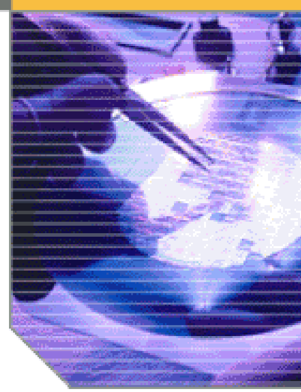
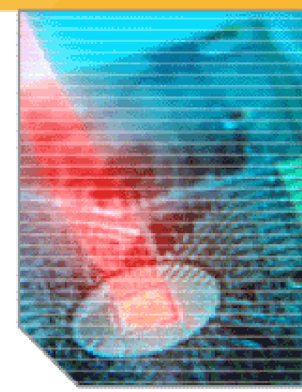
Modeling of Xenon EUV Emission Spectra and MHD Plasma Parameters for a DPF Light Source





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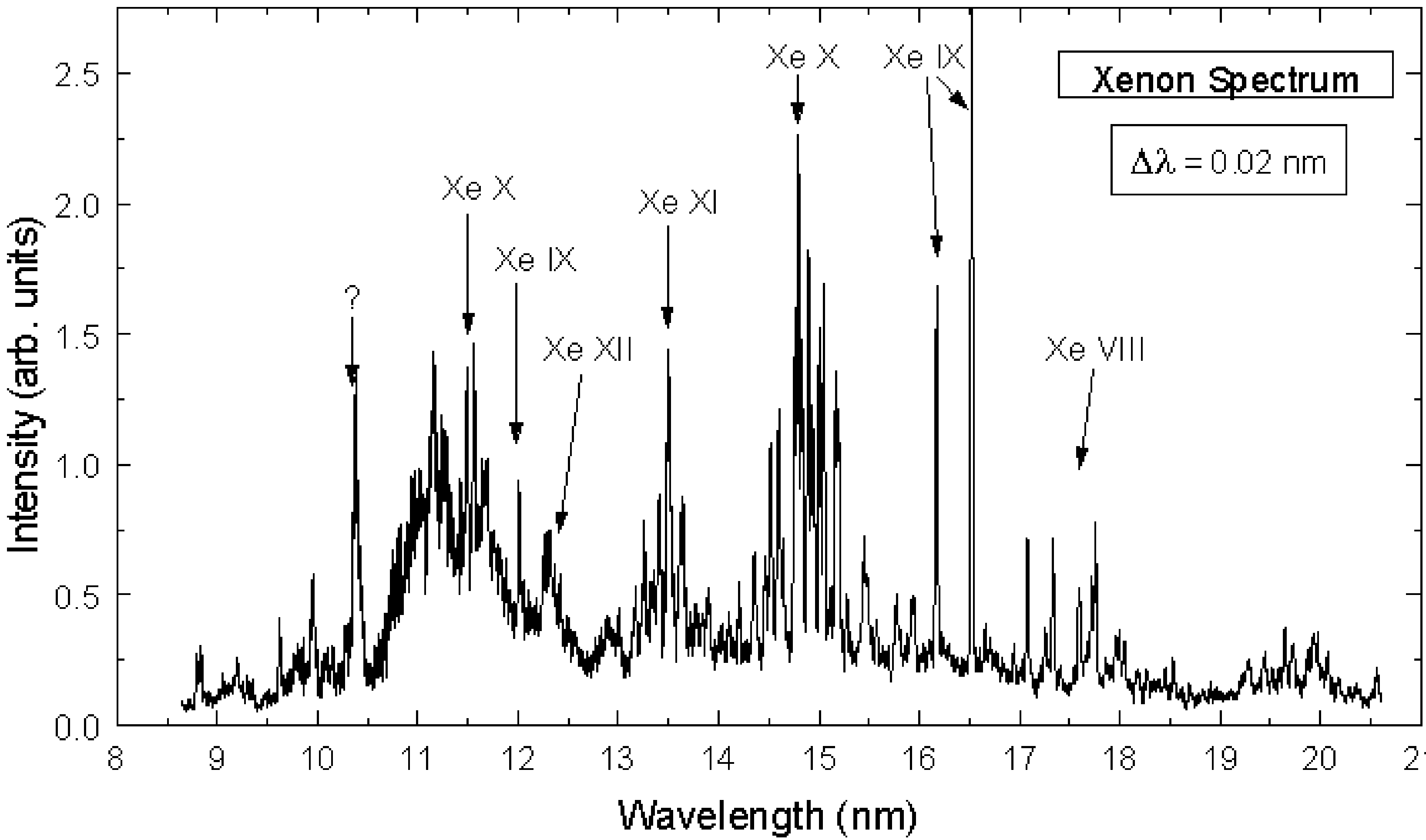
Introduction

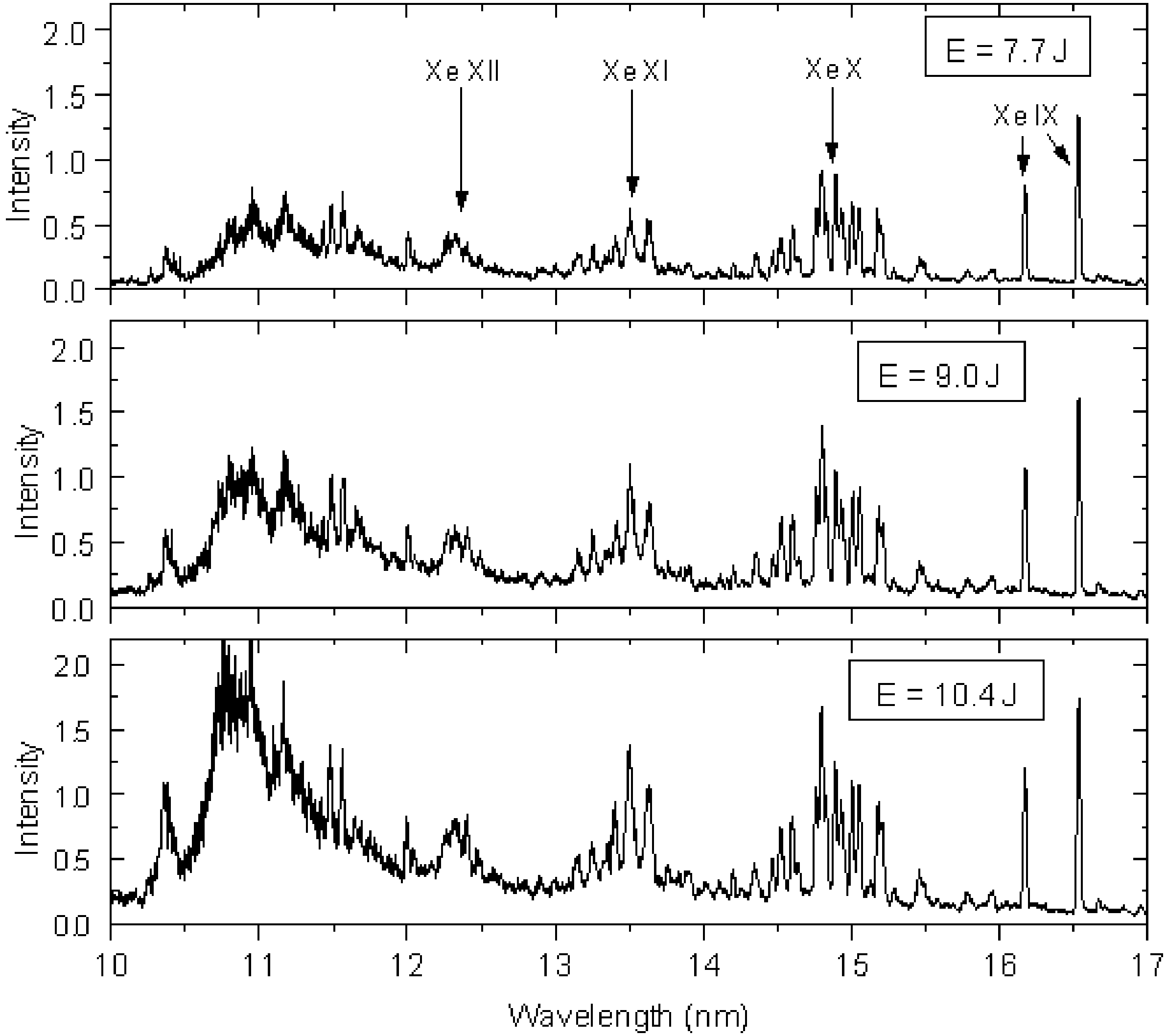
- Xenon EUV emission spectra from a dense plasma focus discharge source are analyzed in order to identify the dominant spectral features and obtain an estimate of the electron temperature.
- Low and higher resolution spectra were recorded in the 8 to 21 nm wavelength range for different operating conditions.
- The emission spectra are calculated ab-initio using the Hartree-Fock method (Cowan code) with additional configuration interaction.
- Both line positions and line intensities are compared.
- Plasma dynamics calculations are also carried out using the two-dimensional MHRDR code developed by Bauer et al. (UNR).

Experimental Results



EUV spectrum of DPF discharge in the region from 8 to 21 nm at 0.02 nm resolution

Experimental Results



Xenon spectra for different DPF input energies

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Modeling of the Spectra

- Hartree-Fock calculations with configuration interaction for Xe^{7+} to Xe^{12+}, *atomic physics only*
- assume quasi-stationary plasma in partial thermal equilibrium, *no plasma dynamics*
- for Corona equilibrium the line strengths (<u>not</u> the ion populations) are weighted by a Boltzmann factor at electron temperature T_e. *Complete LTE is not required.*
- Ion populations are obtained from equilibrium between ionization and recombination *(H. Langhoff, to be published).*
- *Influence of opacity:* The dependence of the optical density on oscillator strength and wavelength is included explicitly.
- The calculated spectra are folded to a given experimental resolution.

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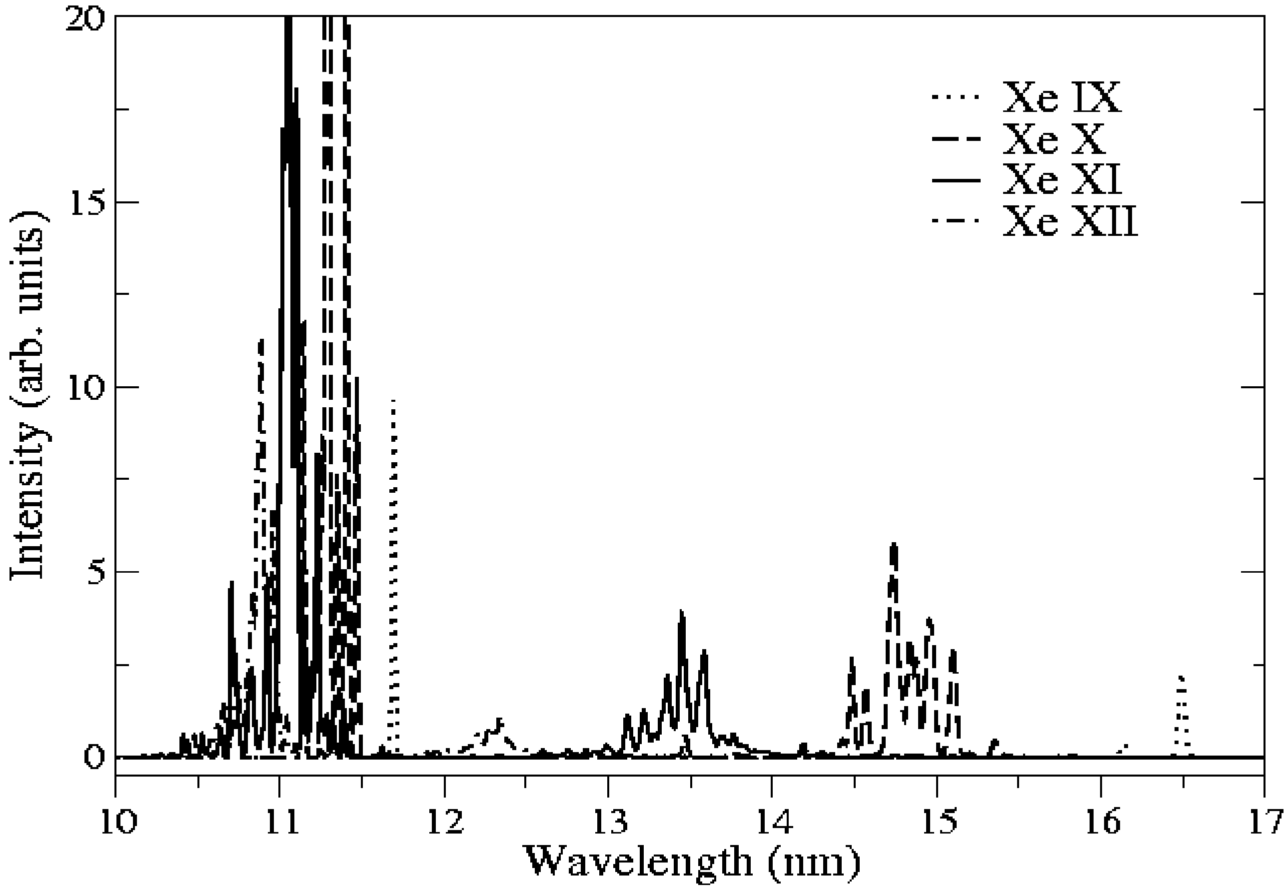
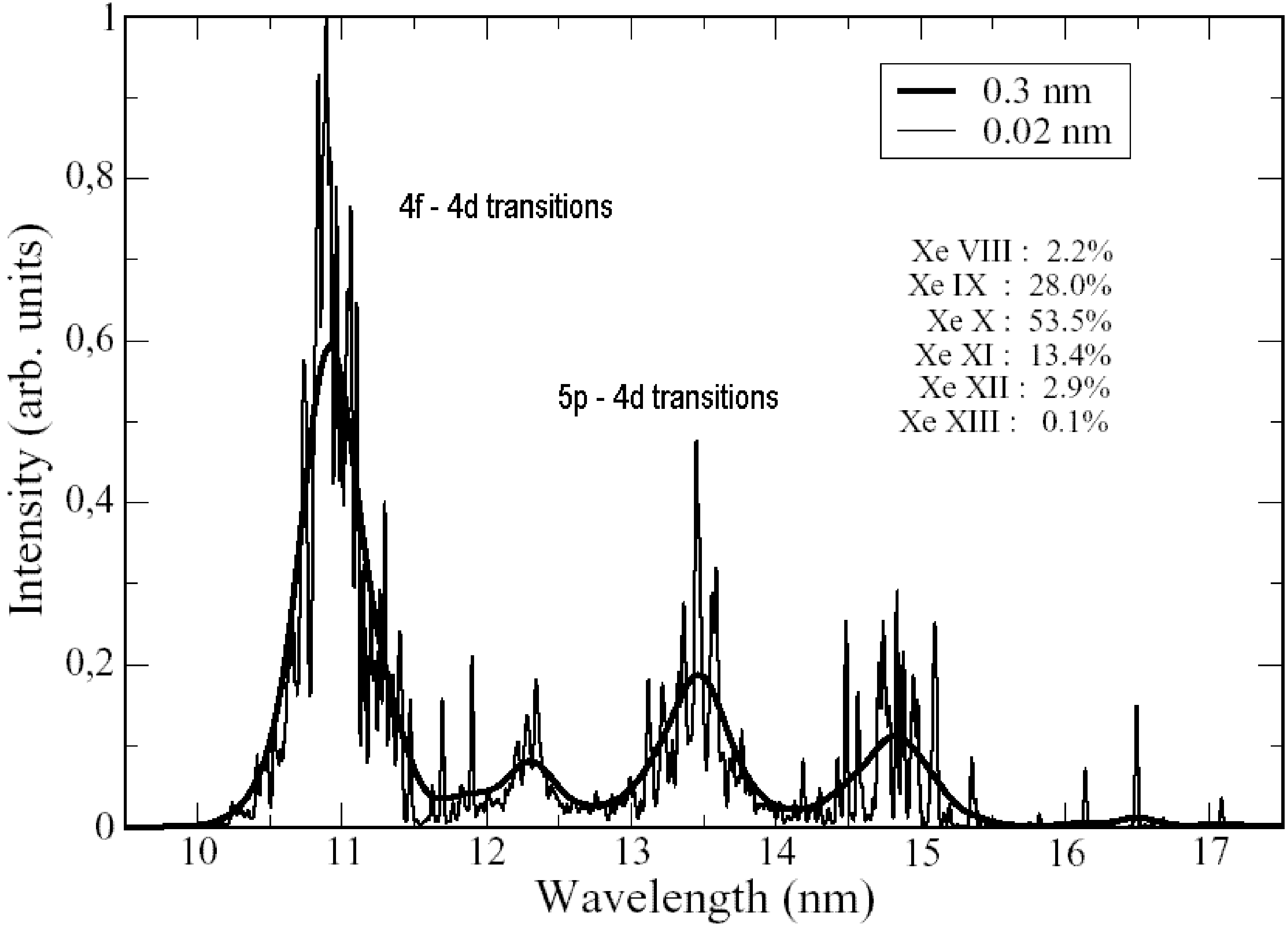
Calculated Results

The 4d - 4f transitions are overlapped at ~ 11 nm, the 4d - 5p transition arrays of the different ion species are fairly well separated in the region from 12 to 17 nm.



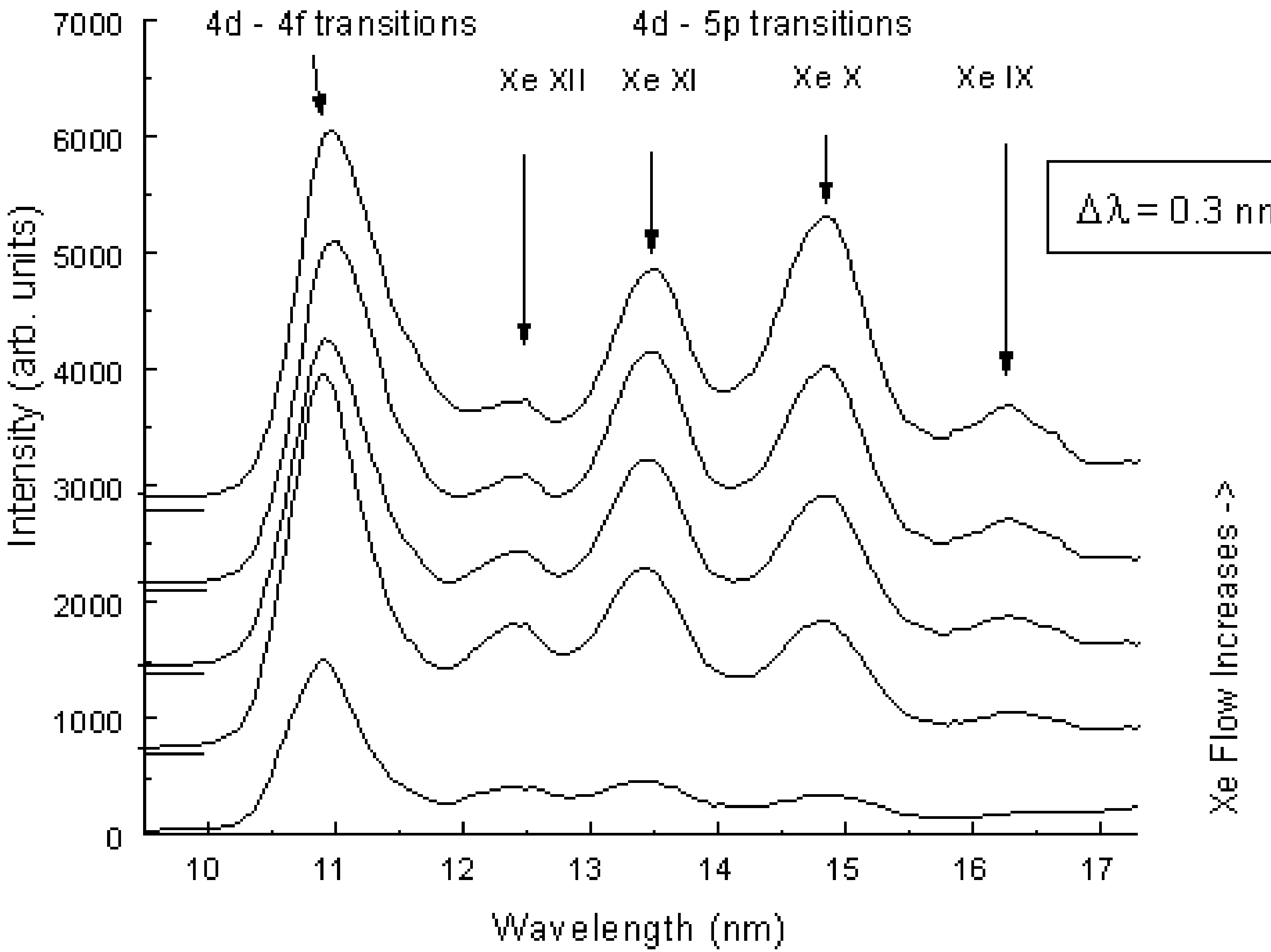
Calculated spectrum for Xe IX to Xe XII ions at Te ~ 30 eV, opacity not taken into account

Calculated Results



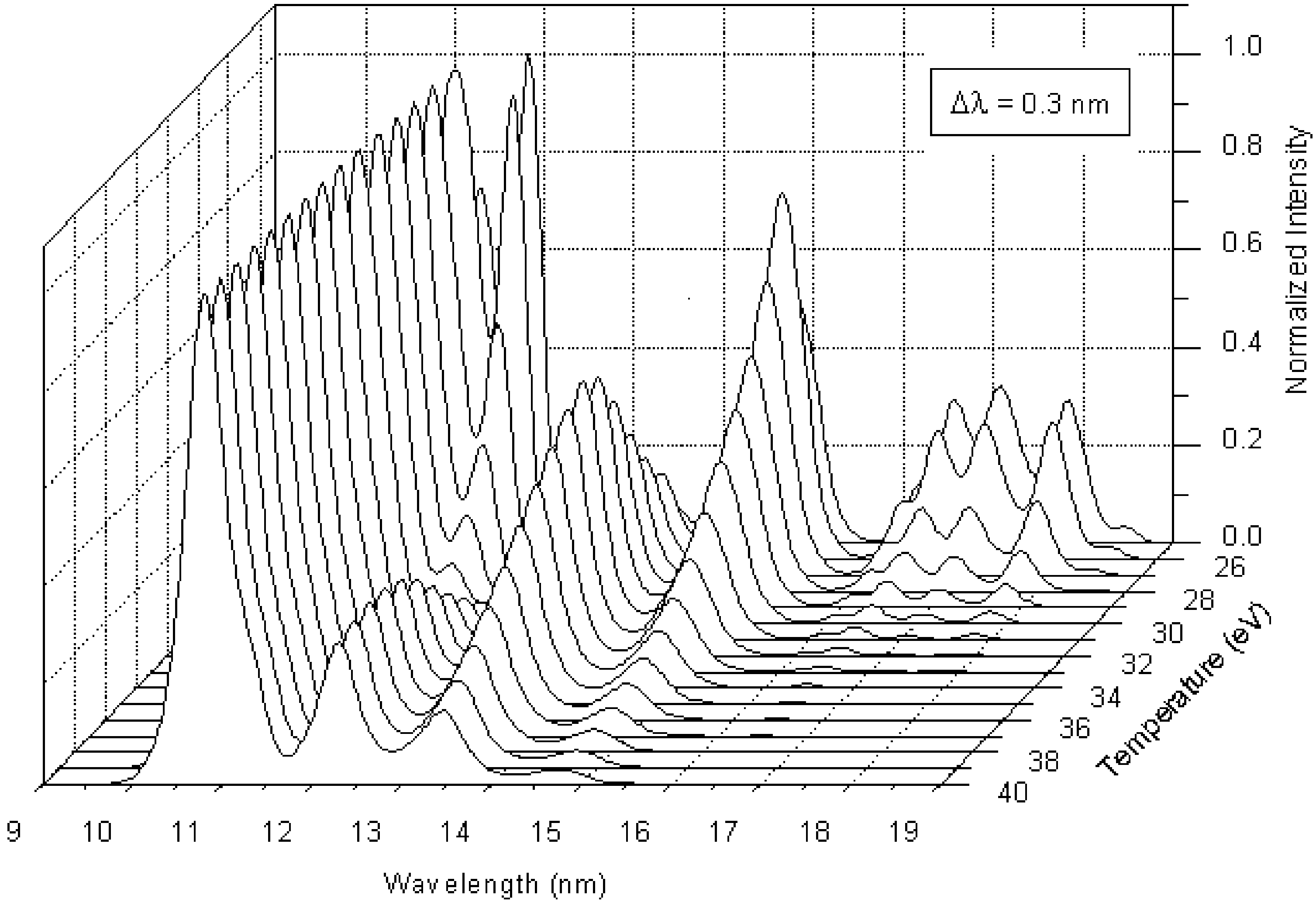
Calculated spectrum for the 10 - 17 nm region at Te ~ 27 eV including modeling of the optical thickness, $n_e \sim 4.4\ 10^{17}\ cm^{-3}$, He-Xe mixture.

Experimental Results with Transmission Grating Set-up



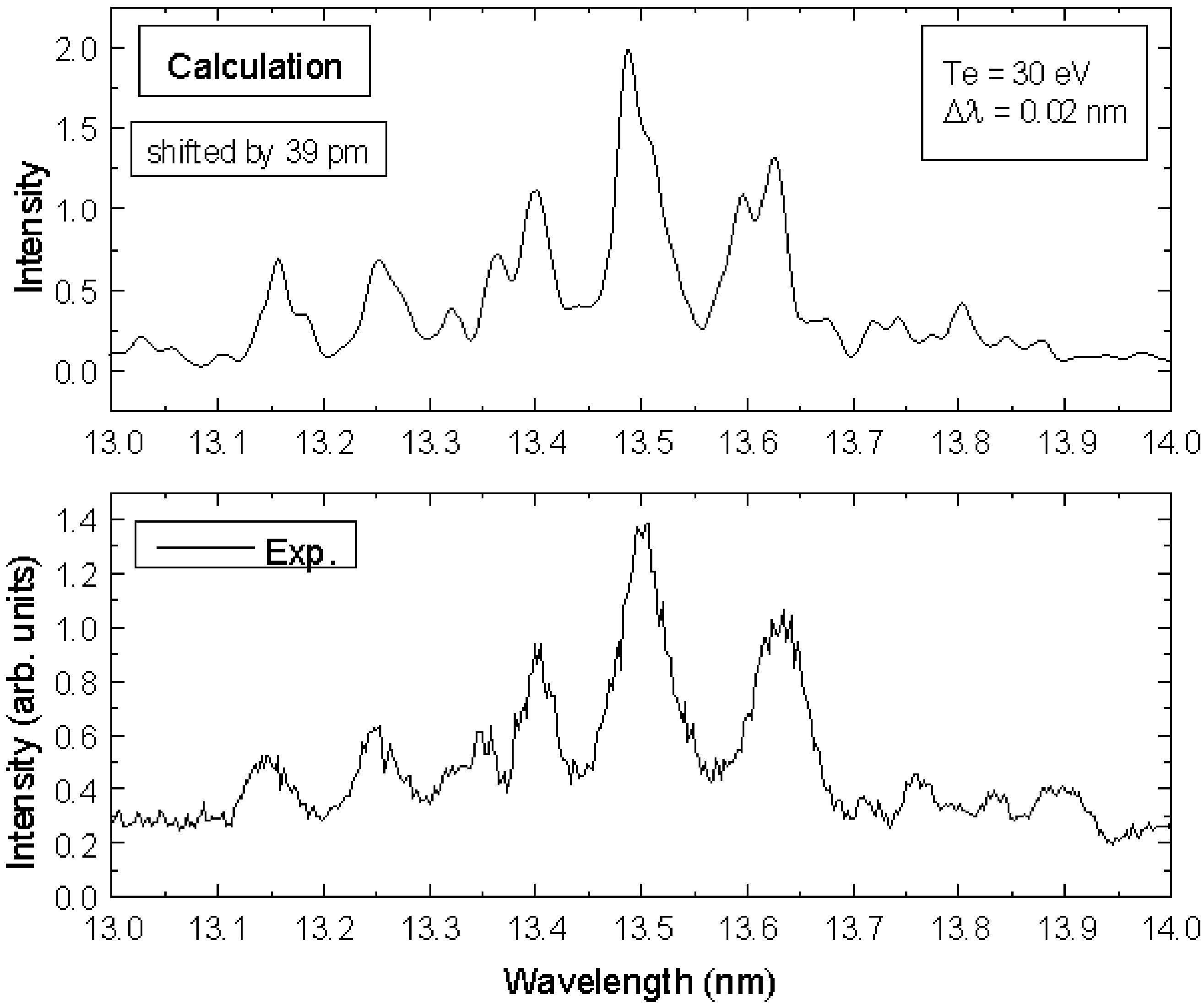
Spectra for 5 different xenon flow rates at same total pressure, average of 50 pulses

Calculated Spectra at Different Electron Temperatures



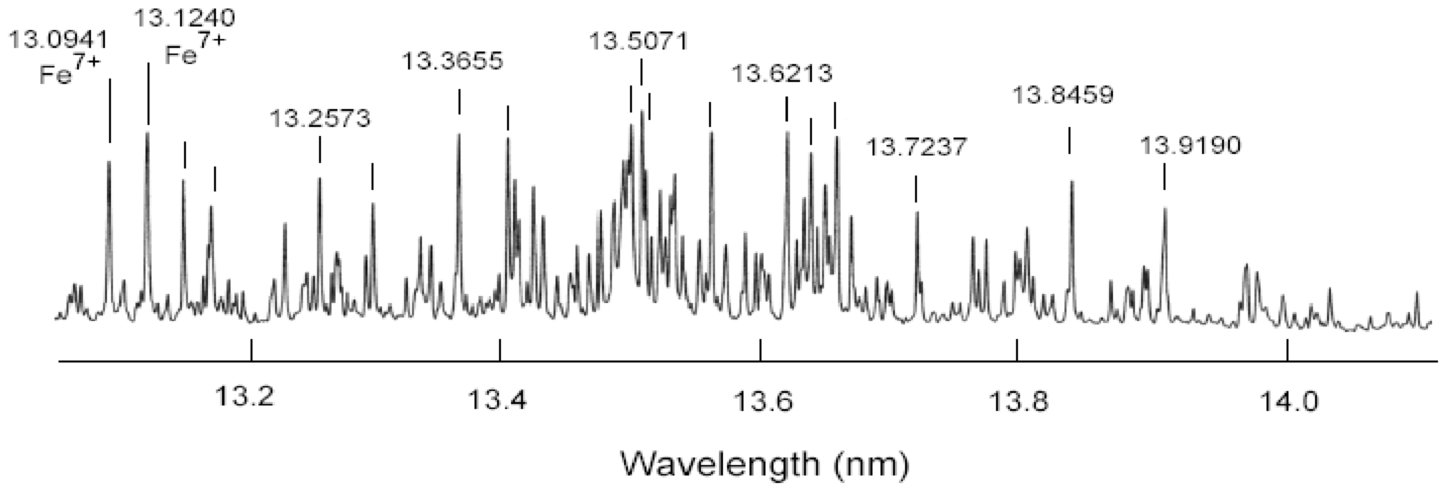
Spectra for different electron temperatures, including ion stage populations and opacity effects

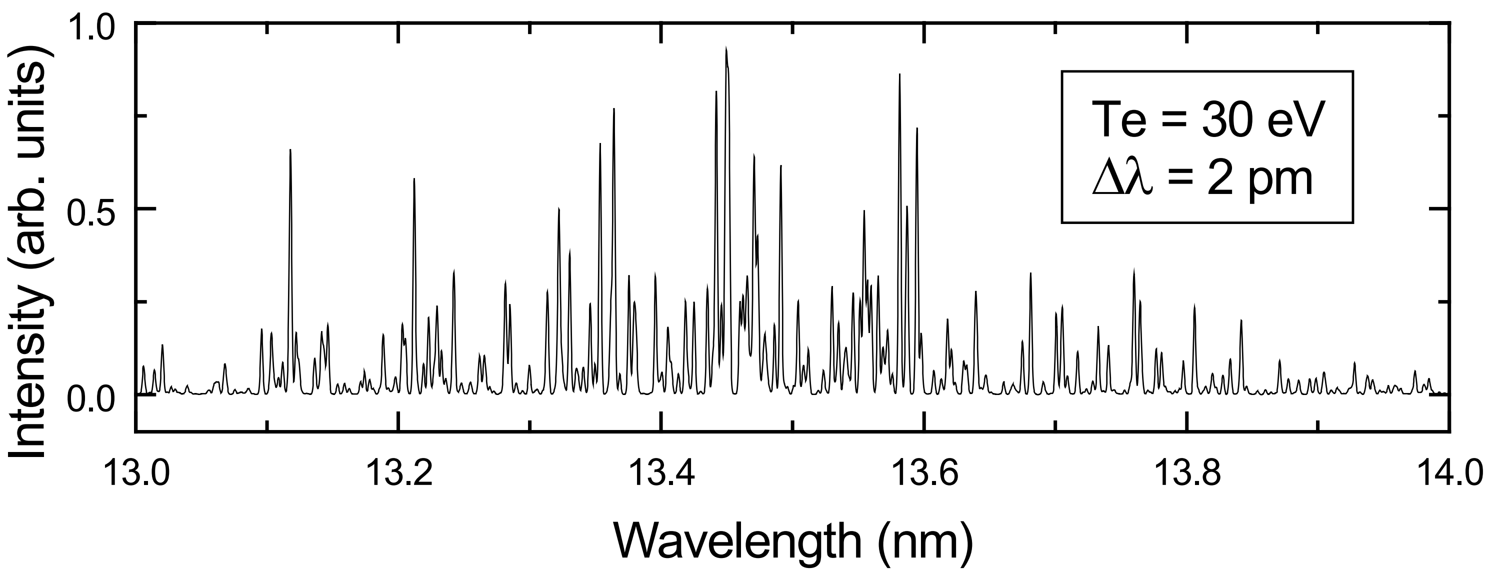
Comparison of Calculation and Experiment at 13.5 nm



Comparison of spectra for the 13 - 14 nm region

Comparison of Calculation to High-Resolution NIST Spectra





Calculated spectrum folded to a resolution of 2 pm, experimental spectrum: Churilov et al. (NIST)

Most Intense Transitions Near 13.5 nm

Lower level		Upper level		wavelength (nm)	rel. intensity
$4d^8$	$(^3F)^3F_2$	$4d^75p$	$(^2P)^1P_1$	13.396	0.235
$4d^8$	$(^3F)^3F_2$	$4d^75p$	$(^4P)^3D_2$	13.376	0.206
$4d^8$	$(^3P)^3P_2$	$4d^75p$	$(^2P)^3D_2$	13.330	0.221
$4d^8$	$(^3F)^3F_2$	$4d^75p$	$(^2D)^3D_3$	13.452	0.343
$4d^8$	$(^3P)^3P_2$	$4d^75p$	$(^2G)^3G_3$	13.451	0.376
$4d^8$	$(^3F)^3F_3$	$4d^75p$	$(^4P)^5P_2$	13.473	0.299
$4d^8$	$(^3F)^3F_3$	$4d^75p$	$(^2F)^3G_3$	13.555	0.432
$4d^8$	$(^3F)^3F_3$	$4d^75p$	$(^2G)^3F_3$	13.354	0.437
$4d^8$	$(^3F)^3F_3$	$4d^75p$	$(^2H)^3G_4$	13.442	0.824
$4d^8$	$(^3F)^3F_4$	$4d^75p$	$(^4P)^5D_3$	13.681	0.247
$4d^8$	$(^3F)^3F_4$	$4d^75p$	$(^4F)^3F_3$	13.364	0.756
$4d^8$	$(^1G)^1G_4$	$4d^75p$	$(^2D)^1F_3$	13.212	0.527
$4d^8$	$(^1G)^1G_4$	$4d^75p$	$(^2F)^1F_3$	13.118	0.385
$4d^8$	$(^3F)^3F_4$	$4d^75p$	$(^4F)^5F_4$	13.595	0.812
$4d^8$	$(^3F)^3F_4$	$4d^75p$	$(^4F)^3F_4$	13.491	0.554
$4d^8$	$(^1G)^1G_4$	$4d^75p$	$(^2G)^3G_4$	13.760	0.228
$4d^8$	$(^1G)^1G_4$	$4d^75p$	$(^2G)^1G_4$	13.581	0.915
$4d^8$	$(^1G)^1G_4$	$4d^74f$	$(^2D)^3G_4$	13.565	0.212
$4d^8$	$(^1G)^1G_4$	$4d^75p$	$(^2H)^1G_4$	13.560	0.221
$4d^8$	$(^3F)^3F_4$	$4d^75p$	$(^2H)^3G_5$	13.449	1.000
$4d^8$	$(^1G)^1G_4$	$4d^75p$	$(^2H)^1H_5$	13.322	0.326

Most intense calculated transitions for Xe^{10+} near 13.5 nm, many more lines contribute, 1247 lines in total were included in our calculations for Xe^{10+}

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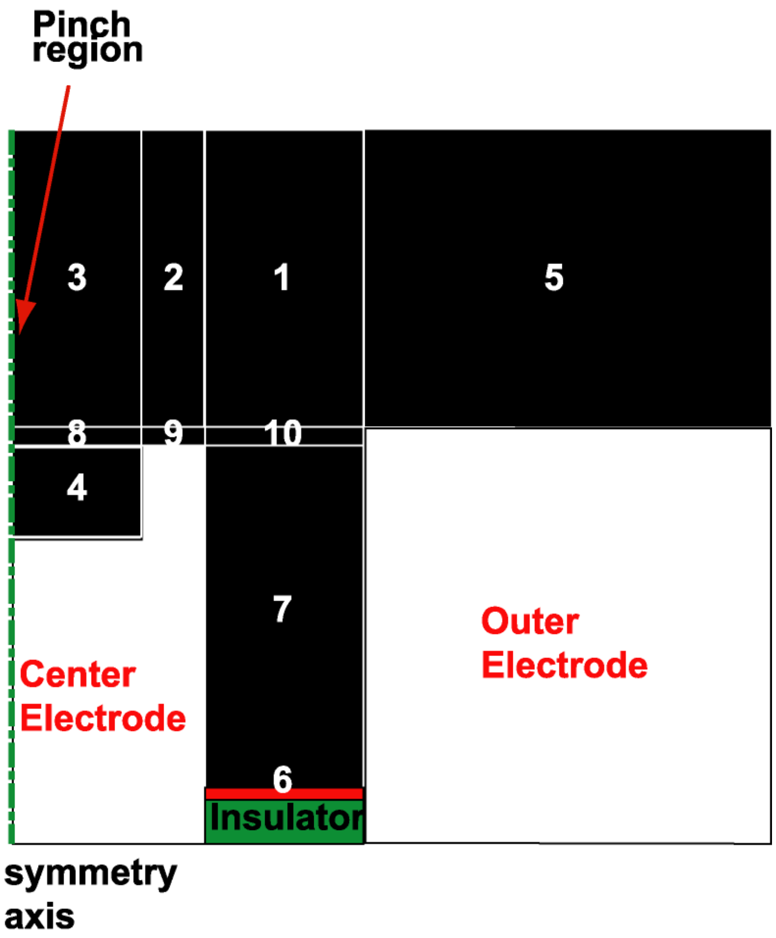
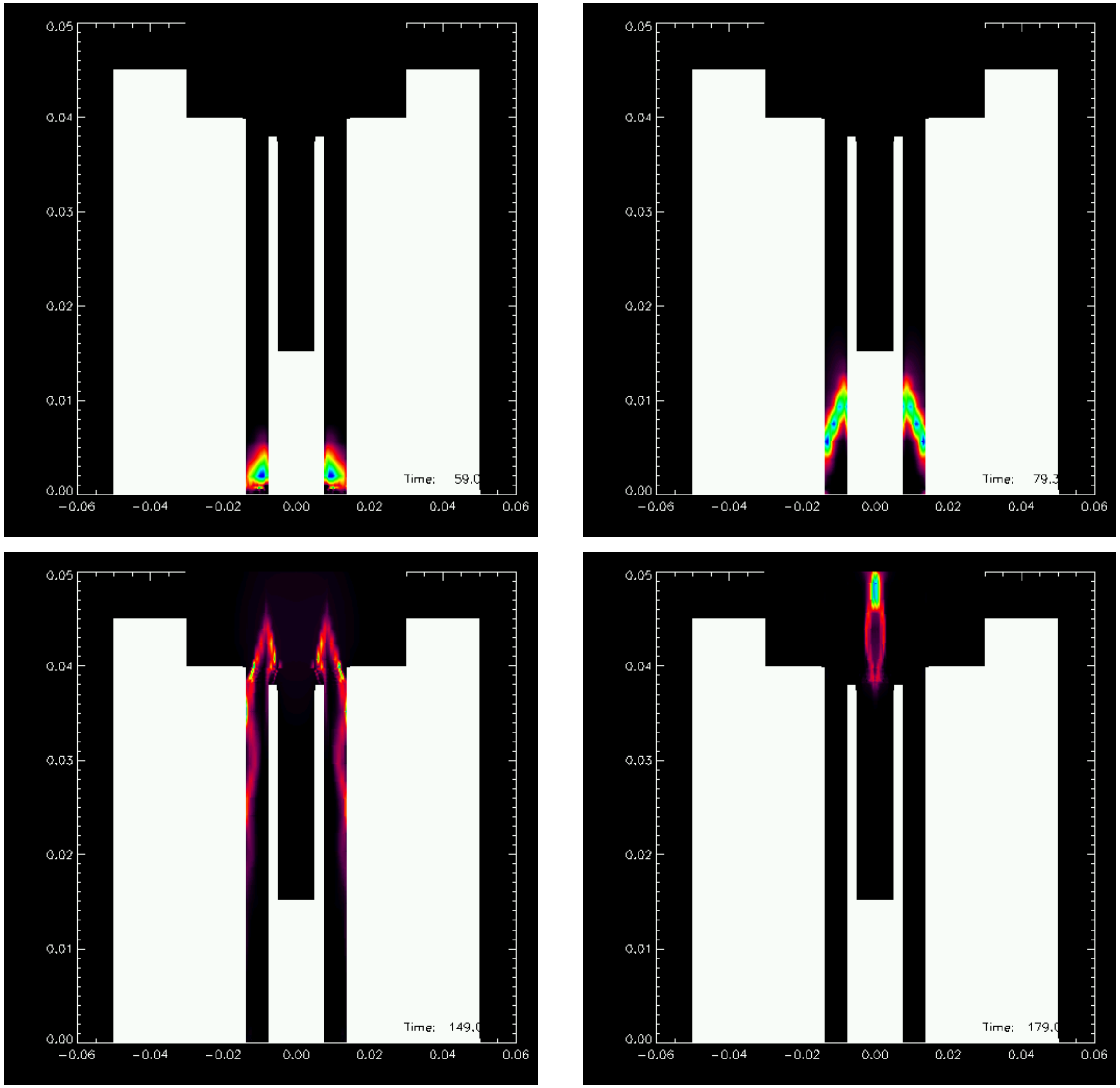
MHD Plasma Simulation of Pinch Dynamics#



- The 2D MHD code "MHRDR", developed by I. Lindemuth and P. Sheehey at LANL and ported to Windows by UNR.
- Plasma fluid equations in 2D axis-symmetric geometry are coupled self-consistently to an electrical circuit model for the pulse formation network.
- Equations of state are consulted for: equation of state, ionization level, radiative energy loss, and resistivity.
- A model for the Cymer DPF light source has been created and results are being compared to experimental measurements.

: Further details of MHD modeling using UNR programs were explained at talk at modeling workshop.

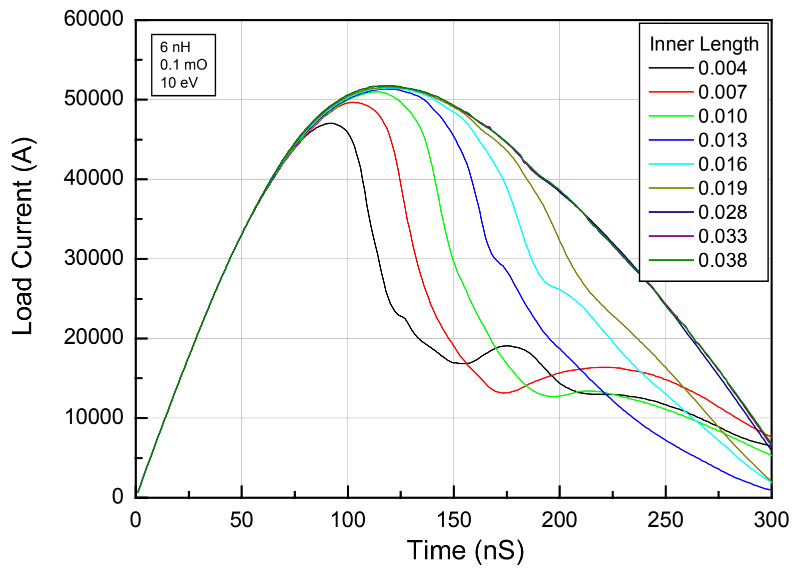
MHD Modeling of DPF

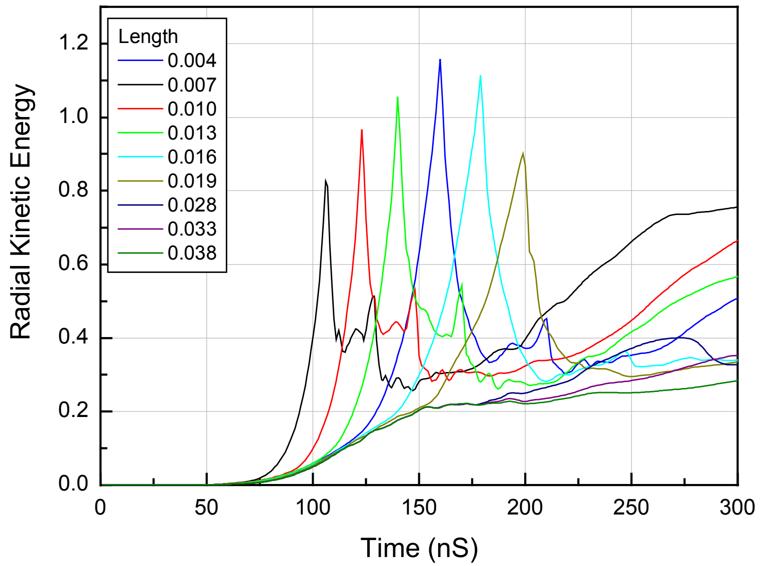


- Color enhanced contours of pressure during axial and radial rundown.
- Maximum pinch occurs well away from electrode end due to axial momentum.

Electrode Length Scan

- Discharge dynamics for varying electrode length.
- There exists an optimum length for coupling to radial kinetic energy.
- Optimum condition is associated with maximizing current at time of pinch.
  - Match to pulsed power timing.





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Conclusions

- When the ion stage populations at a given electron temperature and the dependence of the optical thickness on transition oscillator strength are taken into account, good agreement is obtained between experimental data and Hartree-Fock calculations both with respect to line positions and intensities. A small shift has to be applied to the calculated wavelength positions.
- The emission at 13.5 nm is dominated by 4d - 5p transitions of Xe^{10+}. Many lines contribute, they are usually not resolved.
- Low resolution spectra are also useful for estimations of the mean electron temperature from a comparison with model calculations, since the 4d -5p transition arrays of the ion stages Xe^{8+} to Xe^{11+} are fairly well separated. Electron temperatures are in the range of 25 eV to 40 eV.

See: "EUV emission spectra of highly ionized xenon and their comparison with model calculations" submitted to J. Appl. Phys., preprints will be soon available, send requests to NBowering@cymer.com