Spatial structure, polarization, and spectra from RE emission on Alcator C-Mod

R. Granetz, R. Mumgaard

MIT Plasma Science and Fusion Center

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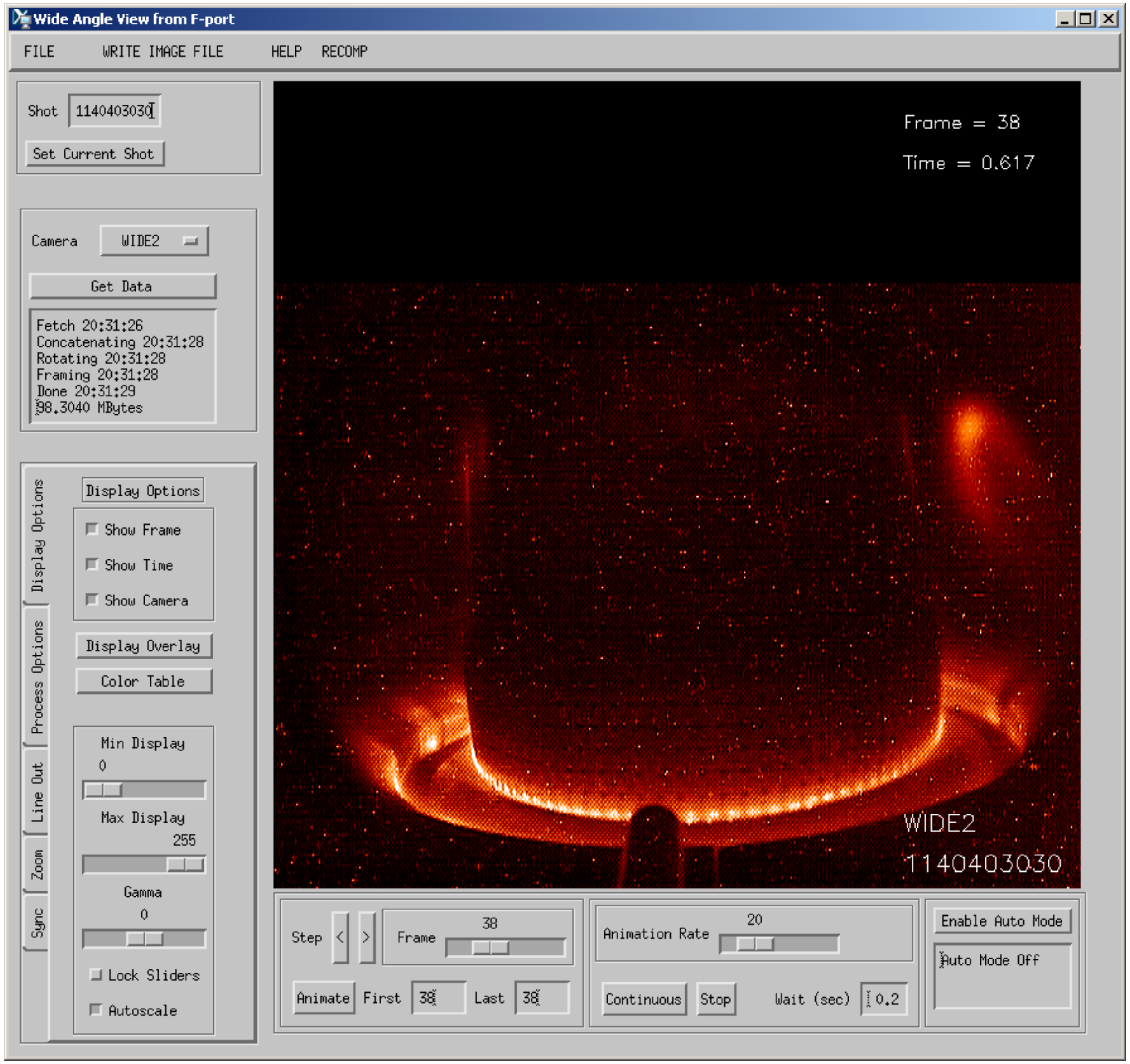
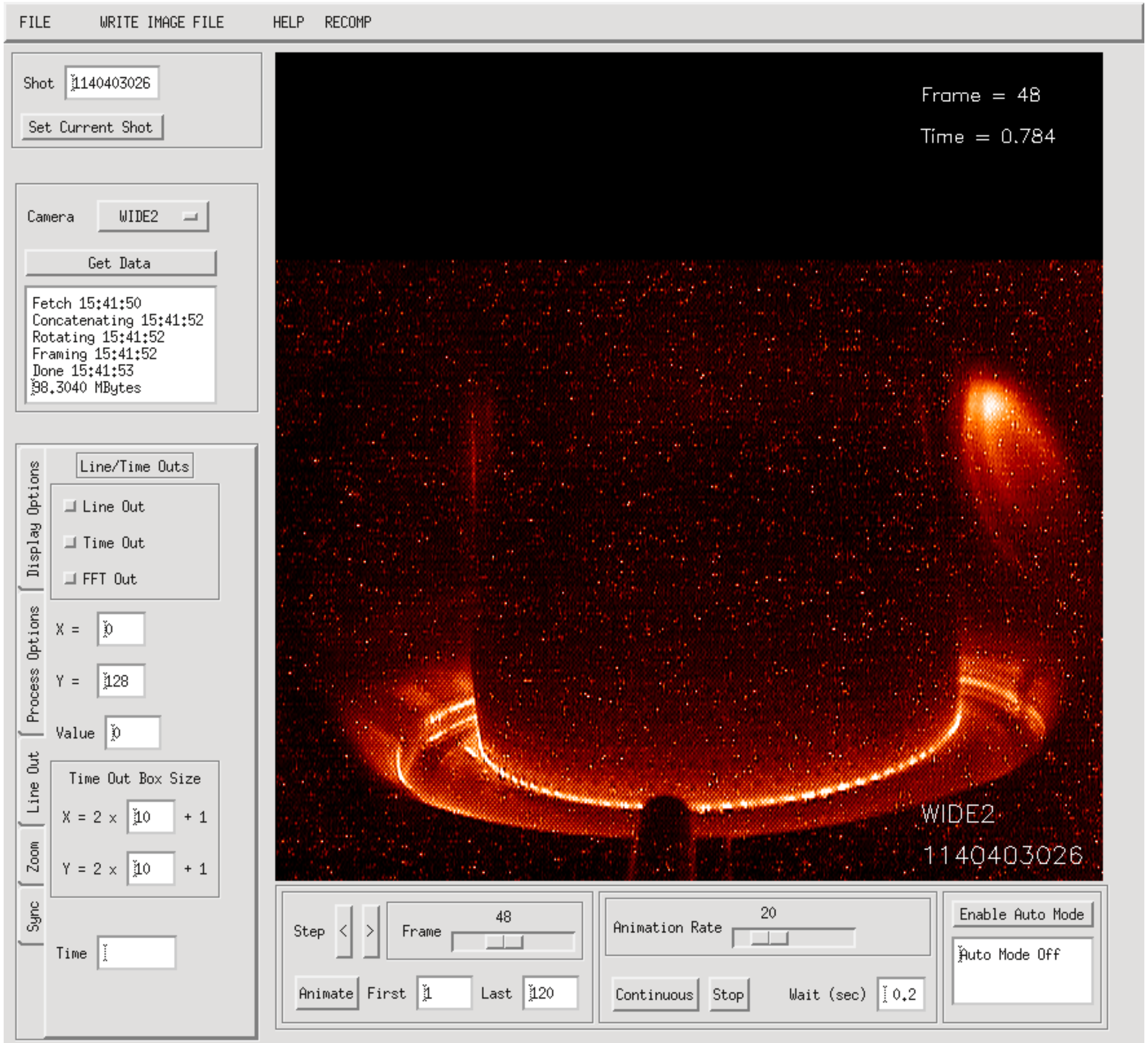
Curious spatial structure sometimes seen



RE forward-peaked emission is often an amorphous blob.

But sometimes unusual spatial structure is observed.

Curious spatial structure sometimes seen



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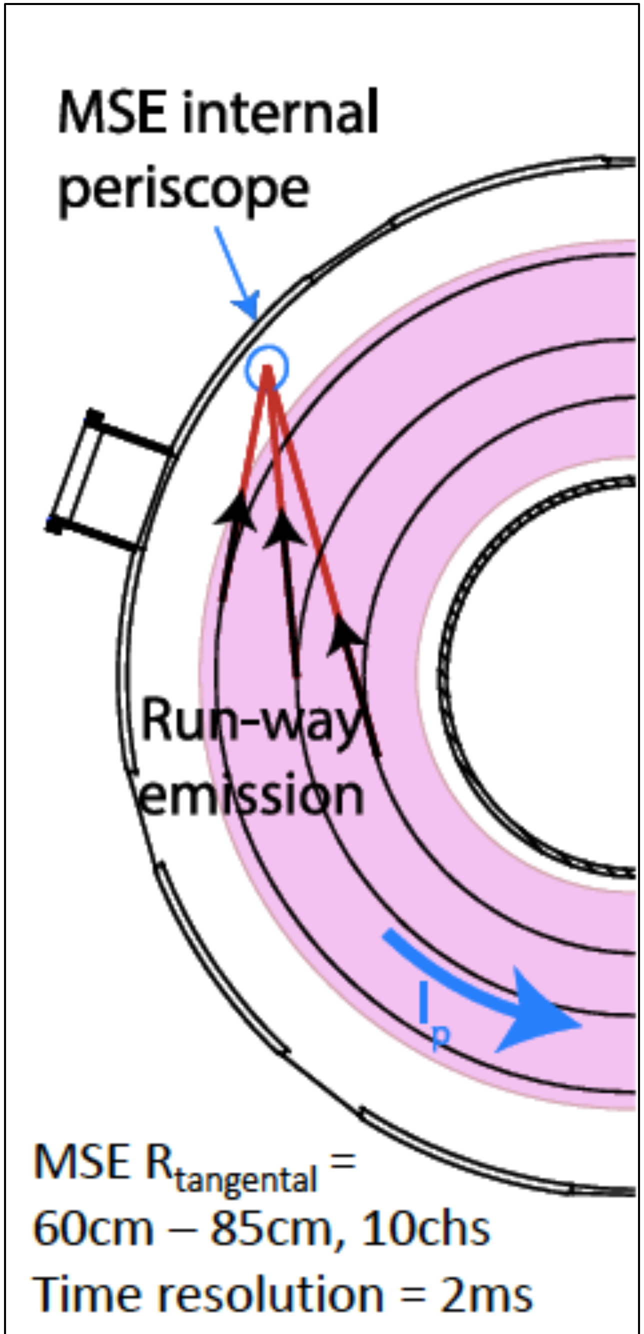
Polarization of RE light

C-Mod has a Motional Stark Effect (MSE) diagnostic to measure q-profiles, usually in conjunction with lower hybrid current drive experiments

- MSE measures the polarization angle of light. Usually the light comes from the interaction of diagnostic neutral beam particles with the plasma.
- MSE has 10 sightlines on the midplane, spanning from just inside the magnetic axis to almost the outer edge of the plasma.
- The geometry of these sightlines is such that they can view forward-peaked RE emission
- Although not by design, our MSE diagnostic is now also used to measure the radial profile of the polarization of the RE emission.



- The RE emission on C-Mod is ~10-100 times brighter than typical levels with the DNB
- We find that the RE emission has a polarisation fraction of up to 60% (Typically 1-10% with the DNB)

The analysis of the MSE polarization data, as well as the operation of the MSE diagnostic, is done by one of our PhD students, Robert Mumgaard (graduating this year)

Theory predicts the radiation should be highly polarized and carry information in the polarization

- Polarization direction of synchrotron emission of relativistic electrons coincides with direction of the particle's acceleration. [Ginzburg 1987]
- Recently explored theoretically due to its importance in astrophysics.
    - Synchrotron emission from quasars
    - Only preliminary measurements of polarization.
- Theory straigh forwardly extended to tokamaks [Sobolev, 2013]
    - Predicts the runaway beam has spatially varying polarization angle and fraction (0-80%) depending on pitch angle, gamma, etc.

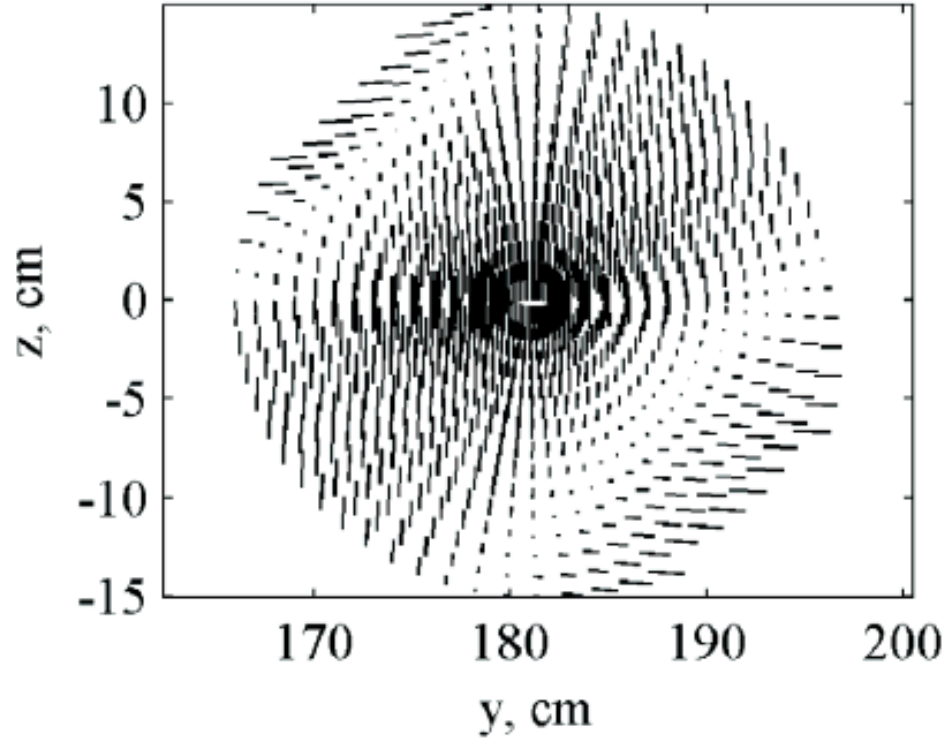
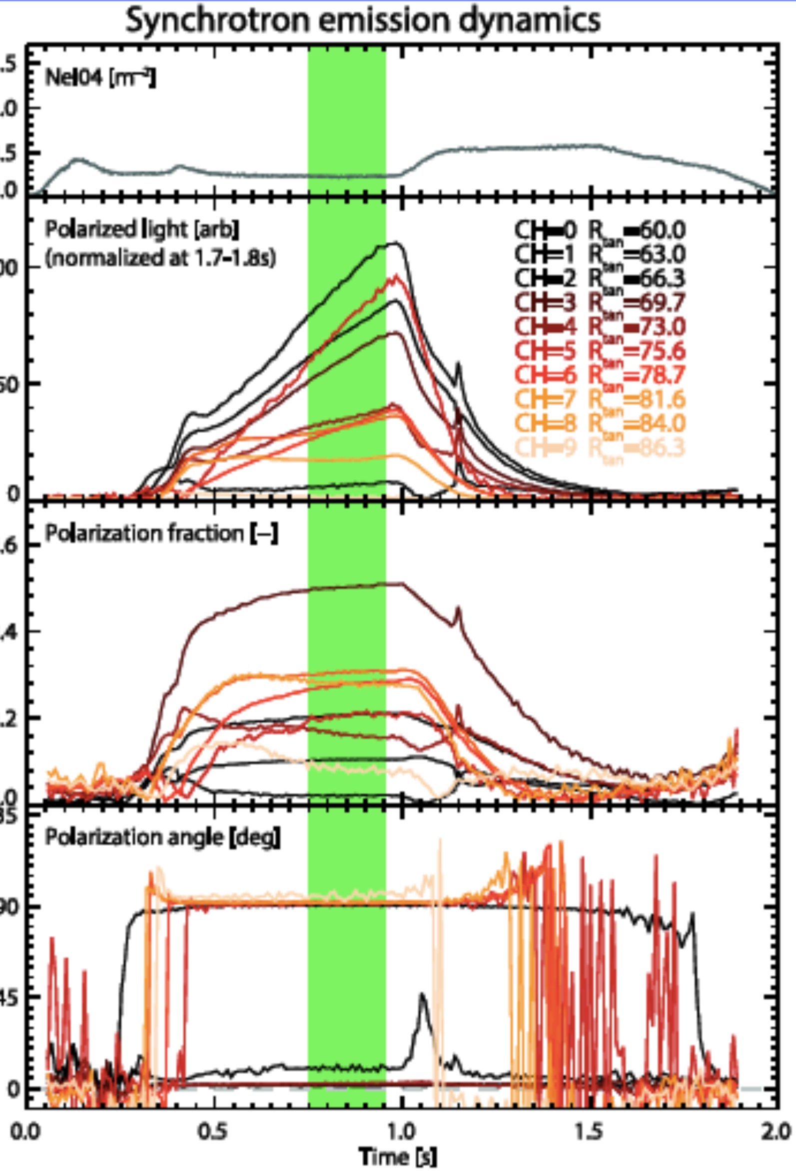
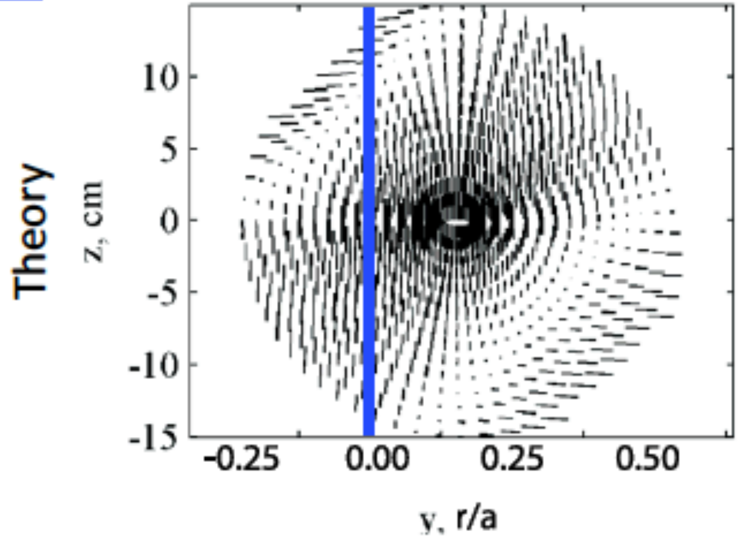


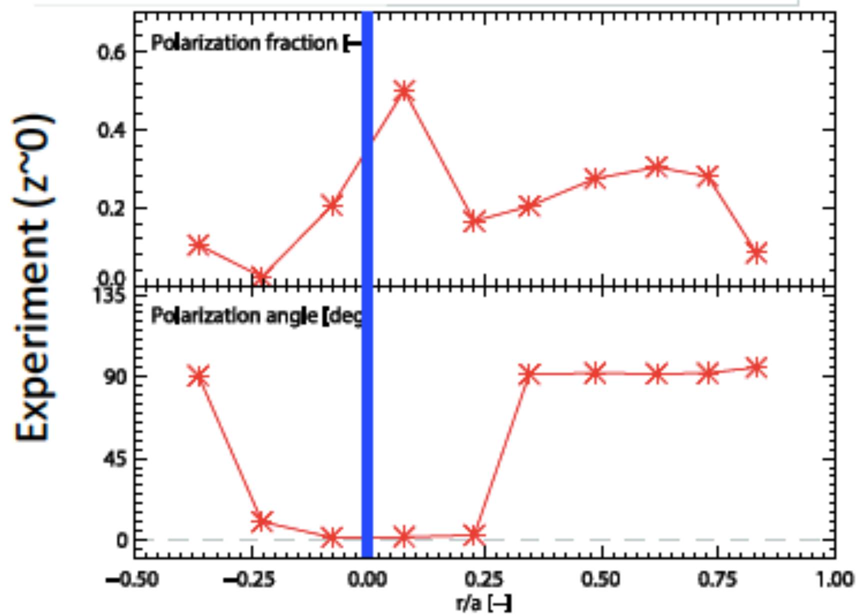
Fig. 3. Polarization of the synchrotron spot (poloidal projection). with parameters: B_0=3·10[4] G; γ =50; $\alpha = 0.1$; $R_0 = 175$ cm; $\delta = 6$ cm; $D = 200$ cm; $q_0 = 1$; $r_b = 15$ cm; $a = 40$ cm

Prediction of the runaway beam polarization in a tokamak (single particle)[Sobolev, 2013]

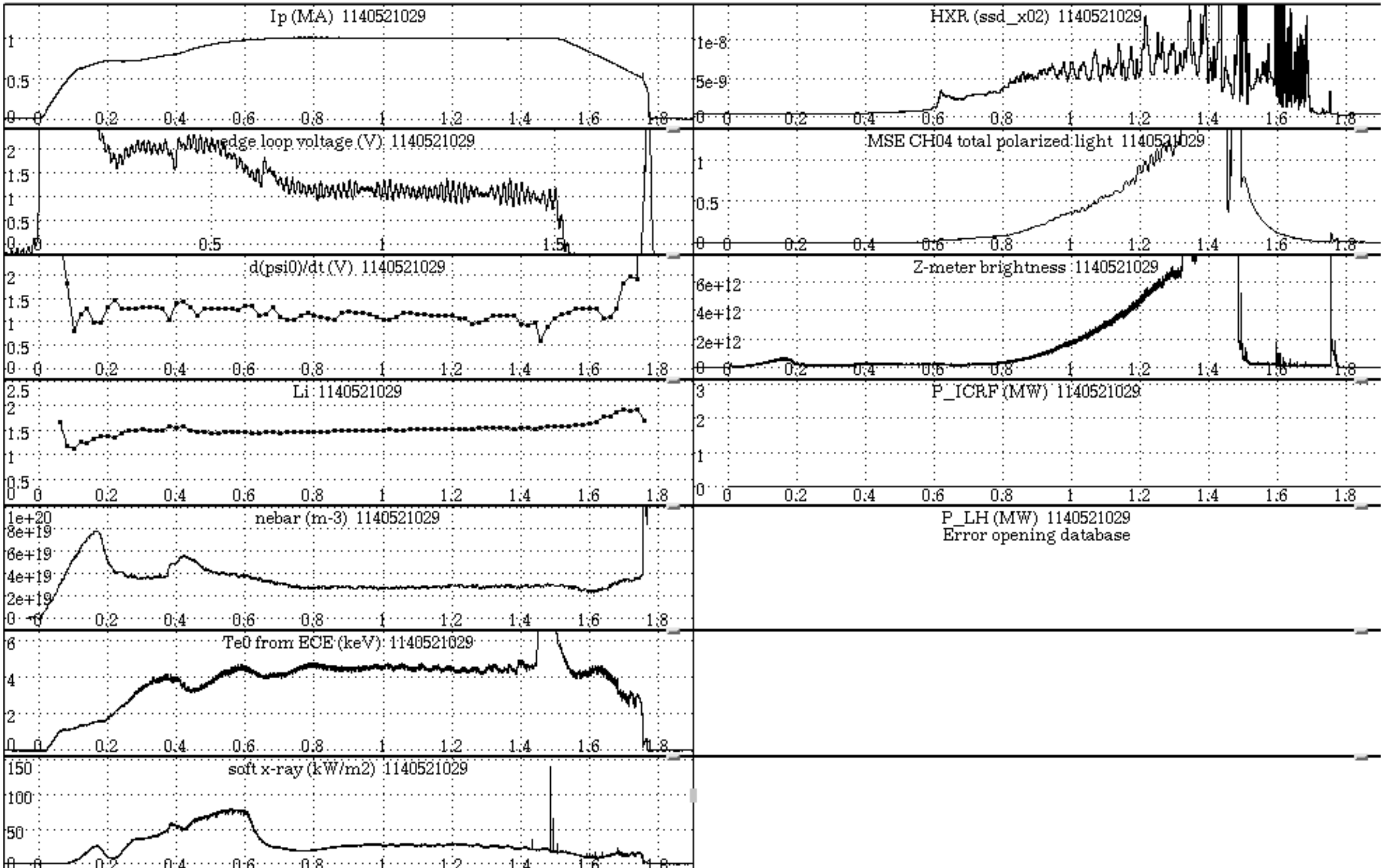
Can get high time resolution, spatial resolution and polarization properties.







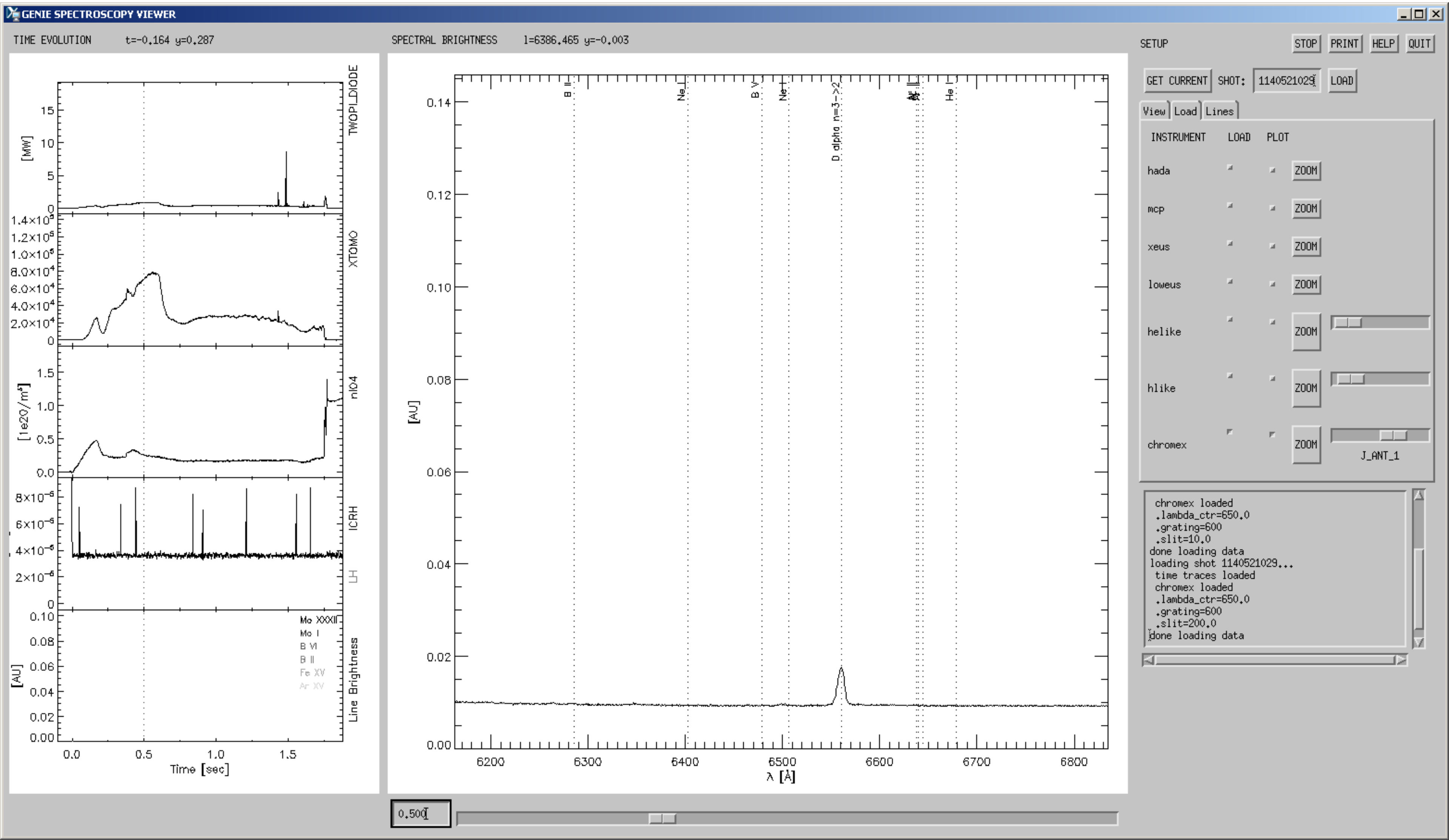
Preliminary spectral measurements



Emission starts at t ~ 0.8 s, continues rising until t ~1.48 s, then rapidly falls

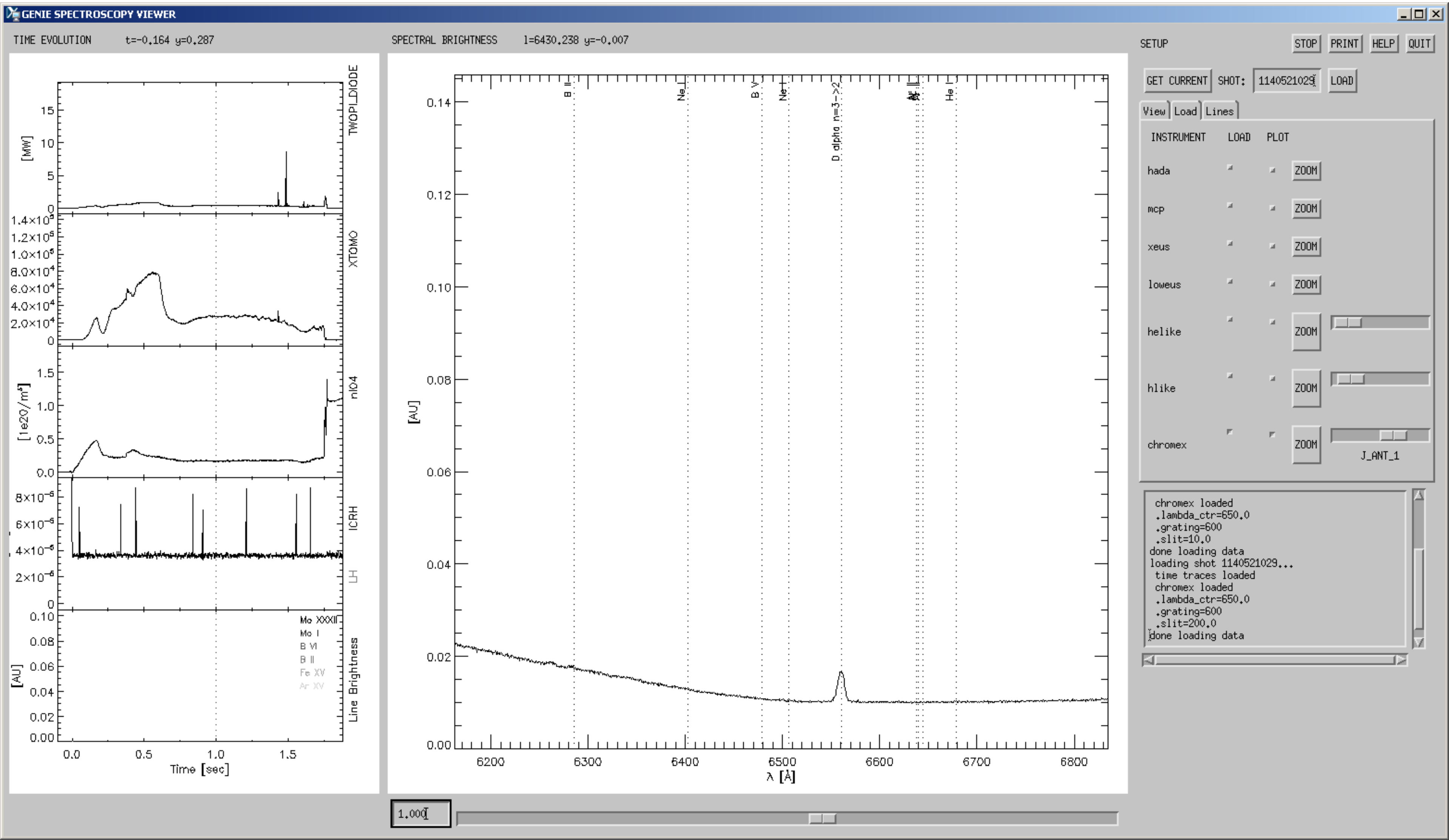
Preliminary spectral measurements viewing into the RE emission

t = 0.5 s



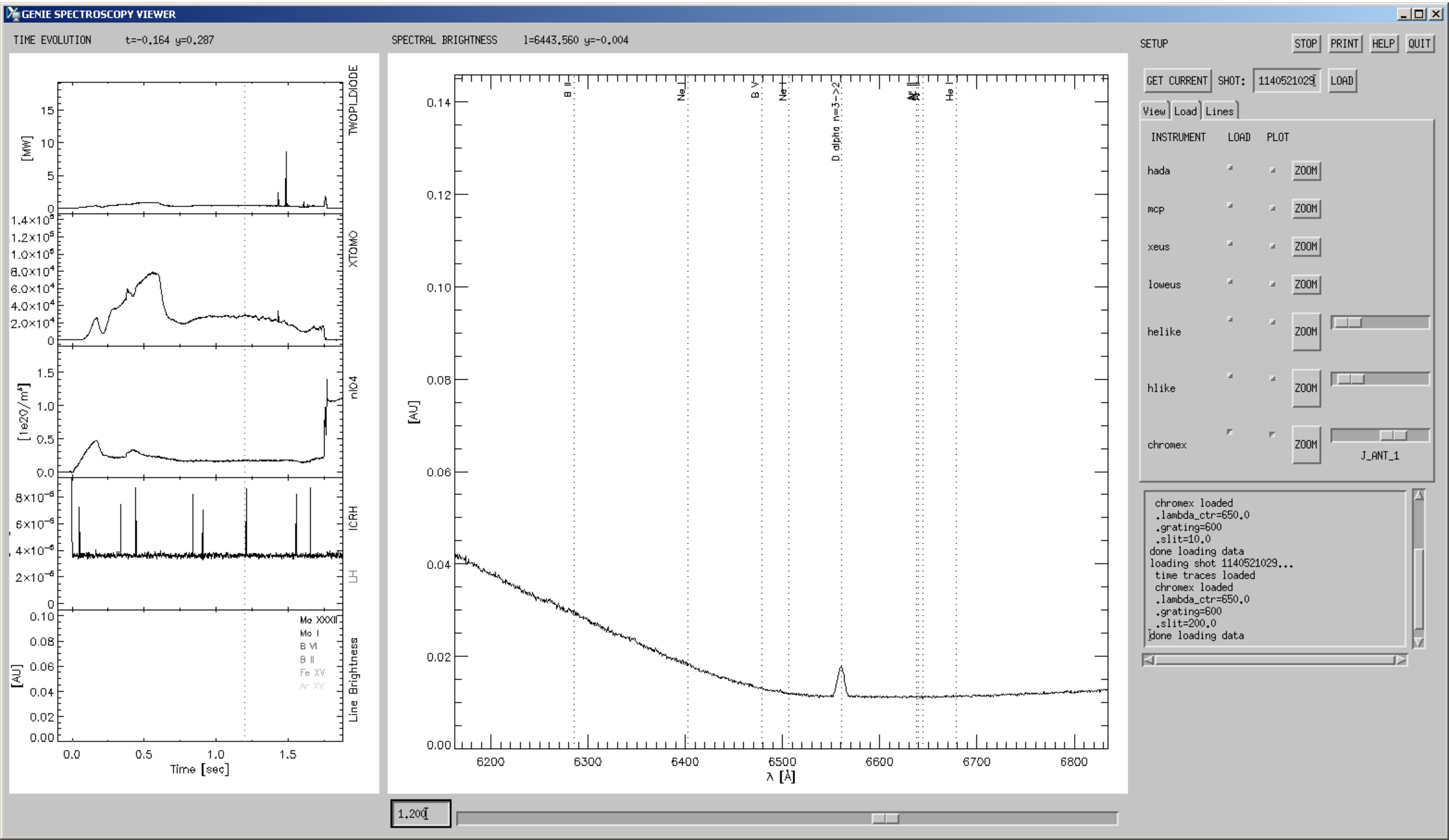
Preliminary spectral measurements viewing into the RE emission

t = 1.0 s



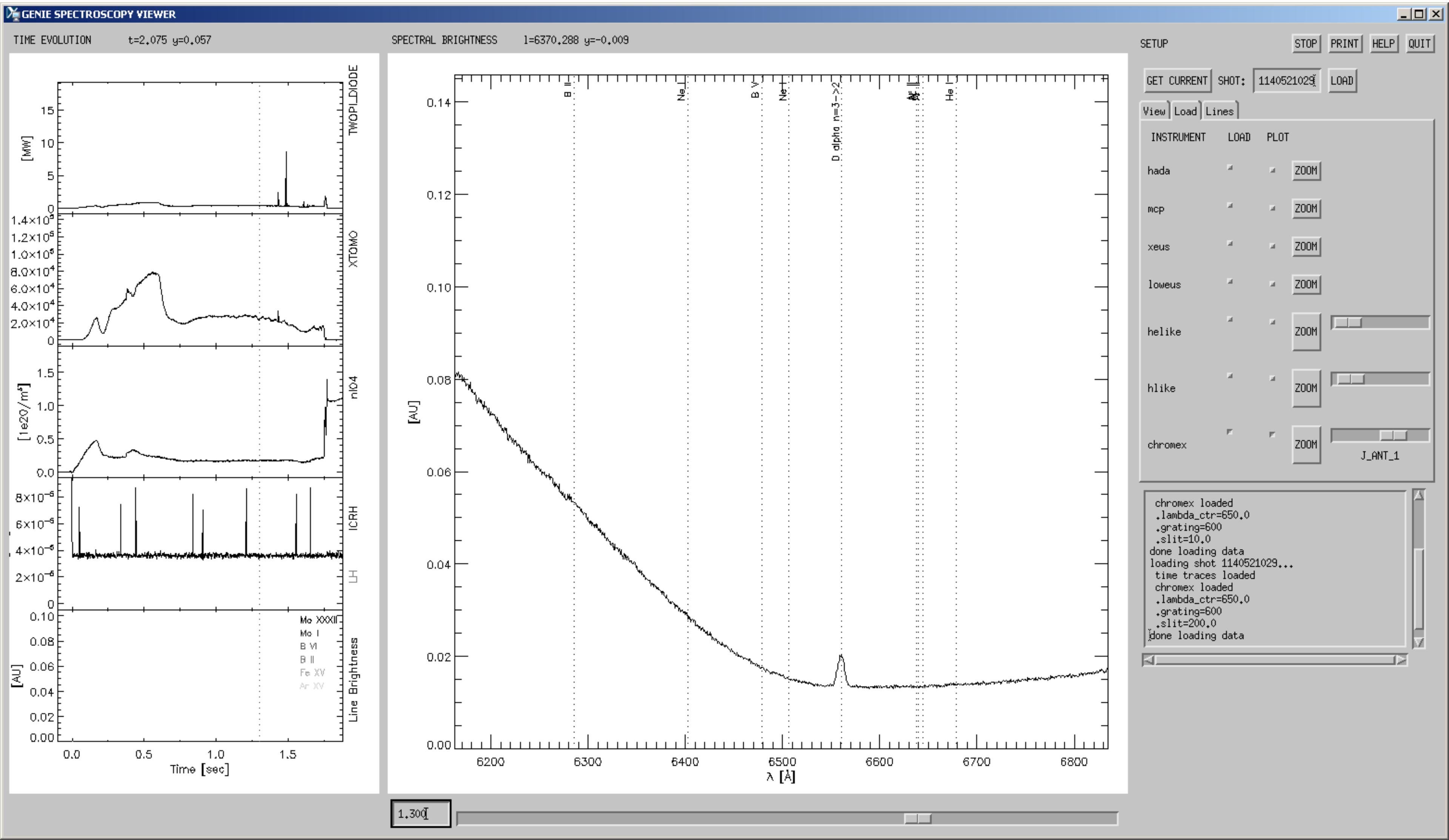
Preliminary spectral measurements viewing into the RE emission

t = 1.2 s



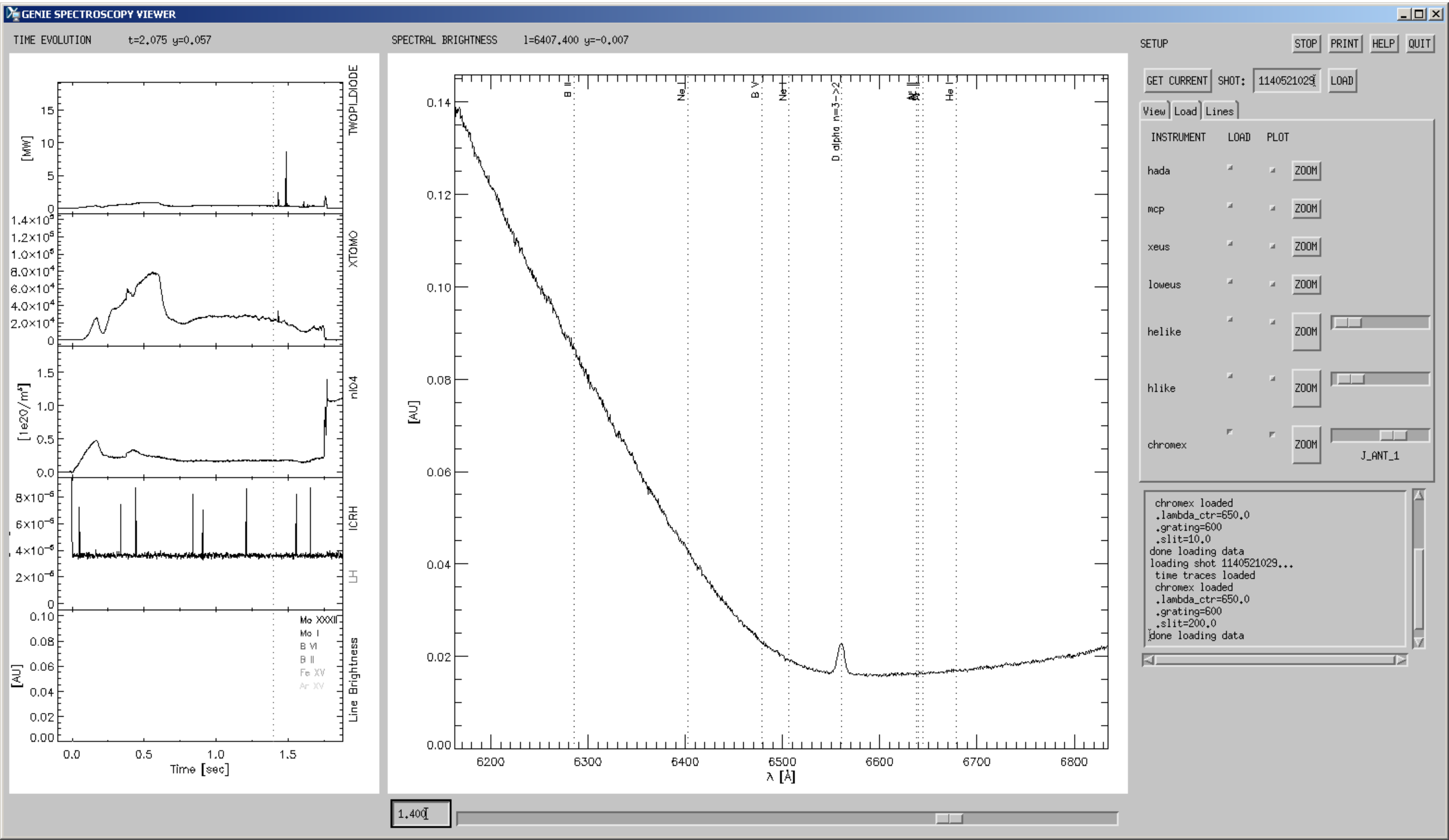
Preliminary spectral measurements viewing into the RE emission

t = 1.3 s



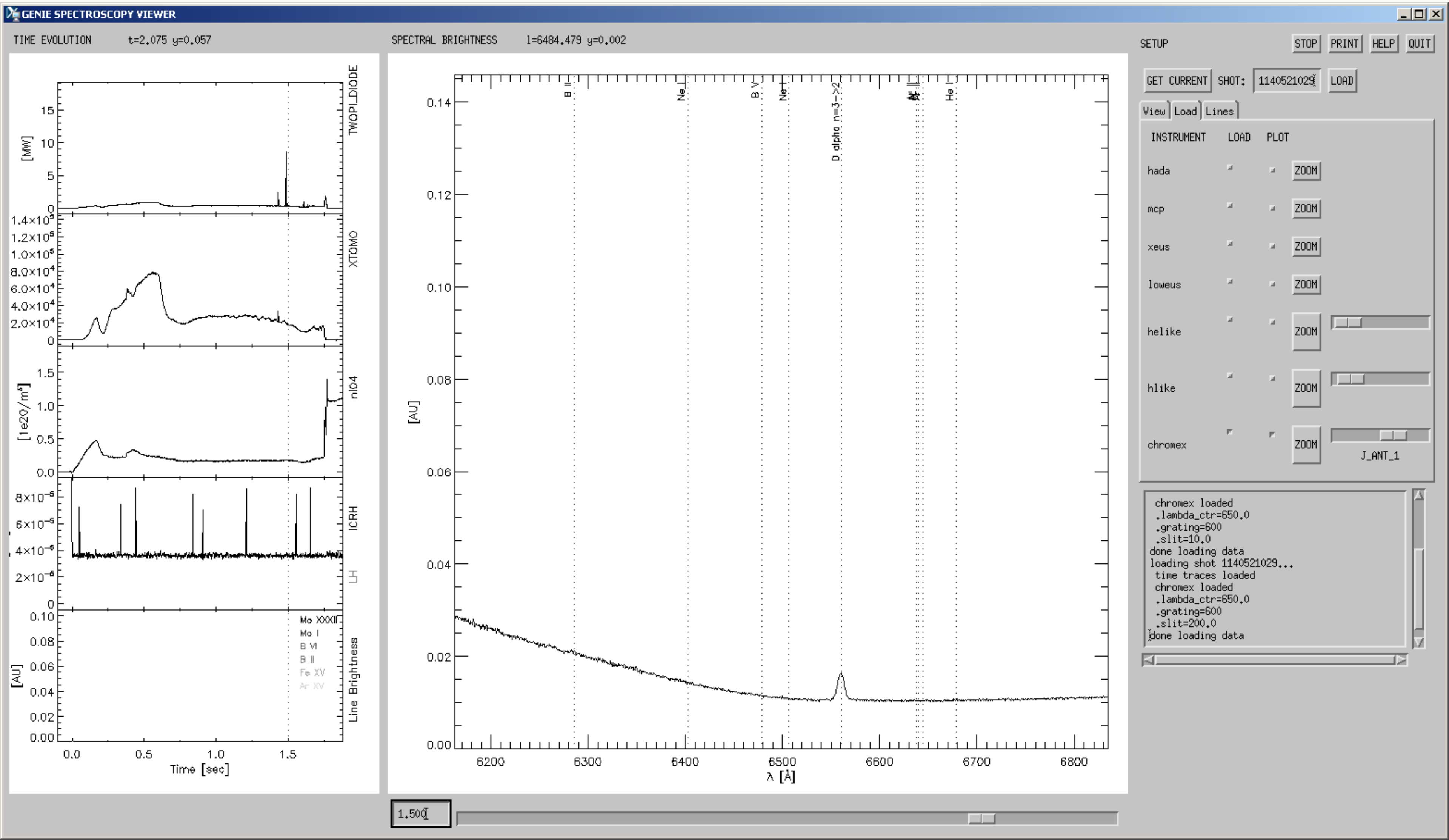
Preliminary spectral measurements viewing into the RE emission

t = 1.4 s



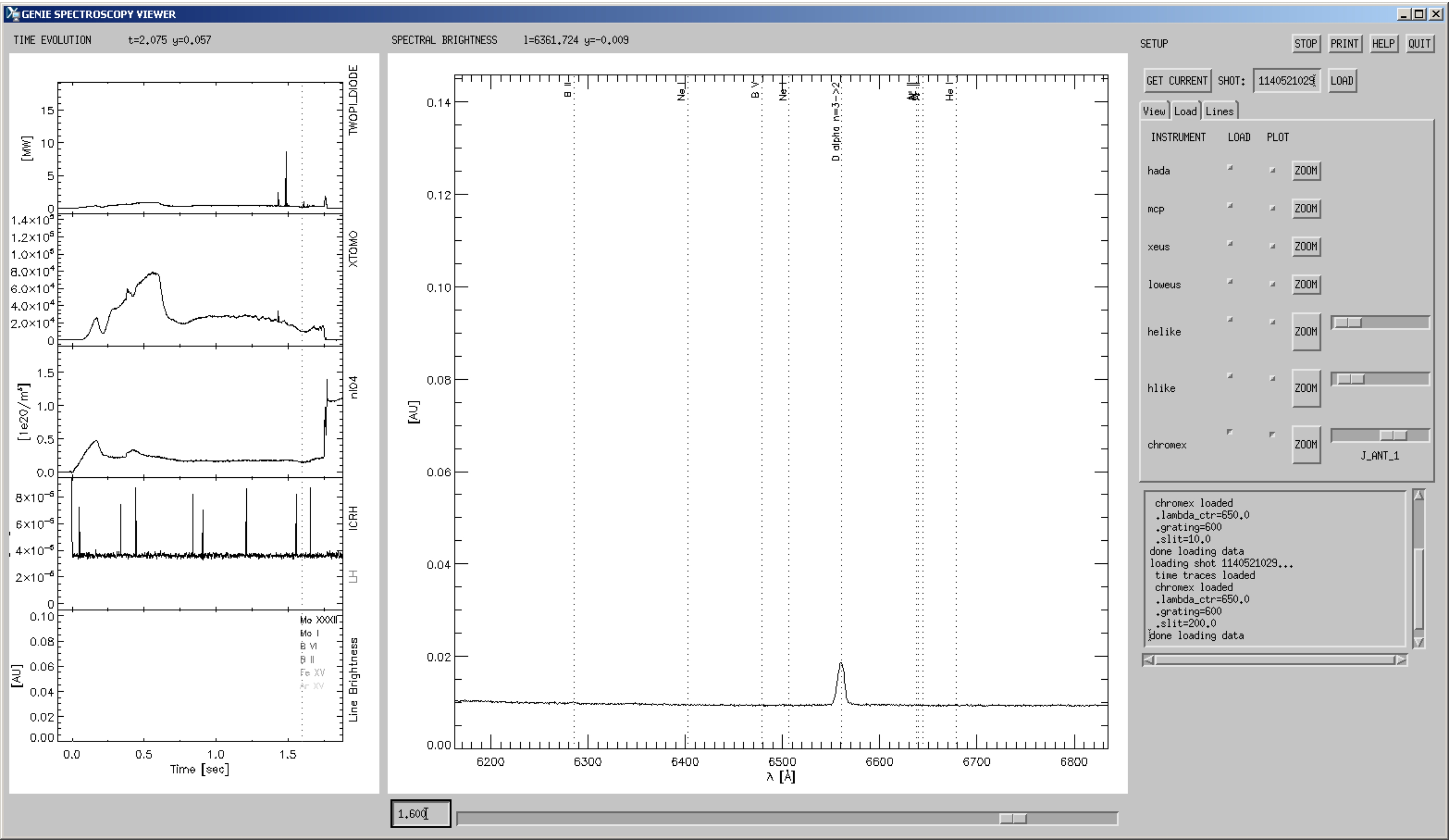
Preliminary spectral measurements viewing into the RE emission

t = 1.5 s



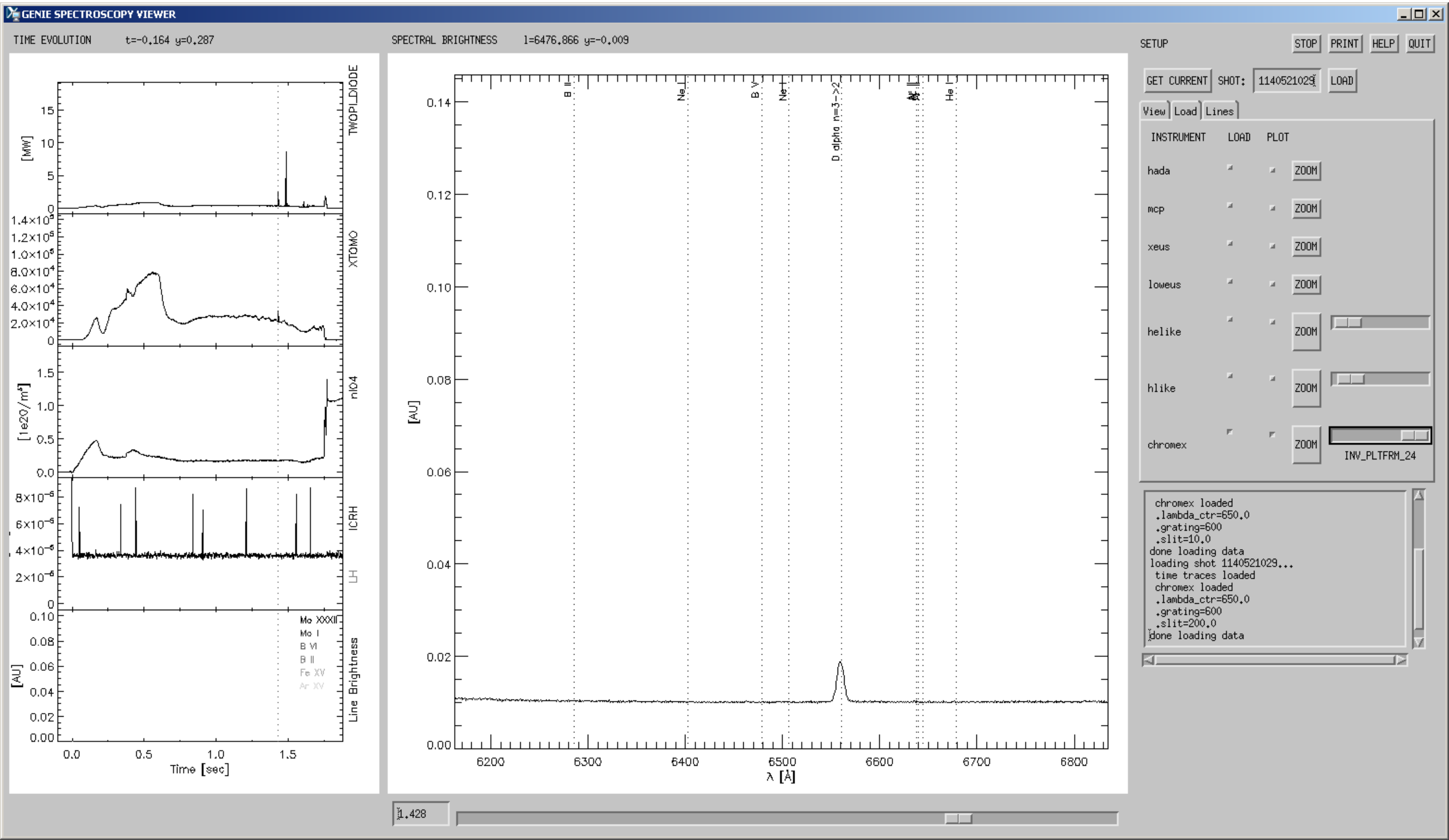
Preliminary spectral measurements viewing into the RE emission

t = 1.6 s



Preliminary spectral measurements viewing AWAY from the RE emission

t = 1.4 s



For TEXTOR, DIII-D, EAST, et al, the theoretical synchrotron spectrum is peaked in the infrared

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$$P(\lambda)=\frac{4\pi}{\sqrt{3}}\frac{m_e c^3}{\Gamma^2\lambda^3}\int_w^\infty K_{5/3}(x)dx$$

$$\approx\frac{4\pi m_e c^3 r_e}{\Gamma^2\lambda^3}\sqrt{\frac{\pi}{2w}}\exp(-w), \qquad (1)$$

where $w=4\pi R/(3\Gamma^3\lambda)$ and the last approximation is only valid for $w\gg 1$. Here m_e is the electron rest mass, c the velocity of light, r_e the classical electron radius, Γ the relativistic mass factor and λ the wavelength. The emission is mainly in the forward direction with an opening angle δ of $\delta=1/\Gamma$.

For the specific situation of runaway electrons in a tokamak, Eq. (1) is still valid when the instantaneous radius of curvature of the orbit R_{curv} is approximated given by[9]

$$R_{\mathrm{curv}}^{-2}\approx R^{-2}[1+\eta^2+2\eta\sin(\Theta+\alpha)] \qquad (2)$$

which may oscillate strongly during the motion in a tokamak. Here $v_\parallel \gg v_\perp$, $\omega_{Bo}=eB_T/m_e$ and $\eta=v_\perp/v_{\mathrm{dr}}$, $v_{\mathrm{dr}}=\Gamma v_\parallel^2/\omega_{Bo}R$, with v_{dr} the drift velocity, Θ the poloidal angle corresponding to the position of the guiding center and α the phase of the cyclotron gyration.

Using the Schwinger approach[10] and taking into account the features of the relativistic electron motion in a tokamak (motion along the magnetic field line, cyclotron gyration, and vertical centrifugal drift) the spectral density of the emitted power was derived in Ref. 9. For the parameter $\xi=4\pi/3\,R/\lambda\Gamma^3\;1/\sqrt{1+\eta^2}\gg 1$ it is given by $(\Gamma\gg 1)$

$$P(\lambda)\approx\pi m_e c^3 r_e\sqrt{\frac{2\sqrt{1+\eta^2}}{\lambda^5 R\Gamma}}$$

$$\times\left[I_0(a)+\frac{4\eta}{1+\eta^2}I_1(a)\right]\exp(-\xi), \qquad (3)$$

where $I_{0,1}(a)$ is the modified Bessel function and $a=(4\pi/3)(R/\lambda\Gamma^3)(\eta/(1+\eta^2)^{3/2})$. At

$$\lambda_m\approx\frac{8\pi}{15}\frac{R}{\sqrt{1+\eta^2}}\frac{1}{\Gamma^3}, \quad (a(\lambda_m)\leqslant 1.25) \qquad (4)$$

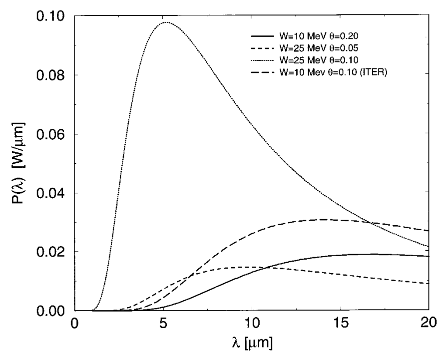

FIG. 1. Synchrotron spectra calculated for one electron for TEXTOR-94 and ITER for different values of energy W and pitch angle θ.

III. TEXTOR-94 SETUP

Synchrotron radiation measurements are routinely made at TEXTOR-94 with a thermographic camera operating in the wavelength range 3–12 μm. However, since CaF_2 optics are used, the effective long wavelength limit is reduced to 8 μm. The thermographic camera is of the type Inframetrics 760 BB. This IR scanner consists of a HgCdTe detector cooled with liquid nitrogen. Two scanning mirrors in front of the detector scan the two-dimensional (2D) field of view in 1/50 s in the horizontal and veritcal direction, respectively. An option exists to fix the vertical mirror, resulting in a 1D scan at a rate of 8 kHz. The analog data was previously recorded on videotape and analyzed afterwards. Recently, the electronics have been upgraded and all signals are digitized to 12 bits before they are transferred by fiber optics to the remote computer for data analysis and storage.[11] Moreover, to avoid electric or magnetic interference (especially during a disruption, when the generation of runaway electrons preserves special attention), the camera head and the electronic box are both well shielded by an iron housing with an internal copper foil.

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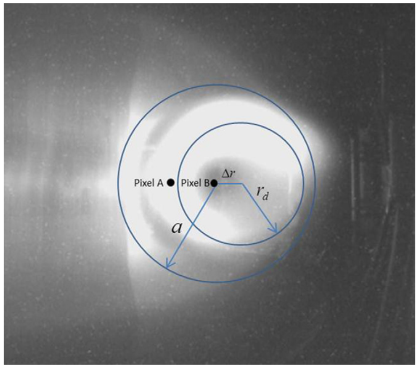


Figure 4. One of the synchrotron spots with a ring-like pattern in the discharge.

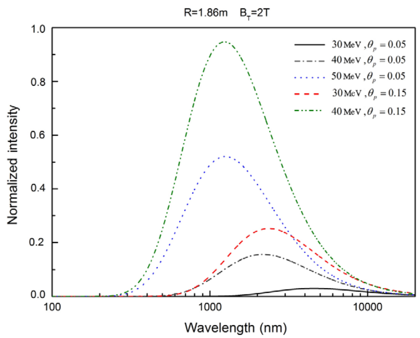
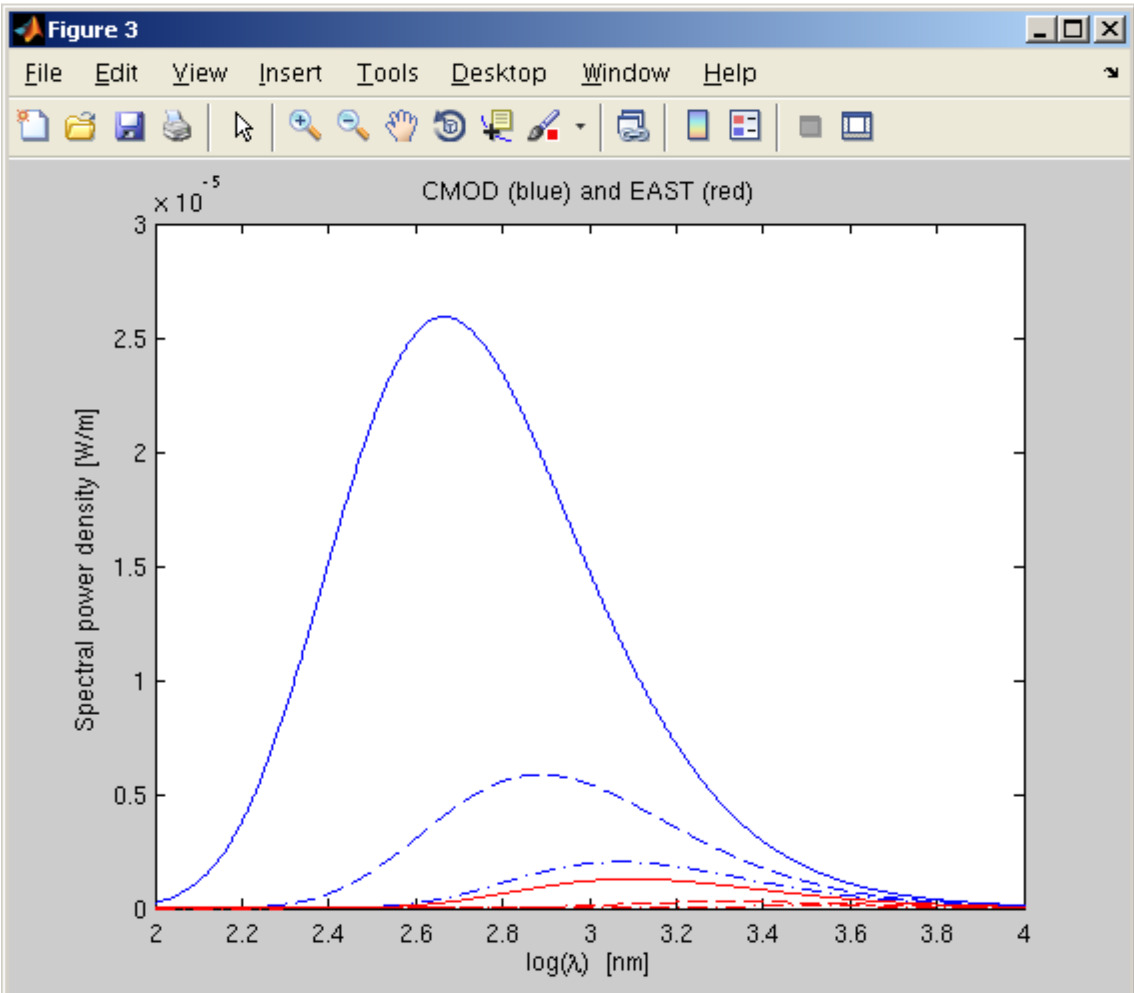


Figure 5. Synchrotron spectra calculated for energetic runaway electrons for typical EAST parameters ($R = 1.86$ m, $B_t = 2$ T) for different values of energy and pitch angle.

part of the total synchrotron radiation can fall onto the camera. If the pitch angle θ is sufficiently large ($\theta = 0.08$ was used there for almost total detection), the total amount of radiation would be detected, and an approximately round shape can be

B ~ 2 T, R ~ 1.7-1.8 m

For the same range of energies and pitch angles, the theoretical synchrotron spectrum in C-Mod is peaked in the visible, not the IR



<u>C-Mod</u>

B = 5.4 T
R = 0.68 m