High Resolution Spectroscopy at Alcator C-mod using a Fabry Perot Interferometer.

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We present high resolution spectroscopic measurements of HeII 4686 and D-alpha emission at Alcator C-Mod obtained with a Fabry Perot interferometer. Temperatures and flows obtained from spectral profiles are important in understanding transport in the scrape-off layer. The HeII 4686 spectral profile is broadened by the Doppler effect and split by fine structure and Zeeman effects. The Fabry Perot interferometer continually scans the spectral profile in time and a Zn lamp emission line at 4680 angstroms is used for absolute wavelength calibration. The D-alpha spectral profiles are used in characterizing the Zeeman splitting and to benchmark the Monte Carlo code DEGAS 2. We will compare the advantages and limitations of Fabry Perot interferometers to spectrometers for high resolution spectroscopy.

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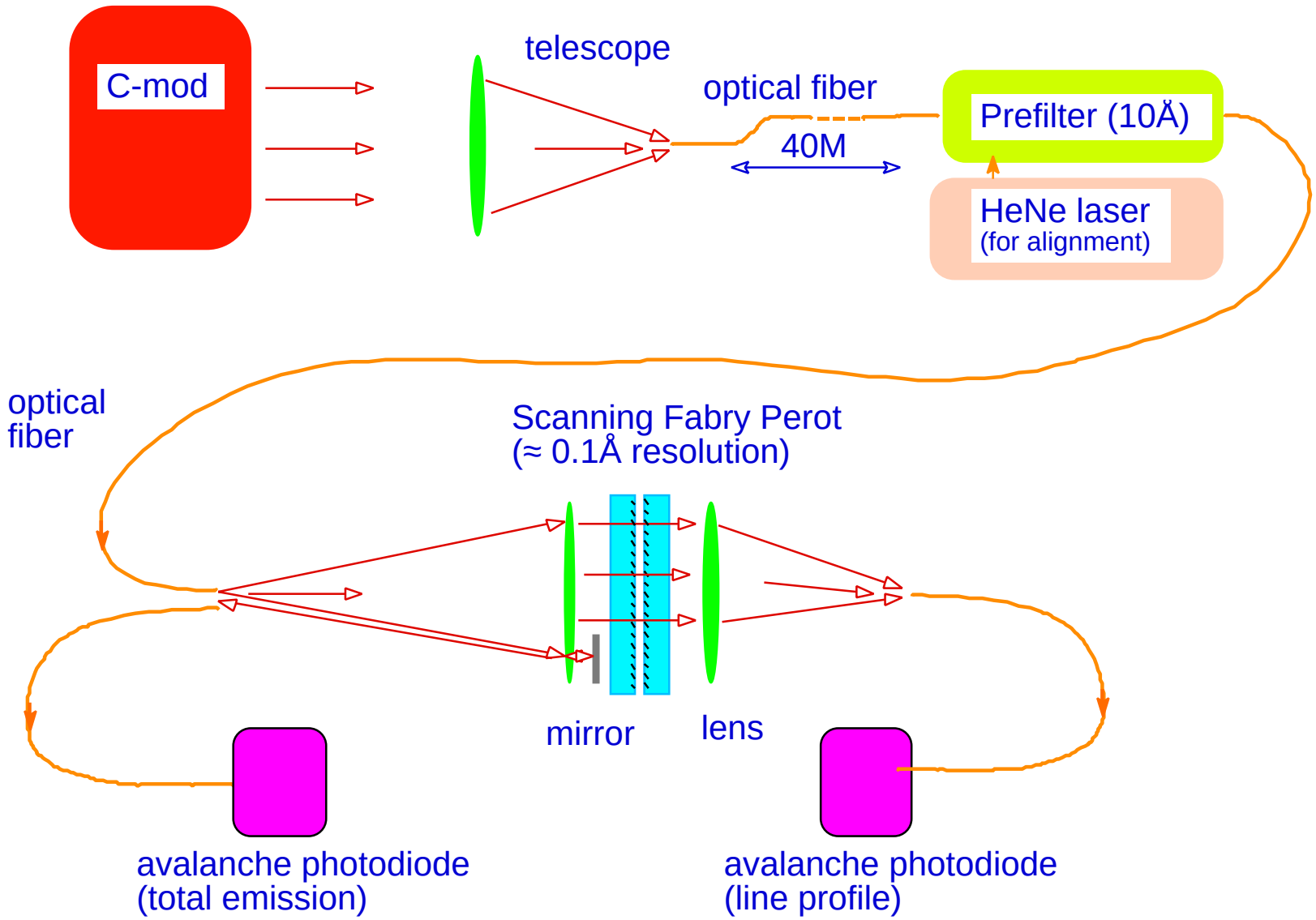
Fabry Perot measurements of ion flows:

- Spectrometer based measurements of flows are limited by low optical throughput of high resolution spectrometers.
- Fabry Perot interferometers offer potential for higher sensitivity.

Comparison of optical throughput:

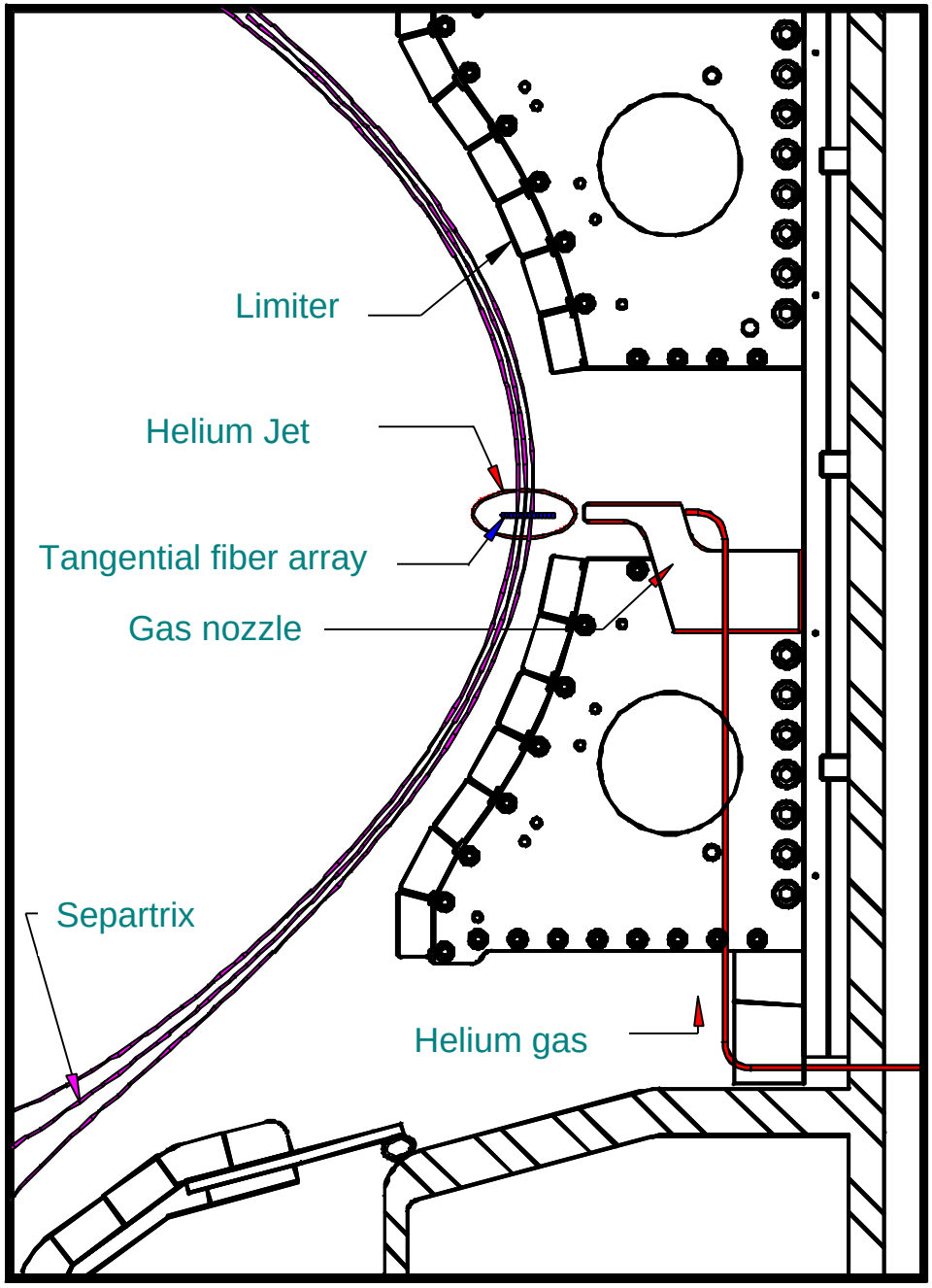
	Fabry Perot	2M spectrograph	Ratio
Resolution	adjustable with free spectral range and finesse. Set to 0.13Å.	0.12 Å	≈1
Fiber coupling	Whole area of 600µ fiber used 0.28 mm^2	Width limited by 20 µm entrance slit 0.012 mm^2	X24
f/number	f/2.3	f/20	X75
Duty cycle	1/ finesse 0.014	Integration/readout time 0.16	X0.08
Instrumental transmission	Pre-filter + FP 3%	Holographic grating ≈ 30%	X0.1
Combined			X14
Other factors:	Limited wavelength coverage. Scanning complicates λ calib.	Low noise CCD detection.	

Experimental Setup:



Viewing Region in C-mod vessel

fiber # 9 in array of 14 fibers.

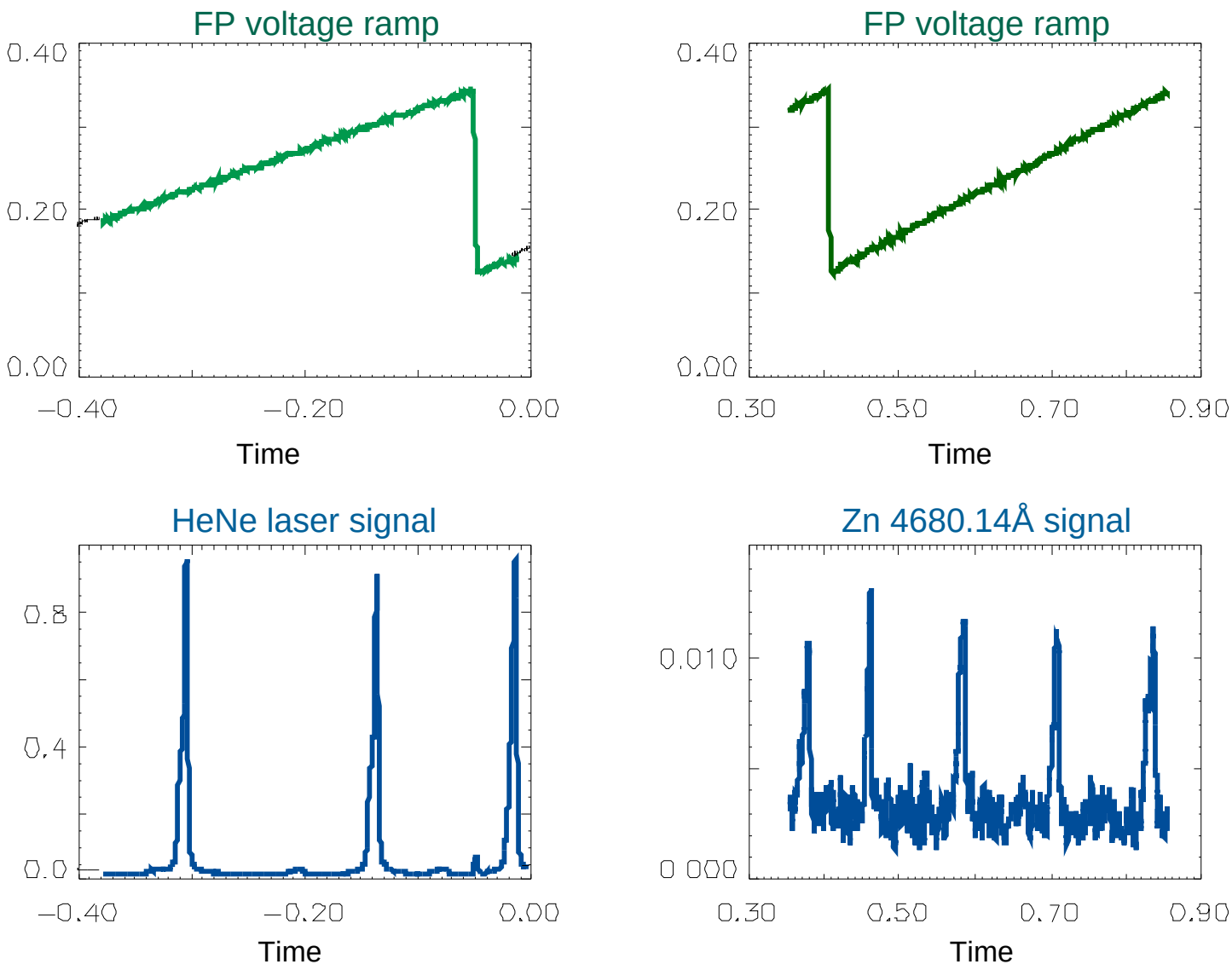


Fabry Perot wavelength calibration:

- FP is scanning continuously in time
- HeNe laser light provides signal in between discharges for tracking alignment
- PenRay Zn lamp with line at 4680.14Å used for wavelength calibration before and after experiment (calibration source must be within free spectral range of FP; He^+ lamp not available).
- Center of gravity of spectral profiles calculated to track reproducibility and wavelength shifts.
- Uncertainty gauged by scan to scan differences.
- Gap between Fabry Perot plates measured optically and used to calculate free spectral range and dispersion.

Measurement hampered by poor transmission of Fabry Perot at 4680Å (about 10% of that @ 6328Å).

Wavelength Calibration

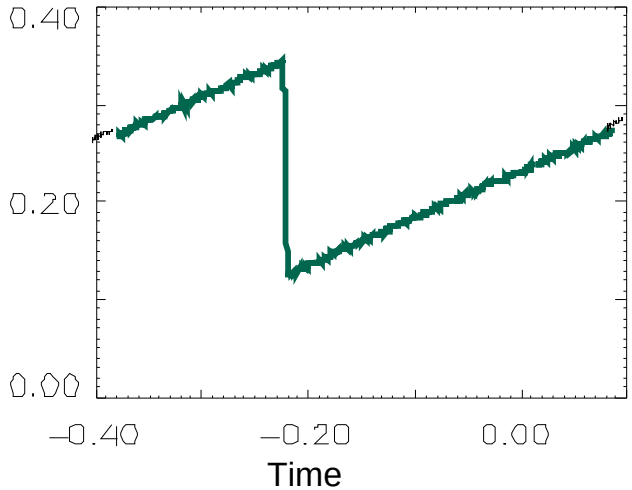


HeII data

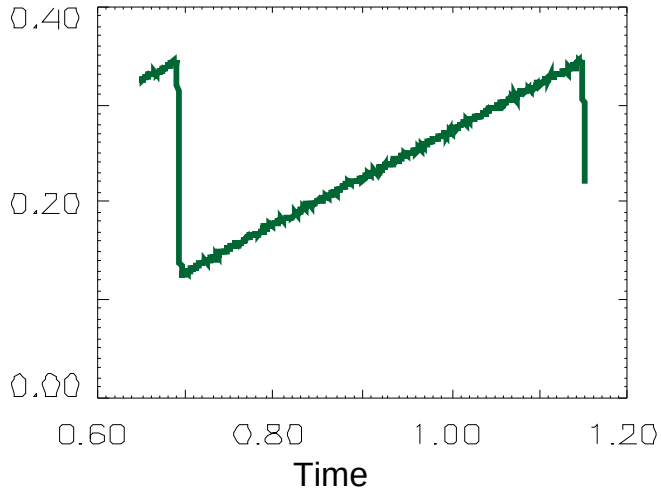
Shot 990520021, Ohmic 1.2 MA, density 2×10^{20} H-mode @ 0.95 s

He puff @ AB limiter 400 ms, 215 torr in manifold

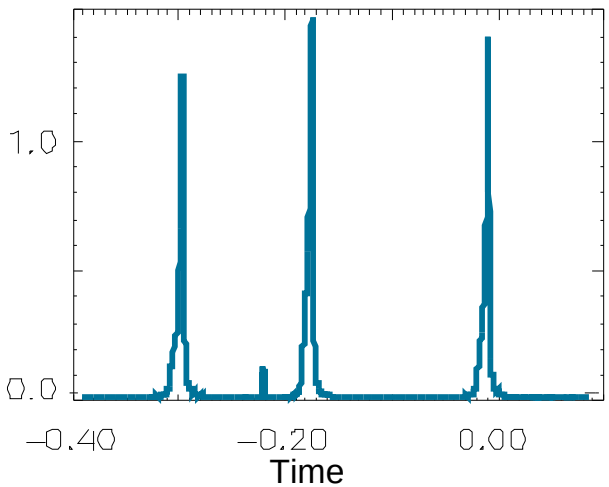
FP voltage ramp



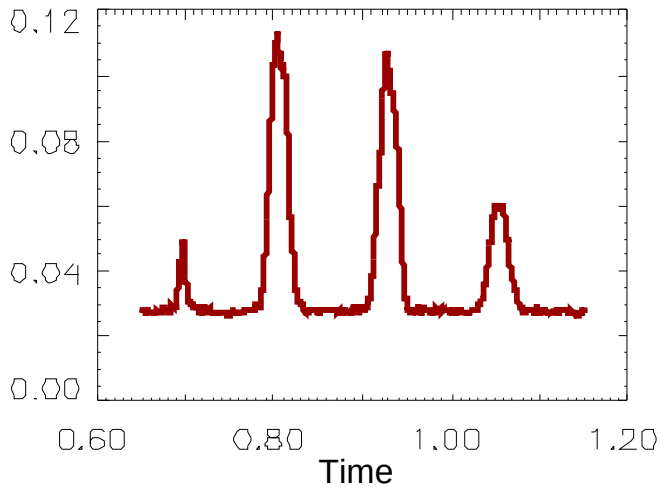
FP voltage ramp



HeNe laser signal



HeII 4686 signal



Measurement of He II shift:

He II 4686 rest wavelength	4685.706	Å		
He II 4686 observed wavelength	4685.516	Å		
Difference:	0.190	Å	(12.2	km/s)
Experimental uncertainty:				
Reproducibility of Zn 4680.114Å calibration line	0.128	Å	(8.2	km/s)
uncertainty in dispersion	0.120	Å	(7.7	km/s)

- Absorption in FP optics reduced FP transmission x10 and resolution x5 !
- Observed shift similar to experimental uncertainty.

Reproducibility of ramp and HeNe laser peaks 10x better than weak Zn line.

To improve accuracy at 4686Å need:

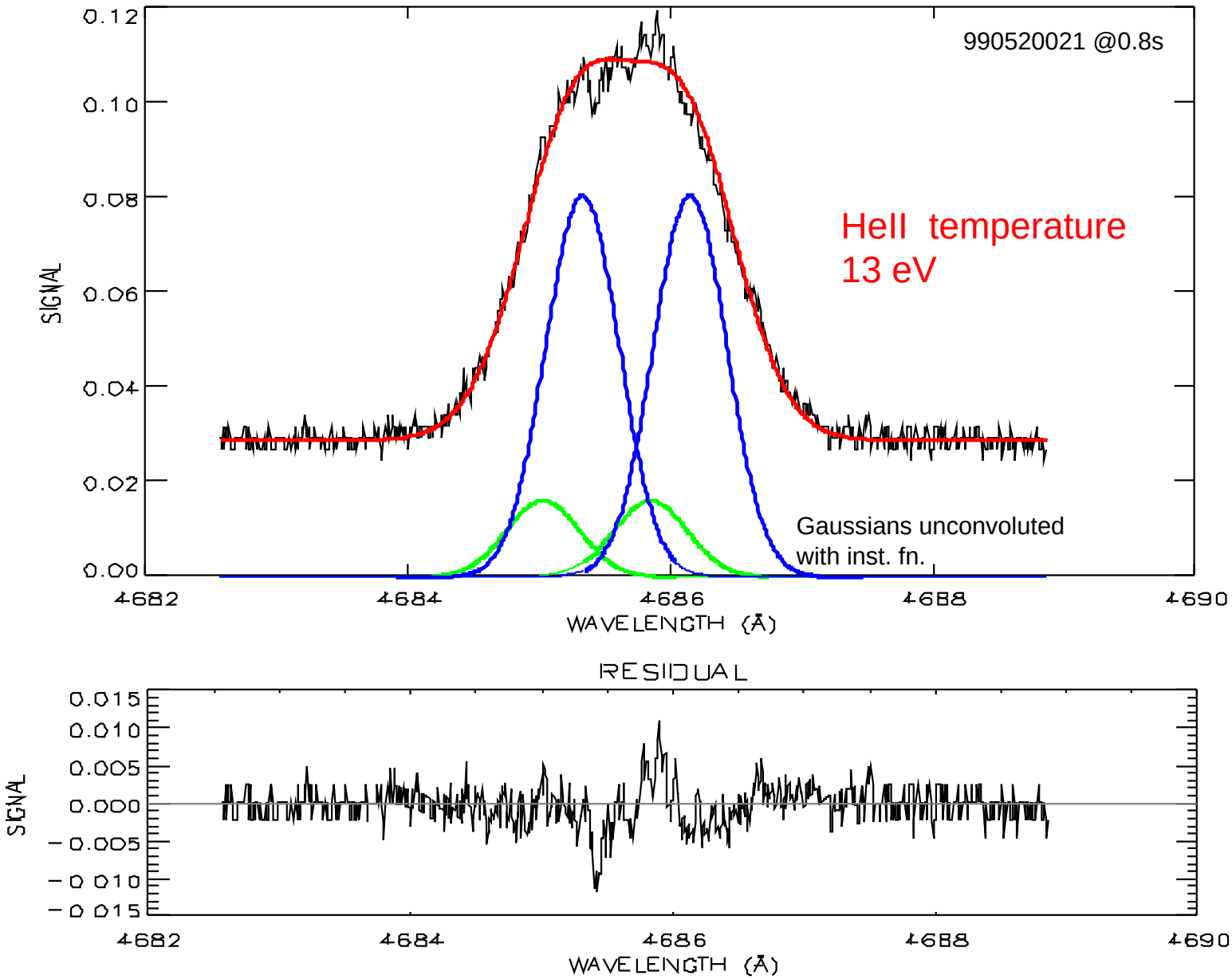
- *He II 4686Å calibration source*
- *New FP plates.*

Analysis of He II 4686Å spectral profile.

- Profile Doppler broadened and split by Zeeman effect and fine structure:
- Two fine structure lines at: 4685.4Å and 4685.7Å of intensity 6, 30.
- View closely aligned to B field (negligible π component in Zeeman pattern - see D-alpha measurements).
- Fit profile with 4 Gaussians, 2 for each fine structure component using known splitting and intensity ratio.
- Deconvolute instrumental profile (from Zn 4680.14Å profile), subtract 1st order background,
- Determine amplitude, width and Zeeman splitting of σ components.

- Derived He II temperature 13.4 eV.

He II 4686 line fit:



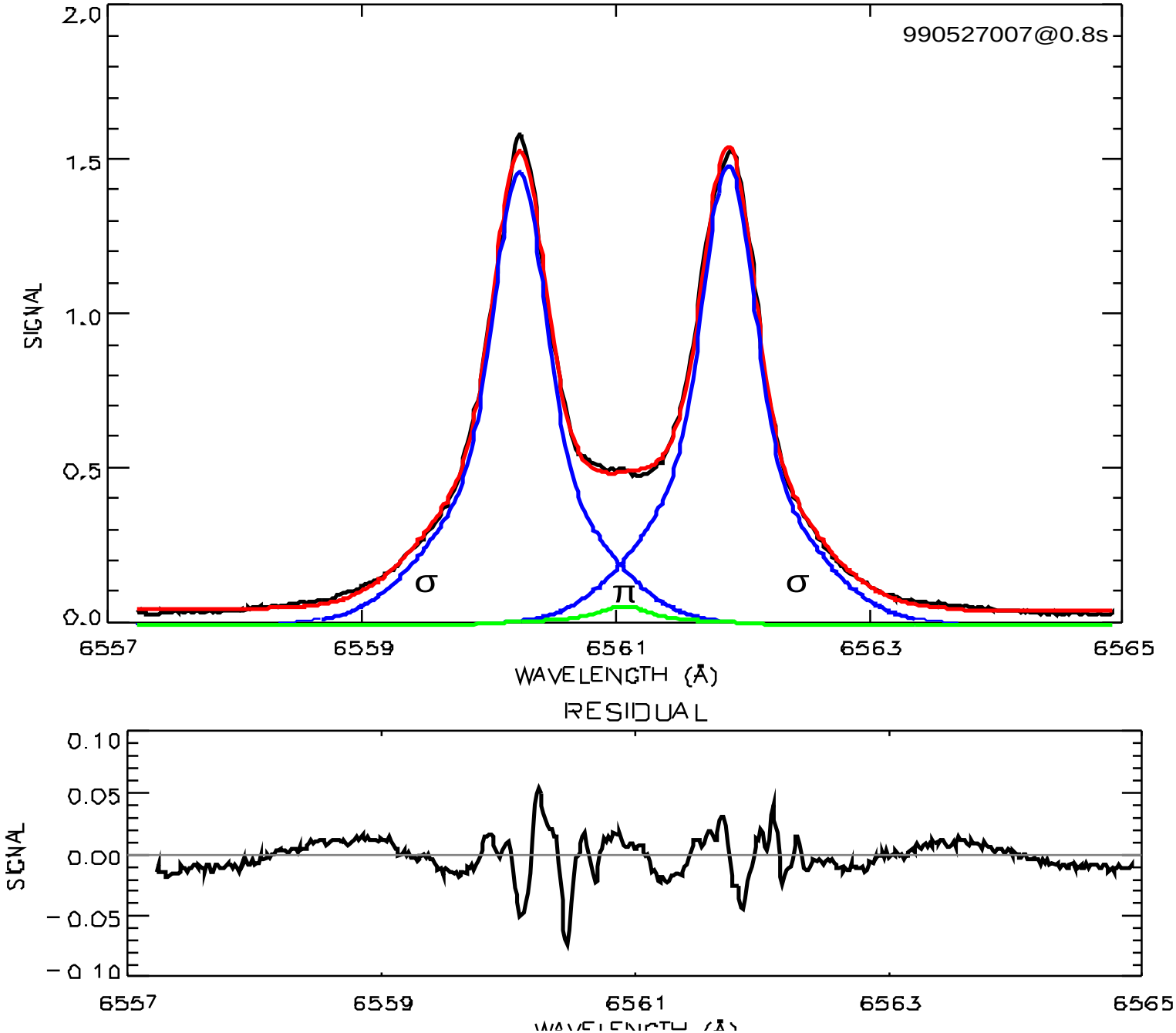
Analysis of D-alpha spectral profile.

- Ohmic L-mode discharge
- Profile Doppler broadened and split by Zeeman effect and fine structure:
- Fit profile with 6 Gaussians, 2 for each Zeeman component.
- Subtract 1st order background,
- Determine amplitude, width and Zeeman splitting of σ components.

- Central π component negligible (4% of σ component):

  view aligned along field lines..

D-alpha line fit:



Numerical deconvolution of Zeeman effect.

Spectral line shapes in magnetized plasmas are split by the Zeeman effect and this can obscure other information, for example the velocity distribution of the emitting atoms. We show that it is possible to use Discrete Fourier Transform techniques to recover the original unsplit spectral line shape, simplifying subsequent analysis.

For an unshifted spectral line $S_o[j]$ the Zeeman effect generates a triplet split by Δ:

$$S_z[j] = \sum_{m=1}^{m=3} A_m S_o[j - \Delta_m] \qquad (1)$$

From properties of the Discrete Fourier Transform:

$$DFT\{(S_z[j])[k]\} = DFT\{(S_o[j])[k]\} \cdot G[k] \qquad (2)$$

where k is the frequency domain sample point, multiplication is element by element and *G(k)* is:

$$G[k] = \sum_{m=1}^{m=3} A_m \exp(-2\pi i k \Delta_m / n) \qquad (3)$$

where n is the number of sample points.

The unsplit signal can be extracted by performing an Inverse Discrete Fourier Transform:

$$S_0[j] = IDFT\{DFT\{(S_z[j])[k]\} / G[k]\} \qquad (4)$$

Procedure

1) Oversample signal ≈x16 using cubic spline to get acceptable precision for wavelength shifts.

2) Obtain center wavelengths and peak intensities by chi-square fitting with Lorentzians. Generate G(k) using this data. (no assumption made that experimental line shape is Lorentzian).

3) Numerically remove Zeeman splitting by deconvolving Fourier Transform of signal

4) Recover unsplit spectral profile by Inverse Discrete Fourier Transform.

5) Iterate G(k) parameters if necessary to minimize low amplitude fluctuations due to second order effects in line profile.

Matlab 5.3 was used in present work.

Technique can be applied to any arbitrary lineshape that is split by the Zeeman effect.

References:

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'Signals and Systems', Alan V. Oppenheim, Alan S. Willsky. Prentice Hall NJ, 1983 2nd ed.

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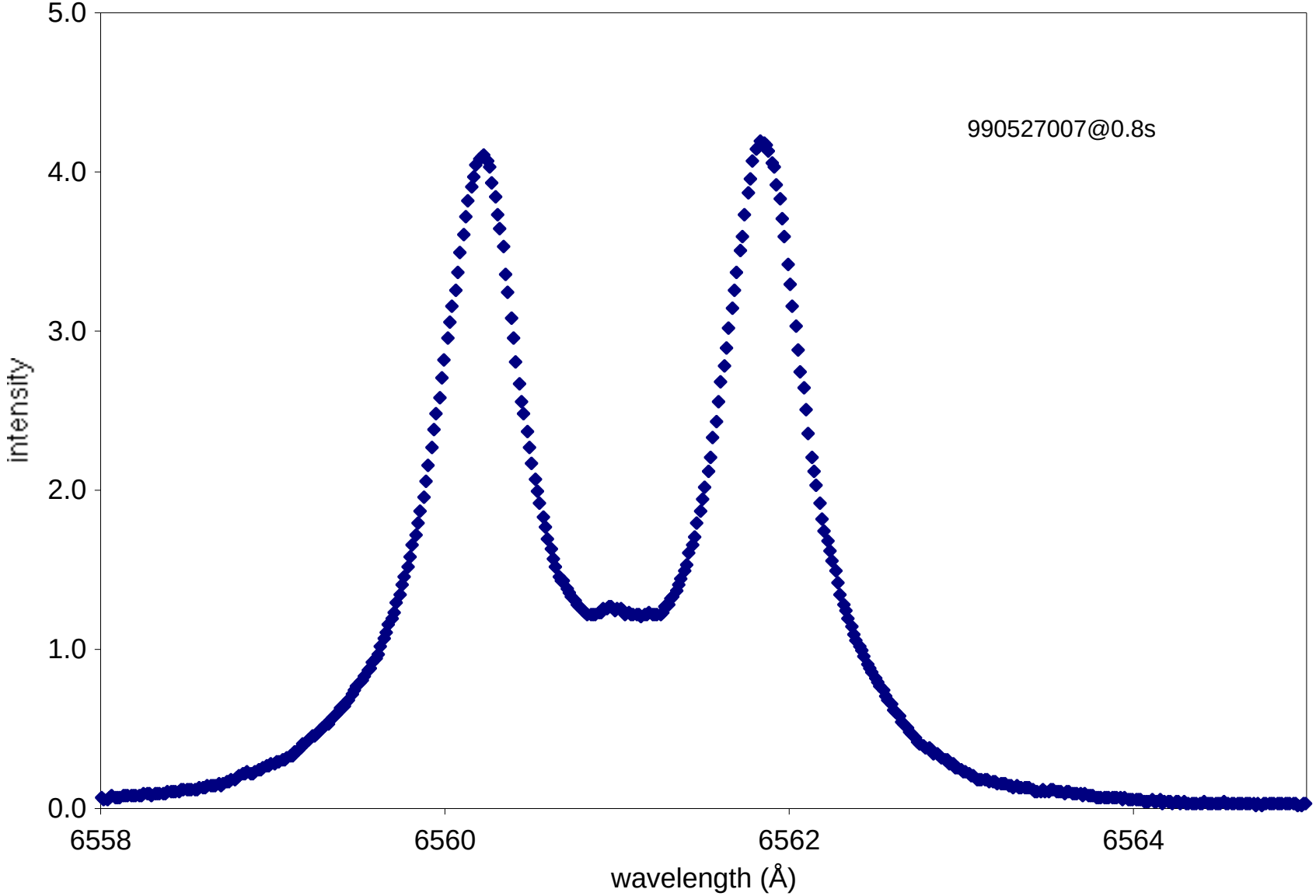
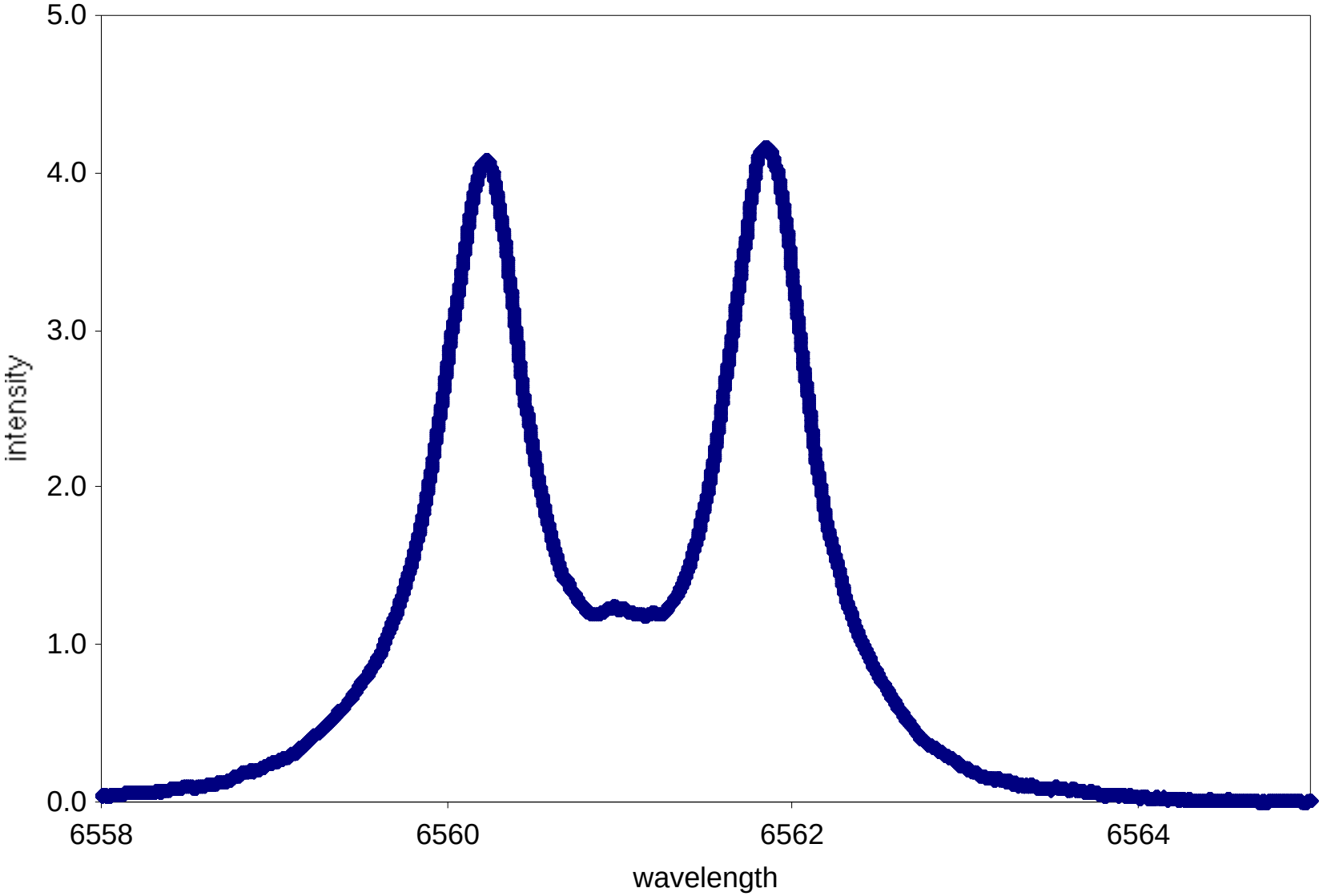
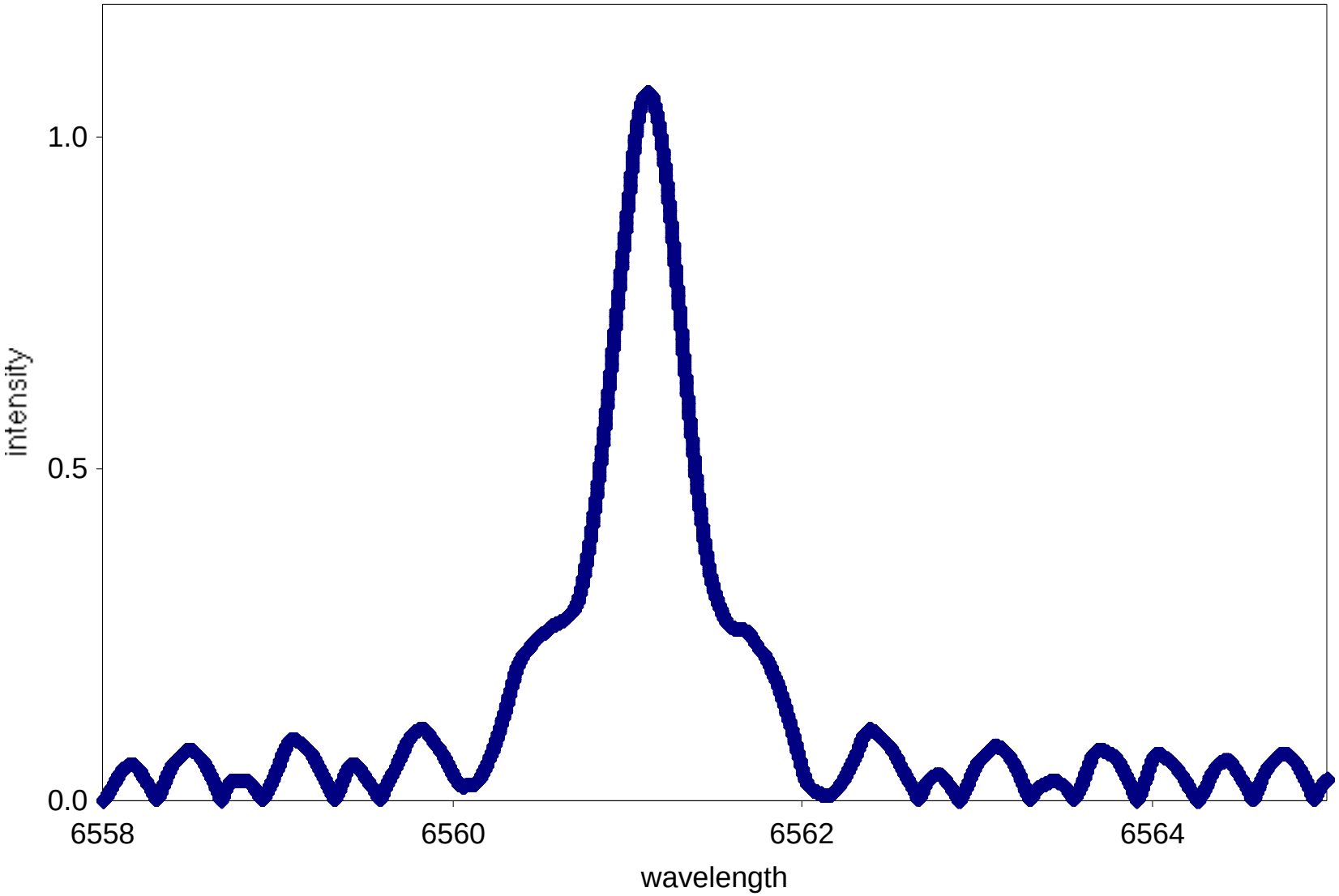
Measured D-alpha profile with two Zeeman σ components



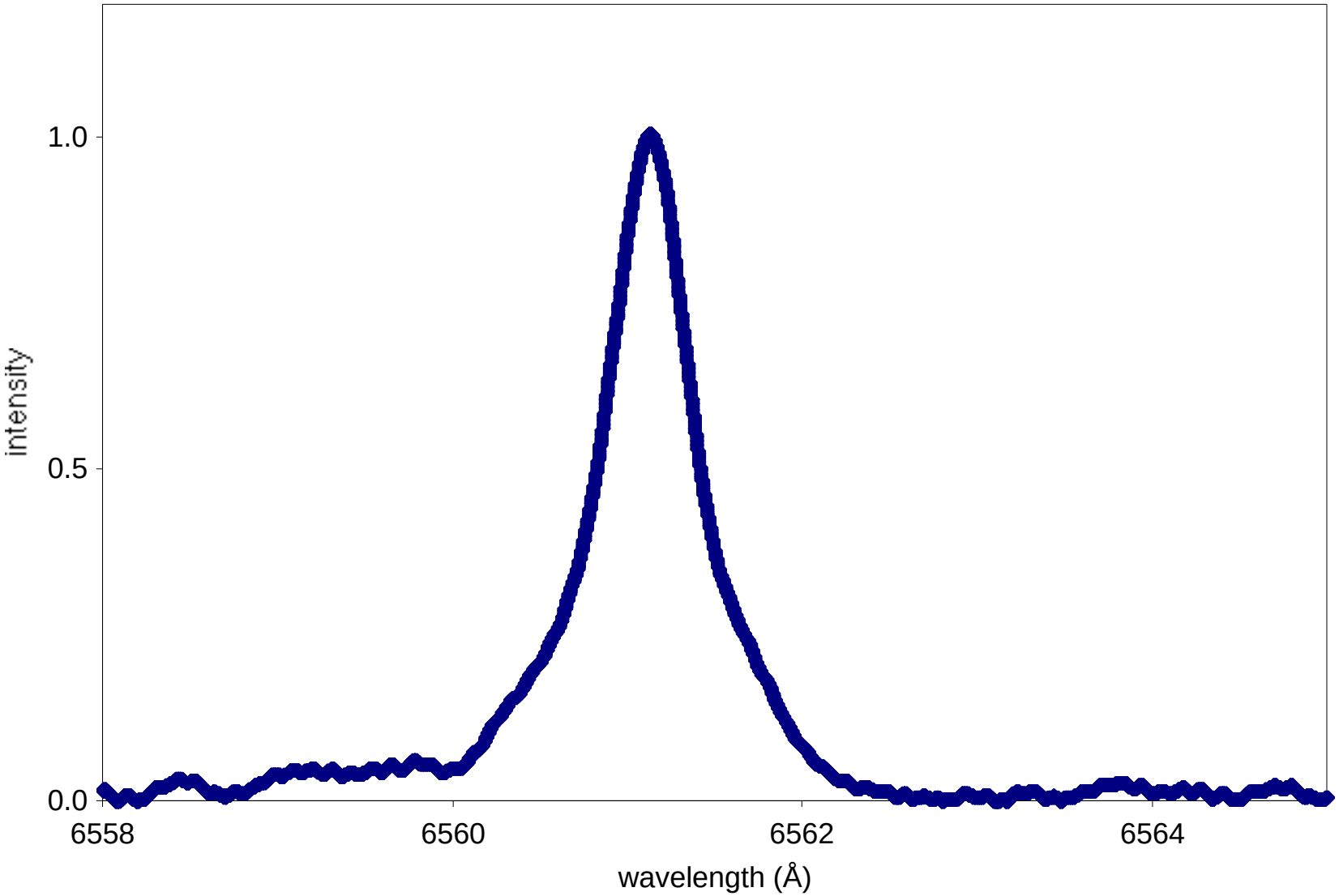
16x oversampled data using cubic spline



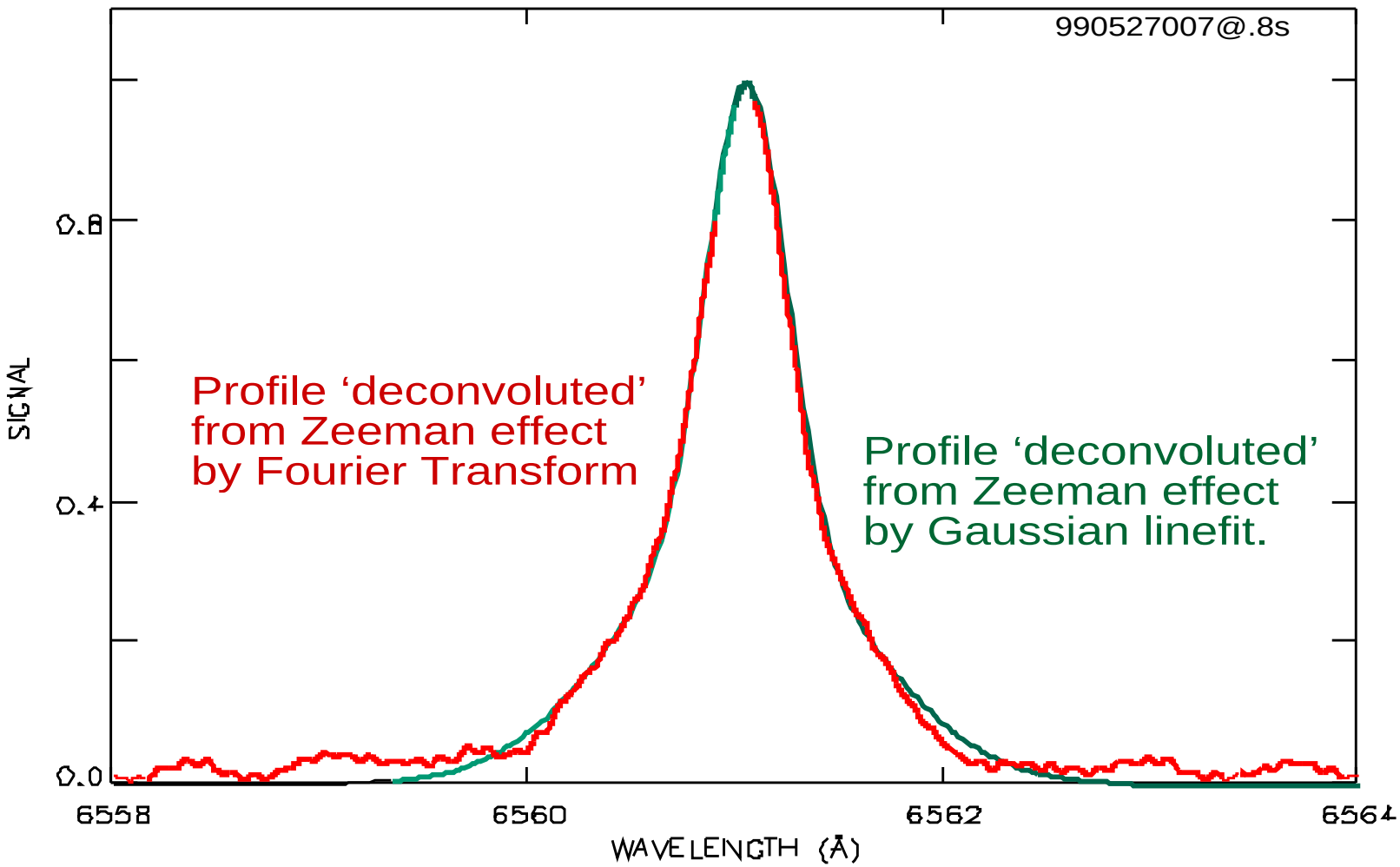
After removal of Zeeman components by Fourier Transform - 1st iteration.



After removal of Zeeman components by Fourier Transform - final iteration.



Comparison of Fourier Transform to Gaussian linefit:



Conclusions

- He II 4684A line shift measured at ≈0.1 Å but shift comparable to uncertainties in wavelength calibration.
- Absorption in FP plates compromised experiment (new plates should give 10x more signal).
- HeII calibration source required to achieve ≈ km/s accuracy
- HeII ion temperature measured to be 13eV from line fits.
- Novel Fourier Transform method to 'deconvolute' Zeeman effect demonstrated. Particularly applicable for non thermal (e.g. Frank Condon) velocity distributions.