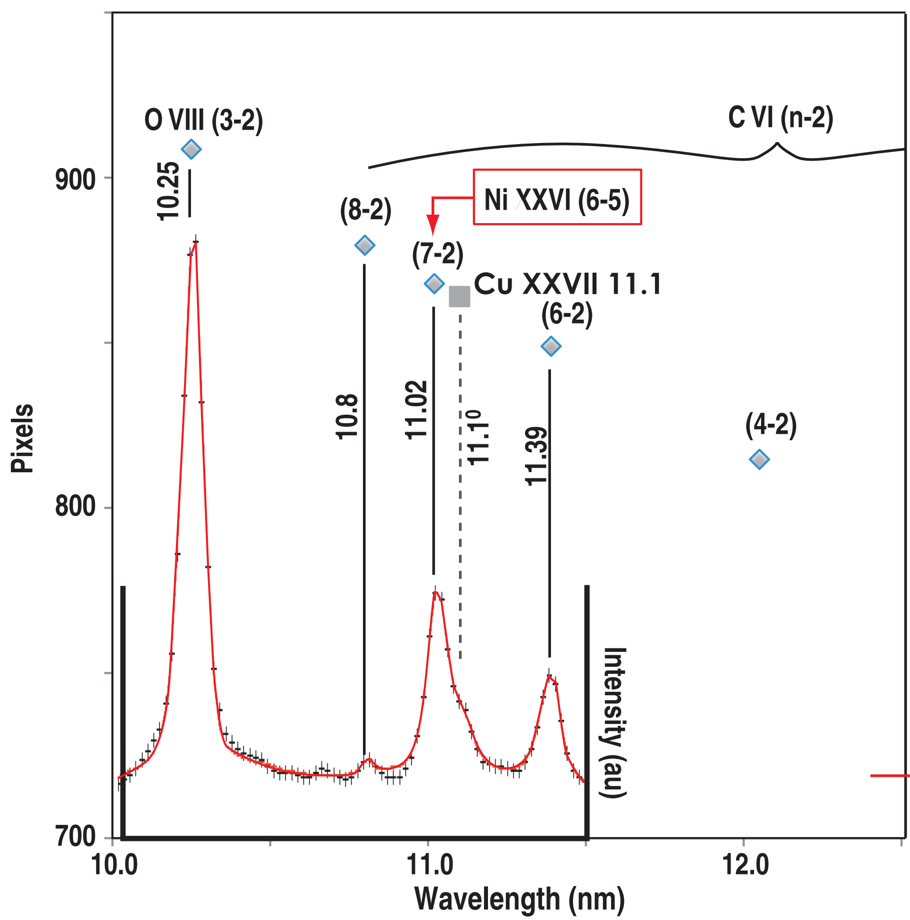


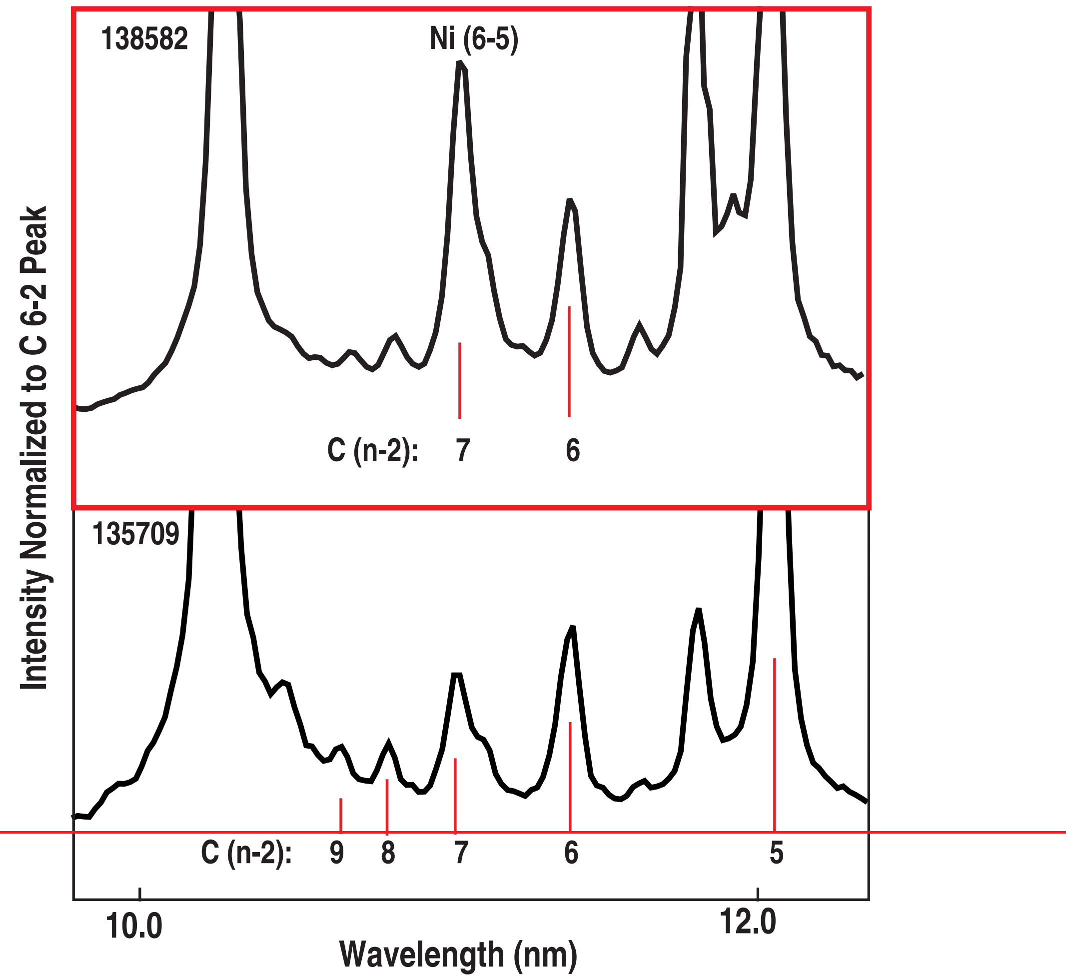
Transition	Ni XXVI	Cu XXVII
6–5	11.023	10.221
8–6	11.10	
9–7	16.73	
7–6	18.284	16.954
10–8	23.98	
8–7	28.174	26.125



The high intensity of the 11.0 peak stood out when spectra for metal-rich and metal-free discharges were compared

- **Least squares fitting of the instrumental profile to the data in the carbon Rydberg series provides very accurate wavelengths for unknown features.**
- **All the carbon n-2 transitions have self-similar time histories, except 7-2.**





Digital lock-in spectra of D beam-correlated emission lend themselves to a variety of applications

- **The instrumental profile has been fit to isolated CER lines; precise wavelengths have been measured during low-rotation, L-mode discharge phases.**
  - Doppler shifts deduced from multiple lines of Rydberg series are consistent with those measured with DIII-D's visible CER diagnostic.
- **Simultaneous measurements of CER emission from He, B, C, O, Ne, and Ar have been used to monitor relative abundances of low-Z impurities.**
  - The 6-5, 7-6, 8-6 and 10-8 transitions in Li-like nickel and the 7-6 in copper have been detected in discharges with high metal content.
- **Old data from discharges with LiF and CaF pellet injection have been analyzed to identify CER transitions in these elements.**
- **Intensities of □n = 1 and □n = 2 Rydberg transitions in C, O and Ne were used to obtain the instrumental sensitivity vs □. This work will be extended.**

Conclusions

- A digital lock-in technique has been employed to extract beam-modulated CER emission from EUV spectra.

- Long Rydberg line series in H-like ions of low-Z elements are readily visible; they will be used to improve the intensity calibration.

- CER transitions in Li-like nickel and copper has been identified in discharges with high metal content.

- The EUV survey spectrometer enables measurement, simultaneously, of the core impurity concentrations for all low-Z and some medium-Z elements.