UCRL-CONF-223400

LAWRENCE LIVERMORE NATIONAL LABORATORY

Looking for anomalous dispersion in weakly ionized plasmas using X-ray laser interferometry

Joseph Nilsen, John I. Castor, Carlos A. Iglesias, K. T. Cheng, James Dunn, Walter R. Johnson, Jorge Filevich, Jonathan Grava, Mike Purvis, Mario. C. Marconi, Jorge. J. Rocca

August 4, 2006

10th International Conference on X-ray Lasers
Berlin, Germany
August 20, 2006 through August 25, 2006

Disclaimer

Looking for anomalous dispersion in weakly ionized plasmas using X-ray laser interferometry

Joseph Nilsen, John I. Castor, Carlos A. Iglesias, K. T. Cheng, James Dunn
Lawrence Livermore National Laboratory
Walter R. Johnson
University of Notre Dame
Jorge Filevich, Jonathan Grava, Mike Purvis, Mario. C. Marconi, Jorge. J. Rocca
Colorado State University

presented at 10th International Conference on X-ray Lasers
Berlin, Germany, August 20 - 25, 2006

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551-0808

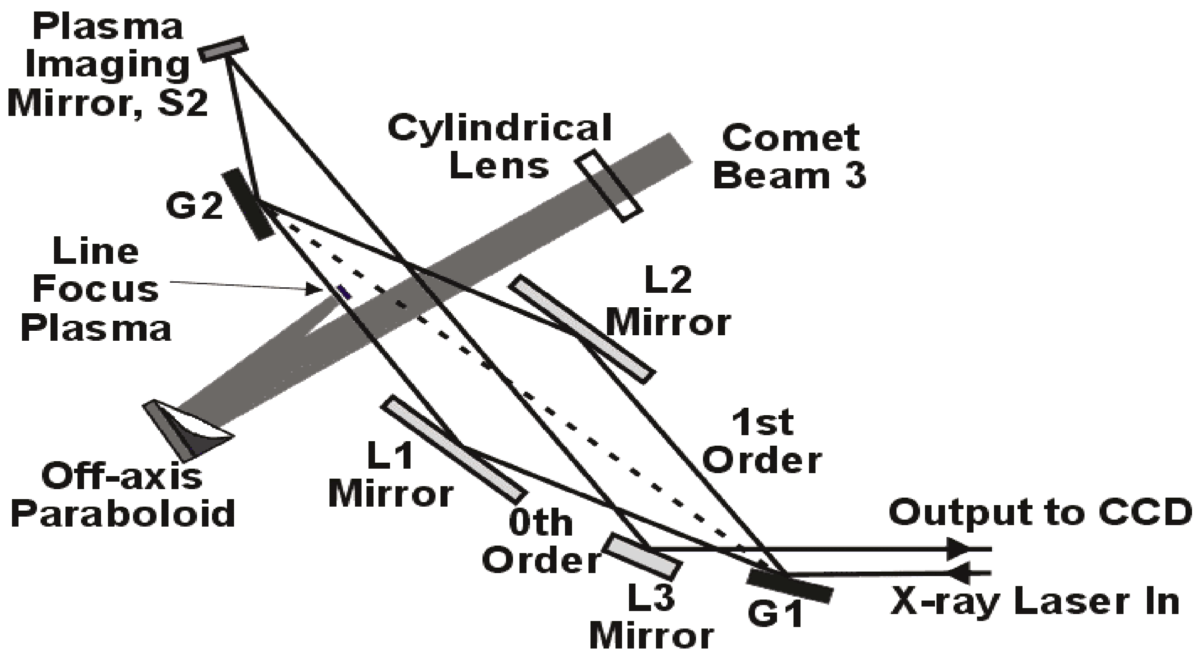
Observe index of refraction greater than one in many plasmas at 26.44 eV energy of Ar X-ray laser

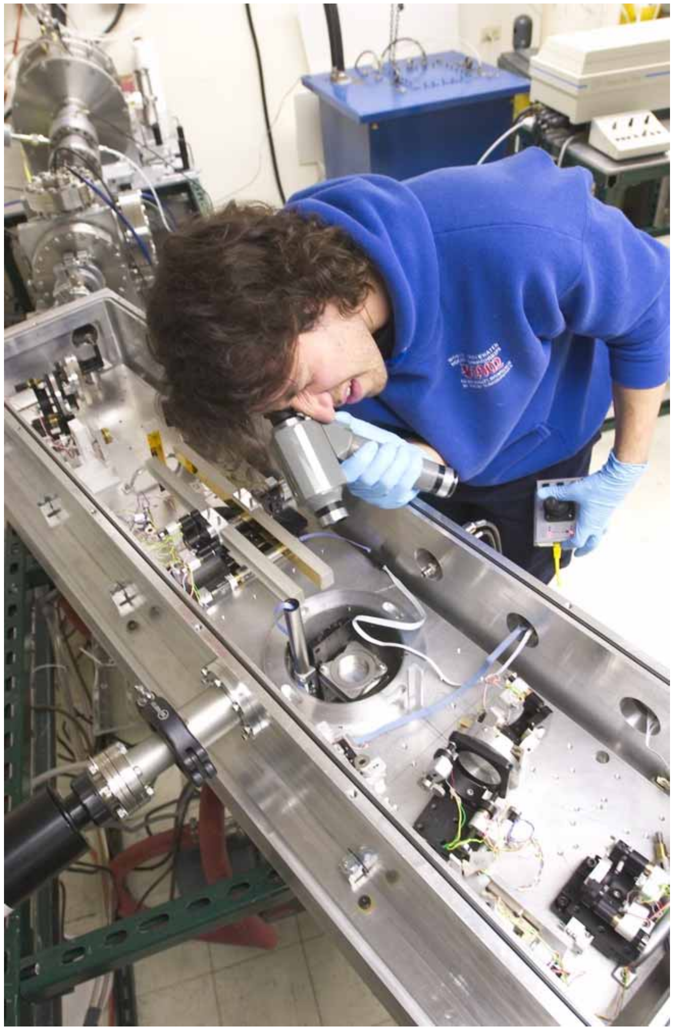
- Plasma index of refraction due to the free electrons is always less than one
- Free electron approximation for index of refraction is not always valid
- Bound electrons can contribute significantly to the index of refraction over a wide range of photon energies
- All partially ionized ions can have lines and edges that affect the index
- Analysis of XRL interferometer experiments require some modeling to estimate contributions from bound electrons and range of validity
- Utilize the Average Atom code developed at Notre Dame to calculate index of refraction for many plasmas
- Predict and measure plasmas with index of refraction greater than one
- Show interferograms of Sn, Ag, and C plasmas that exhibit index of refraction larger than one at X-ray laser energy of 26.44 eV (46.9 nm)

We developed a new tool to calculate the index of refraction for plasmas over a wide range of materials and plasma conditions

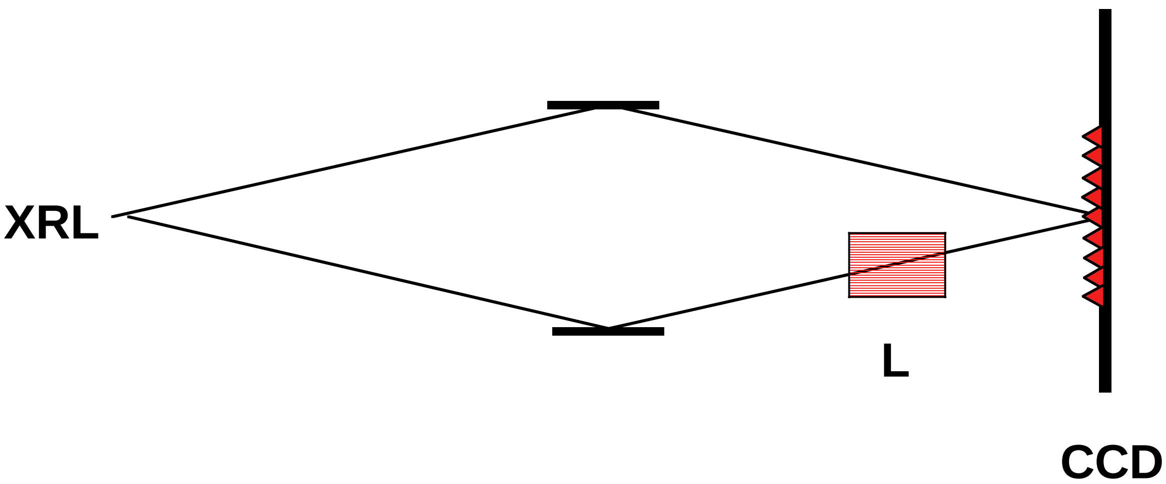
- Kubo-Greenwood formulism applied to the Average Atom code gives us a new tool to calculate the index of refraction for a wide variety of plasma conditions and photon energies
- Average Atom code can calculate any element
- Average Atom code includes a distribution of excited states
- Average Atom does not distinguish individual iso-electronic sequences
- Validate Average Atom calculations against OPAL and experiments for low Z elements

X-ray laser interferometer is used to measure the 2D electron density profile of plasmas



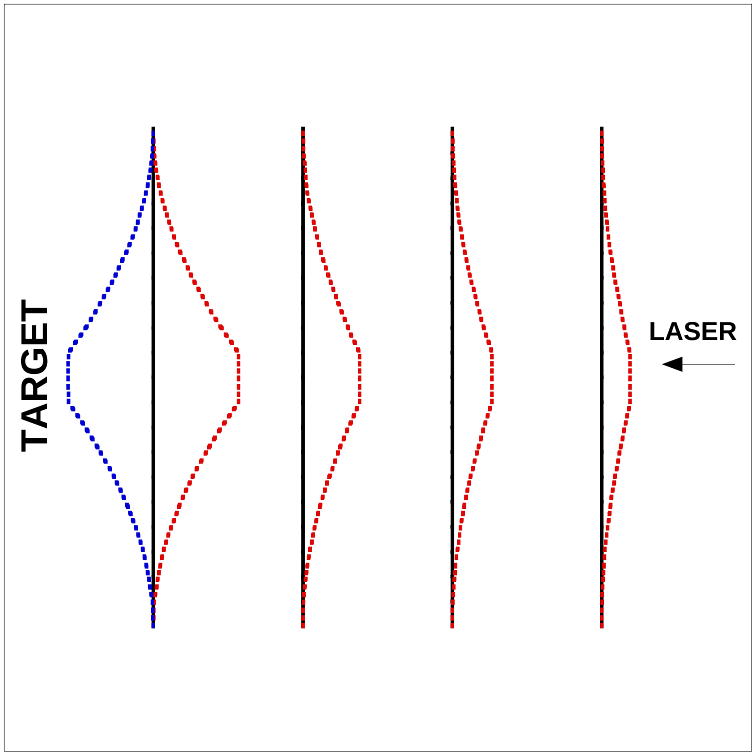


Interferometer measures the electron density by counting the number of fringe shifts which is proportional to the path length integral of (1 - n) through the plasma of length L



$$N_{fringe} = (1 - n)\ L / \lambda \cong n_e\ L / (2\ n_{crit}\ \lambda) \quad \text{assuming } n = 1 - (\ n_e / 2\ n_{crit}\ )$$

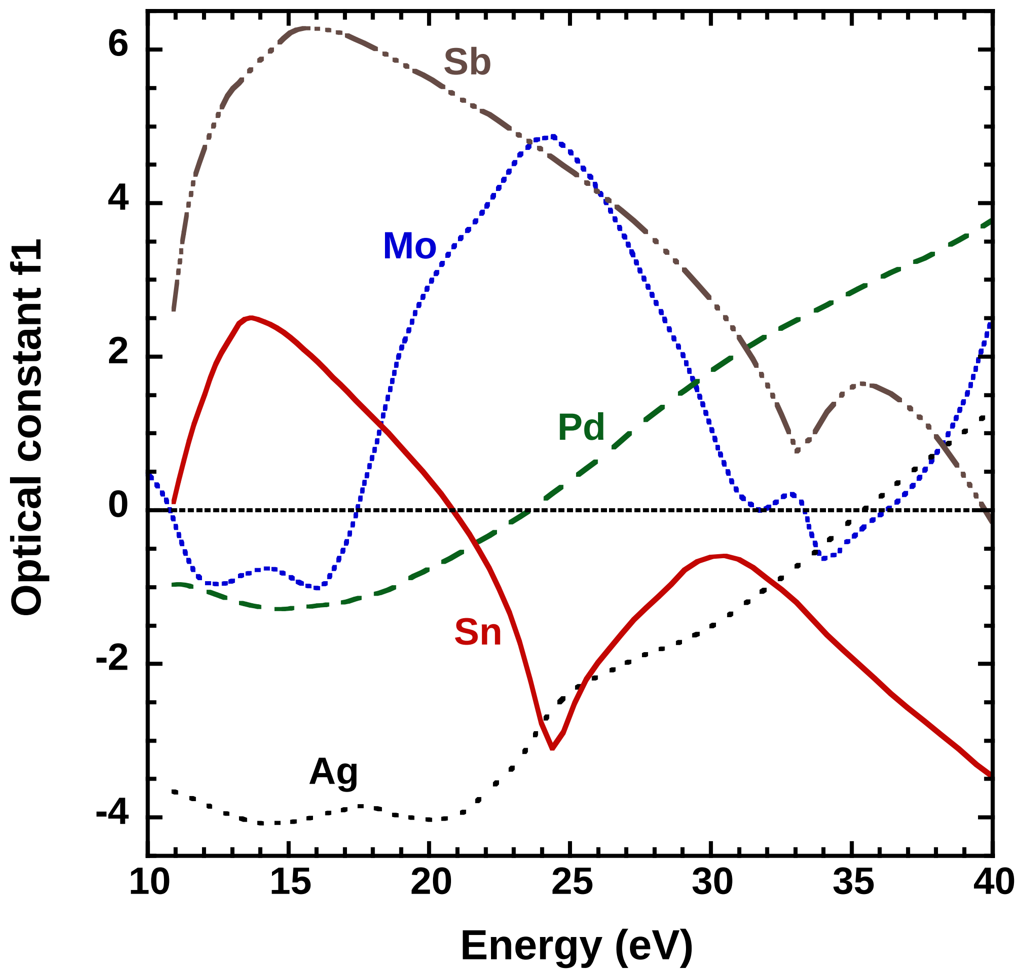
Recent interferometer experiments with Sn, Ag, and C plasmas measured an index of refraction greater than one



$N_{fringe} = n_e L / (4.8 \times 10^{18}/cm^2)$ for Ne-like Ar laser at 46.9 nm (26.44 eV) assumes only free electrons contribute to index of refraction

Anomalous index change can cause fringe lines to bend toward target surface and also cause X-ray laser to bend toward target surface

Extrapolating Henke tables to lower energy below 30 eV enables us to search for candidate plasmas with index of refraction greater than one (f1 < 0)



$n = 1 - f_1 (n_{ion} / 2 n_{crit})$

$\alpha = f_2 (n_{ion} / 2 n_{crit}) (4 \pi / \lambda)$

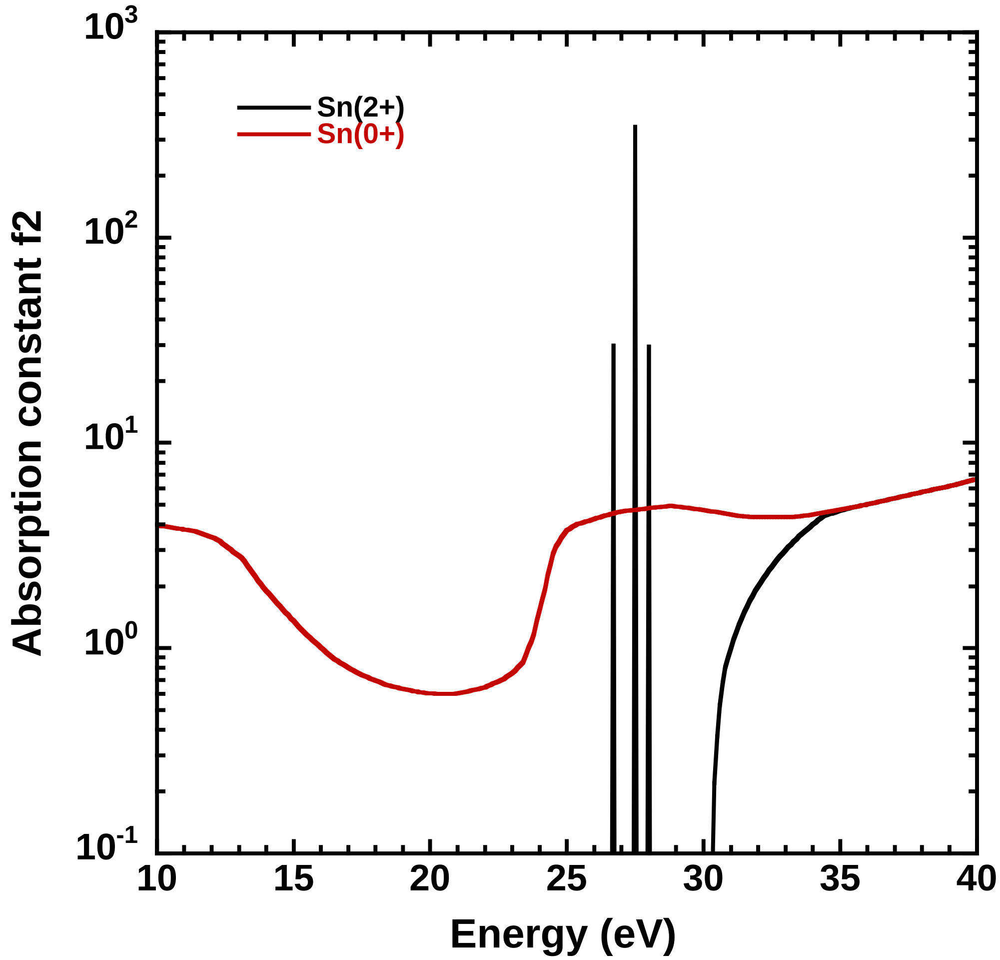
ϕ is maximum grazing angle

$\cos (\phi) = n$

f1 is determined from f2 using Kramers-Kronig dispersion

$$f_1(E) = Z^* + \frac{2}{\pi} \mathrm{P.V.} \int_0^\infty \frac{f_2(\epsilon)\, \epsilon\, d\epsilon}{E^2 - \epsilon^2}$$

Low absorption of Sn^{2+} for Ar XRL at 26.44 eV allows fringes to be observed in Sn plasma



Neutral Sn is [Kr] $4d^{10}$ $5s^{2}$ $5p^{2}$

Ionization Potential

Sn^{0+} = 5.9 eV

Sn^{0+} (N IV) = 24.9 eV

Sn^{0+} (N V) = 23.9 eV

Sn^{1+} = 12.9 eV

Sn^{2+} = 30.1 eV

MFP for $n_{ion}=10^{19}$ cm^{-3}

Average Atom code

Sn^{0+} = 86 μm

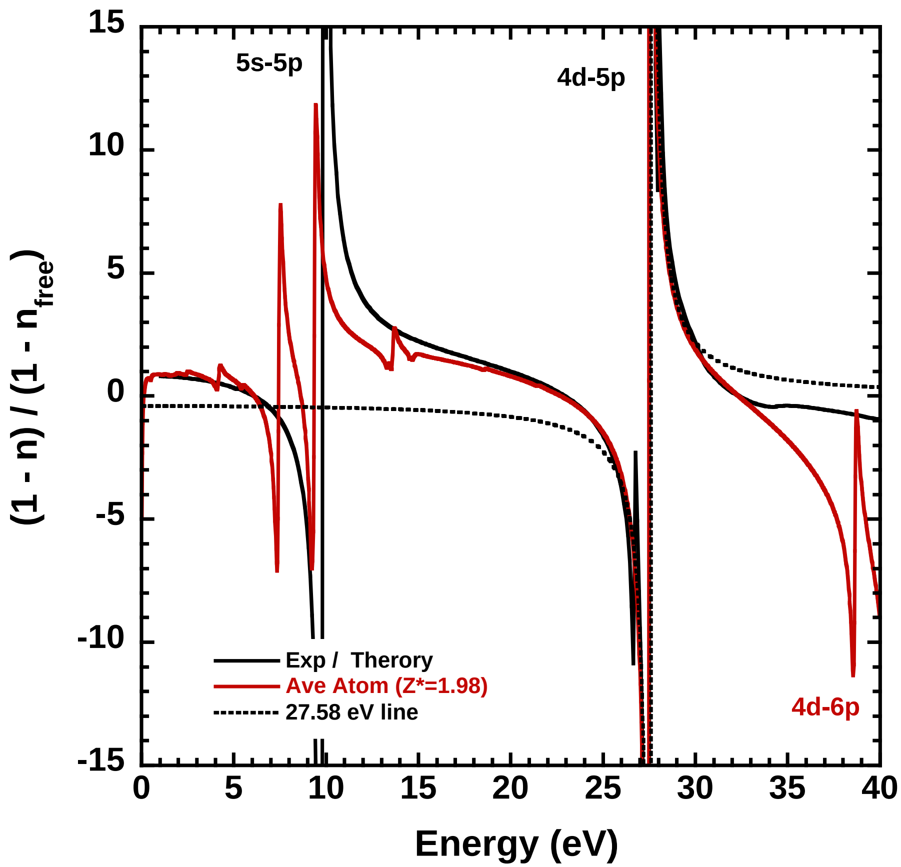
Sn^{1+} = 8 μm

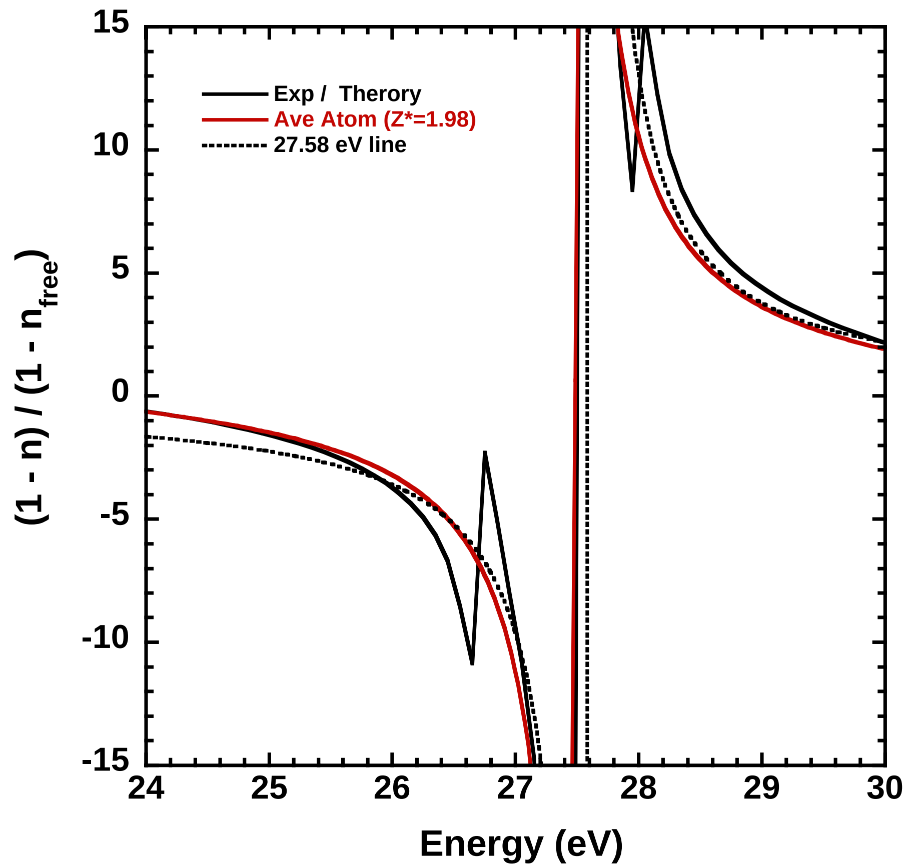
Sn^{2+} = 380 μm

Sn^{1+} (4d-5p) at 26.37 eV

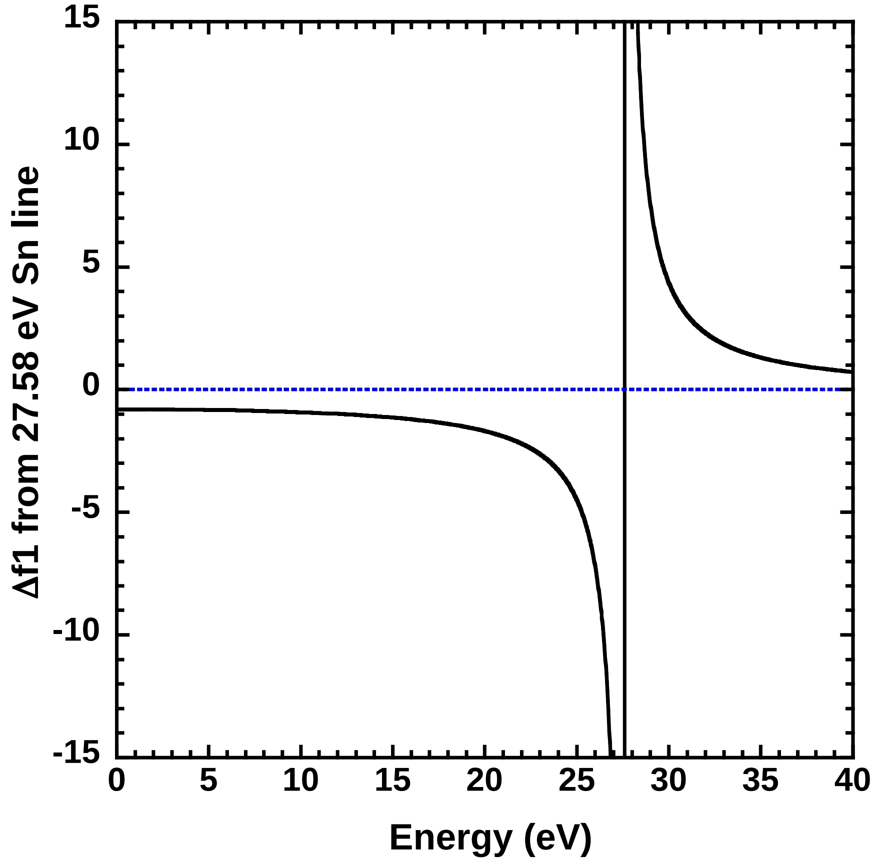
Sn^{2+} has low absorption and large anomalous dispersion for Ar XRL at 26.44 eV that makes index of refraction greater than one

4d-5p lines at 26.72 eV (f=0.071), 27.58 eV (f=0.801), 28.03 eV (f=0.067)
See P. Dunne et al., J. Phys. B 32, L597 (1999)





The contribution to f1 from a single resonance line can extend over a very long range which exceeds the absorption line-width by many orders of magnitude



Consider the strong 4d-5p line in Sn^{2+} with E_0 = 27.58 eV and f_{osc}=0.8

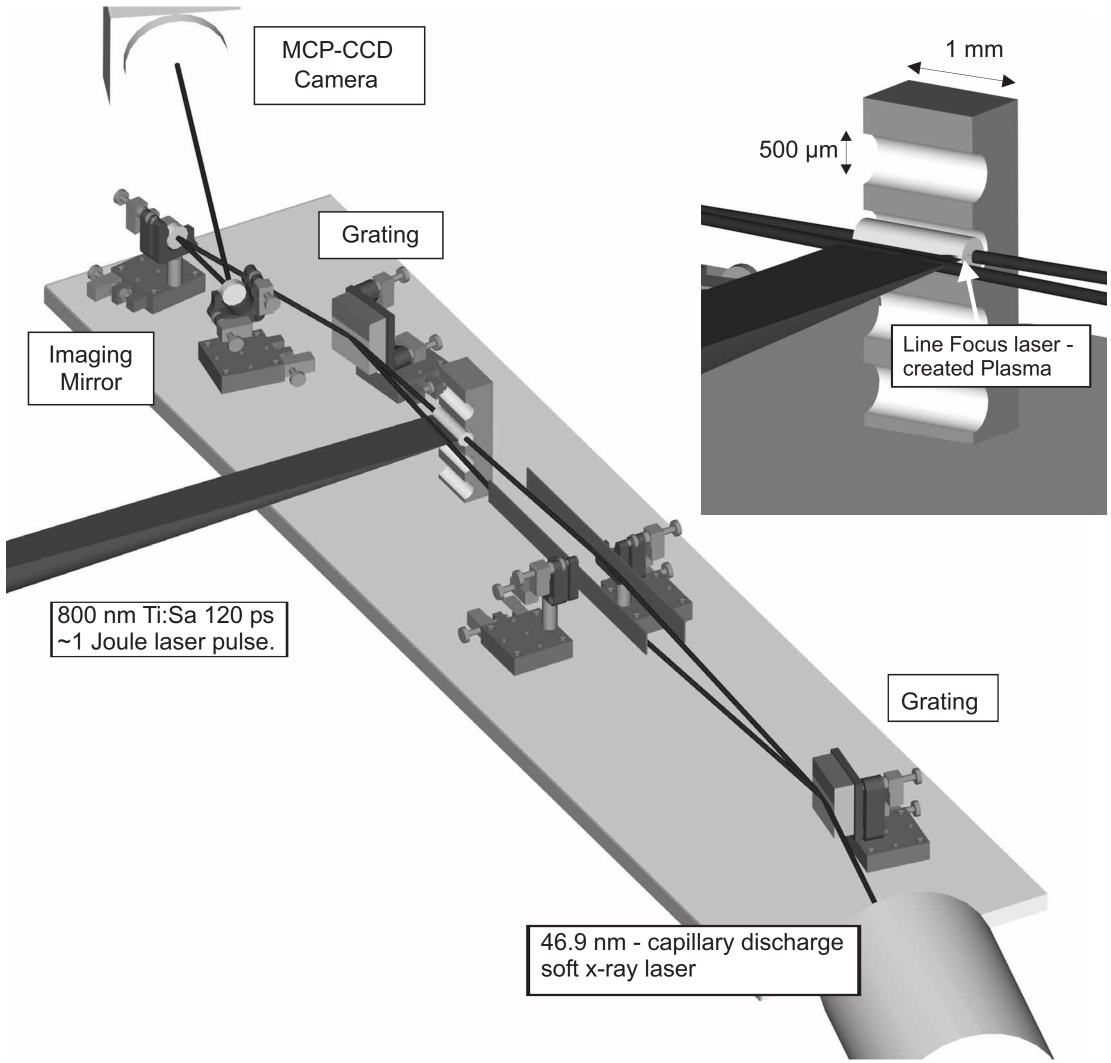
$\Delta f1 = F_{osc} / [(E/E_0)^2 - 1]$

Δf1 = -9.9 at 26.44 eV (Ar XRL)

f1 = - 13.4 (Exp / Theory)

f1 = -9.8 (Ave Atom, Z*=1.98, 4 eV)

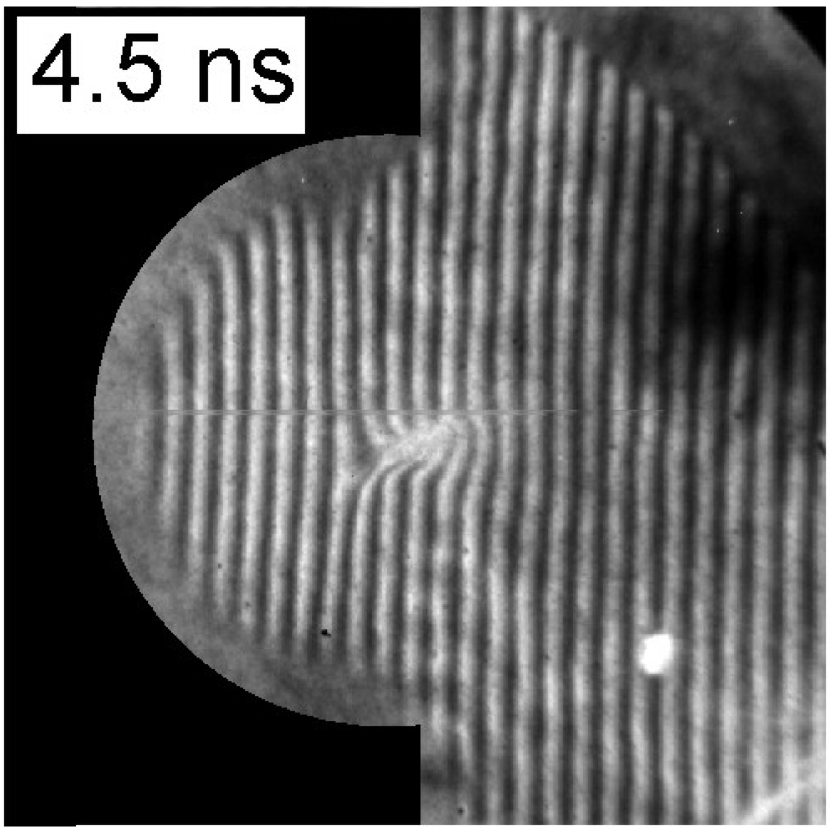
X-ray laser interferometer is used to measure the 2D electron density profile of plasmas

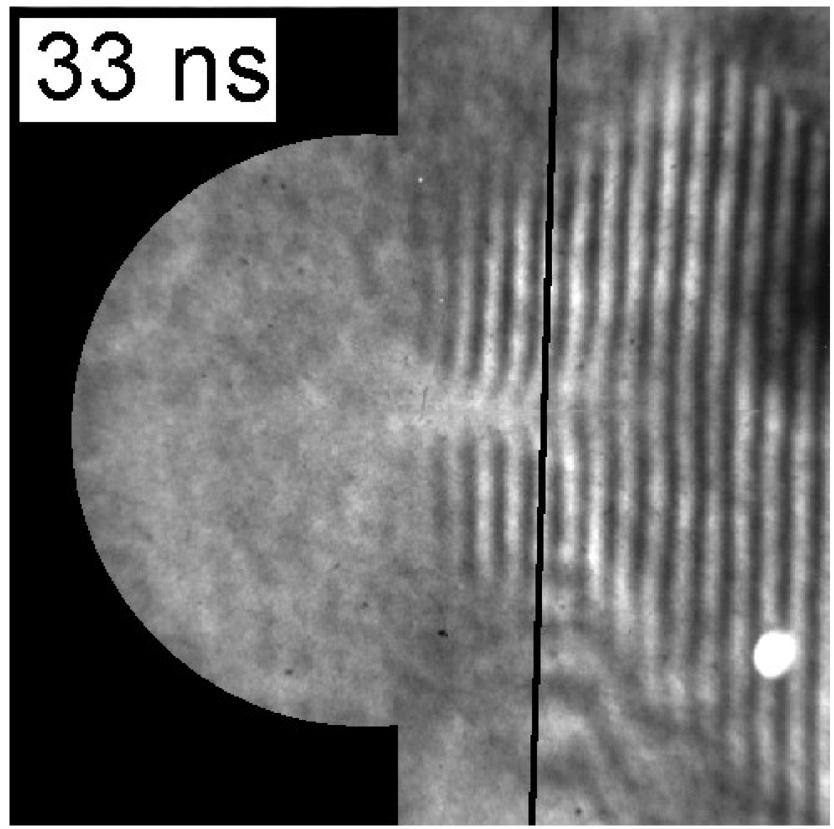


Interferograms of Sn plasma show index of refraction greater than one at late time when plasma near Sn^{2+}

Ionization Potential
Sn^{0+} = 5.9 eV
Sn^{1+} = 12.9 eV
Sn^{2+} = 30.1 eV

Images taken using Ar XRL at 46.9 nm (26.44 eV)

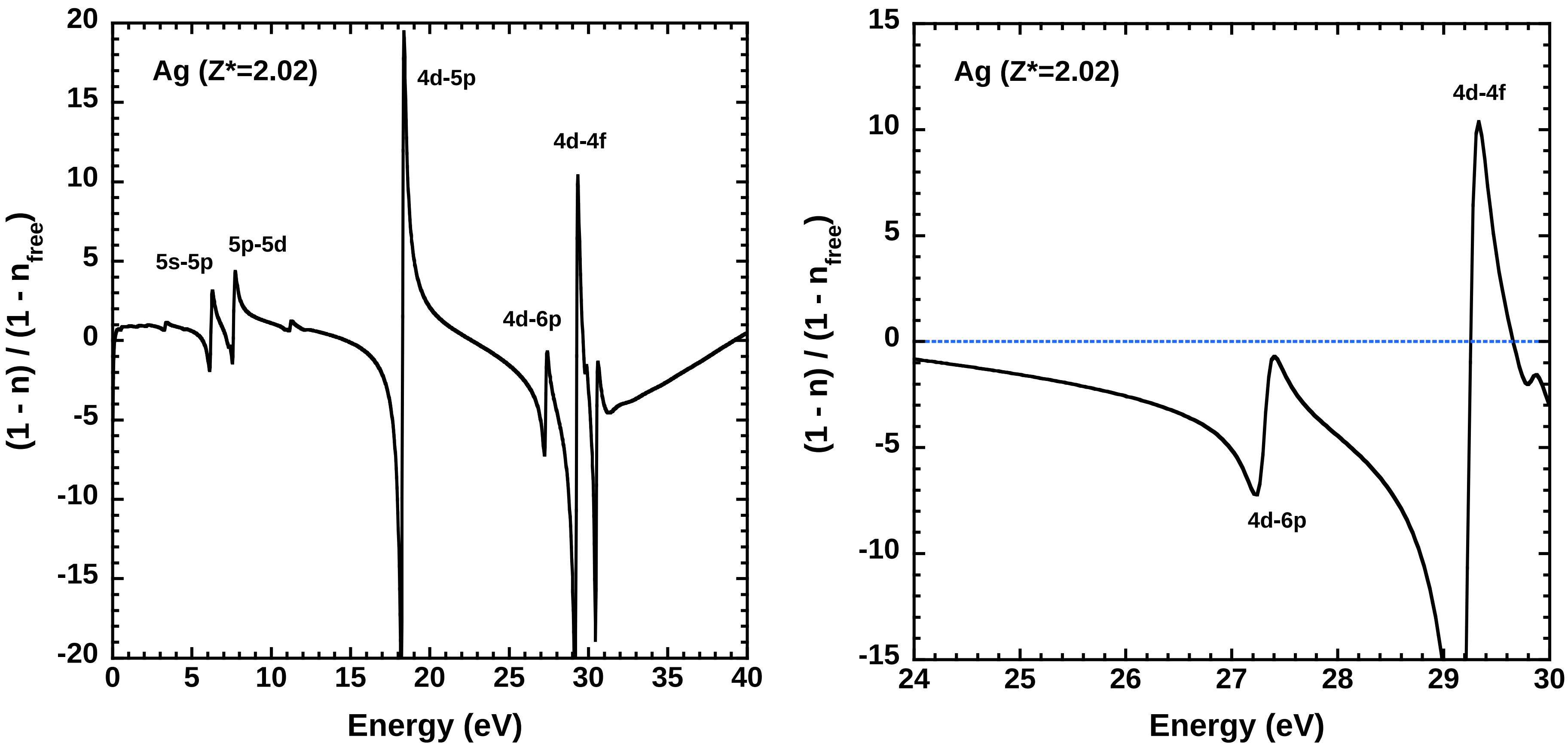




Ag^{2+} has low absorption and large anomalous dispersion for Ar XRL at 26.44 eV that makes index of refraction greater than one

Ave Atom calculations show 4d-6p and 4d-4f lines near 27 eV

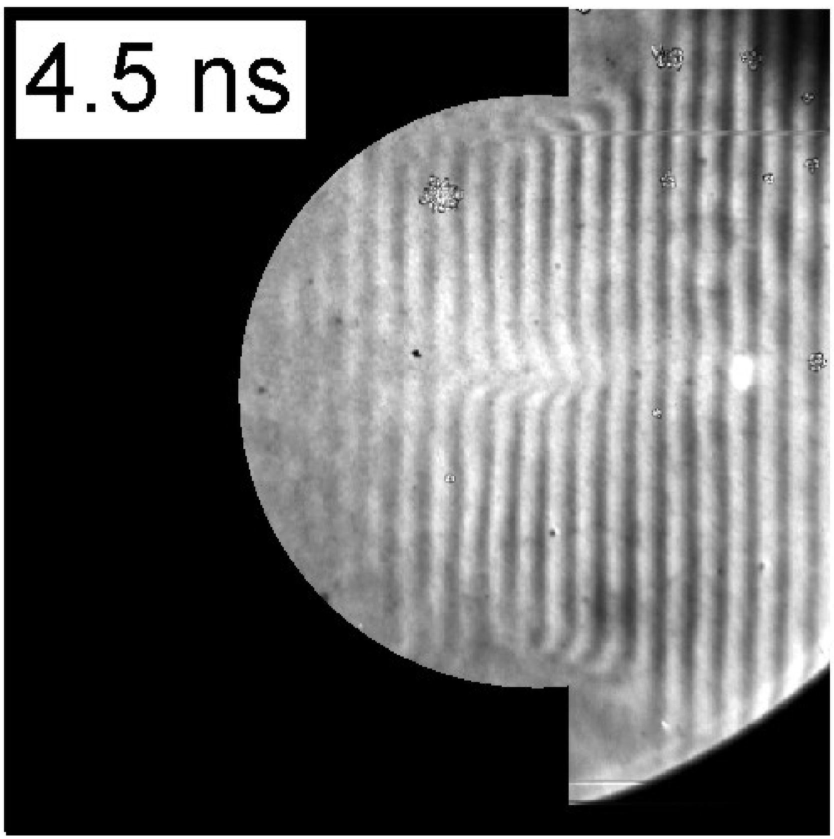
$(1 - n) / (1 - n_{free}) = -3.3$ at 26.44 eV

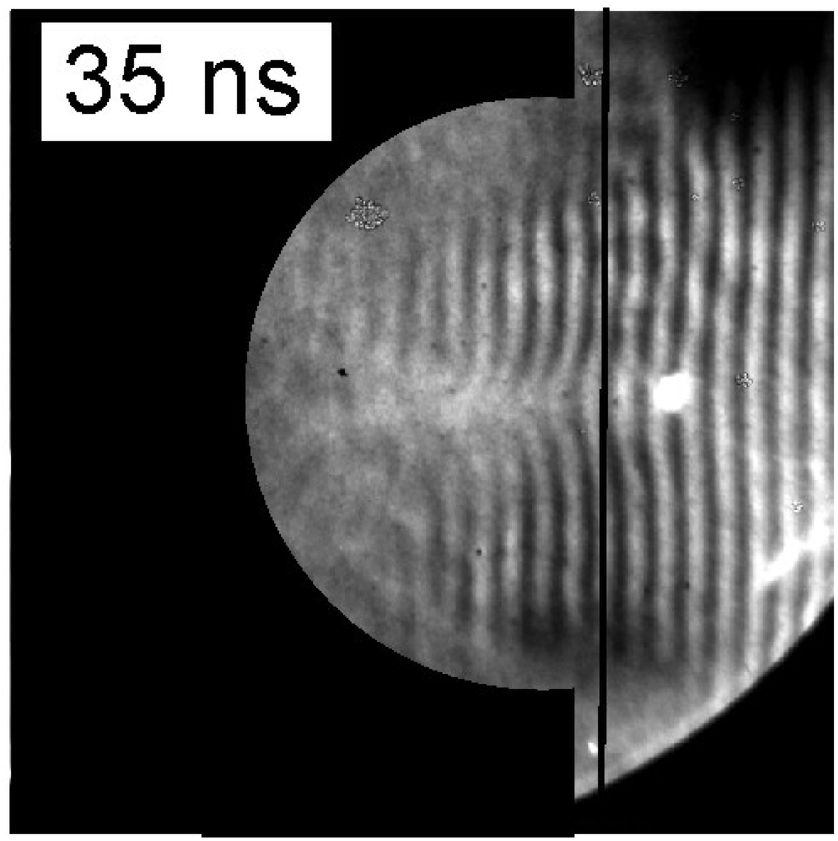


Interferograms of Ag plasma show index of refraction greater than one at late time when plasma near Ag^{2+}

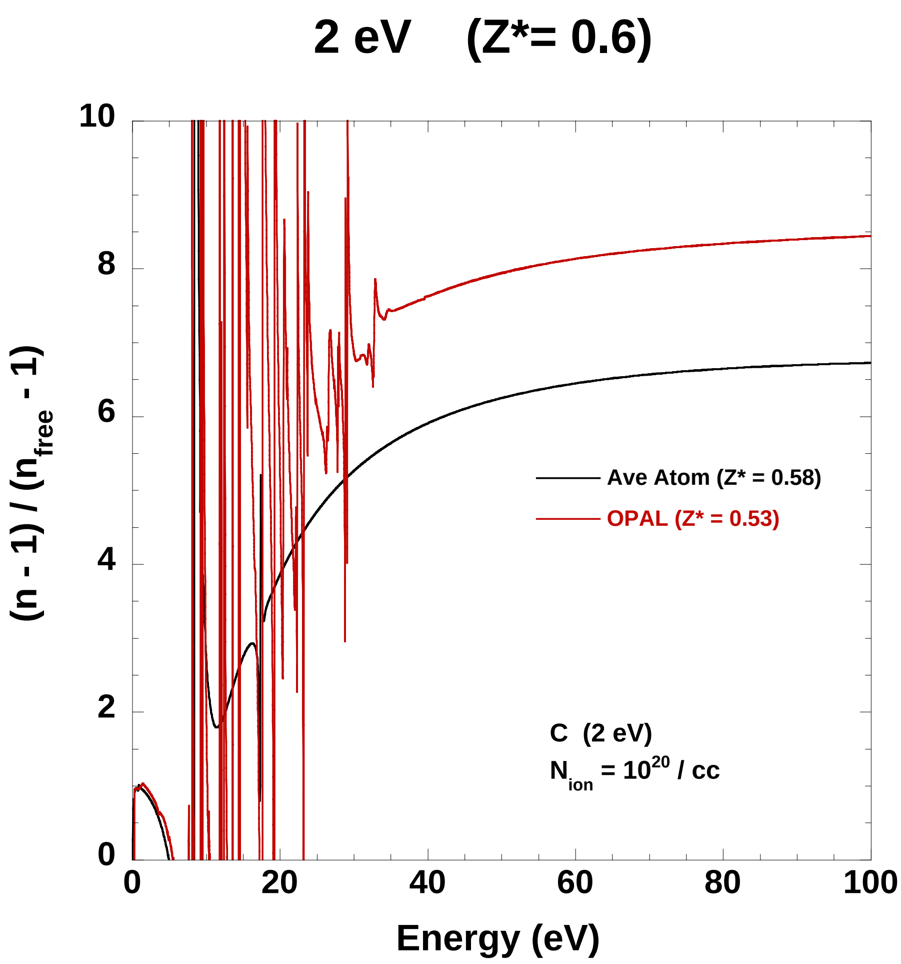
Ionization Potential
Ag^{0+} = 6.9 eV
Ag^{1+} = 20.8 eV
Ag^{2+} = 35.0 eV

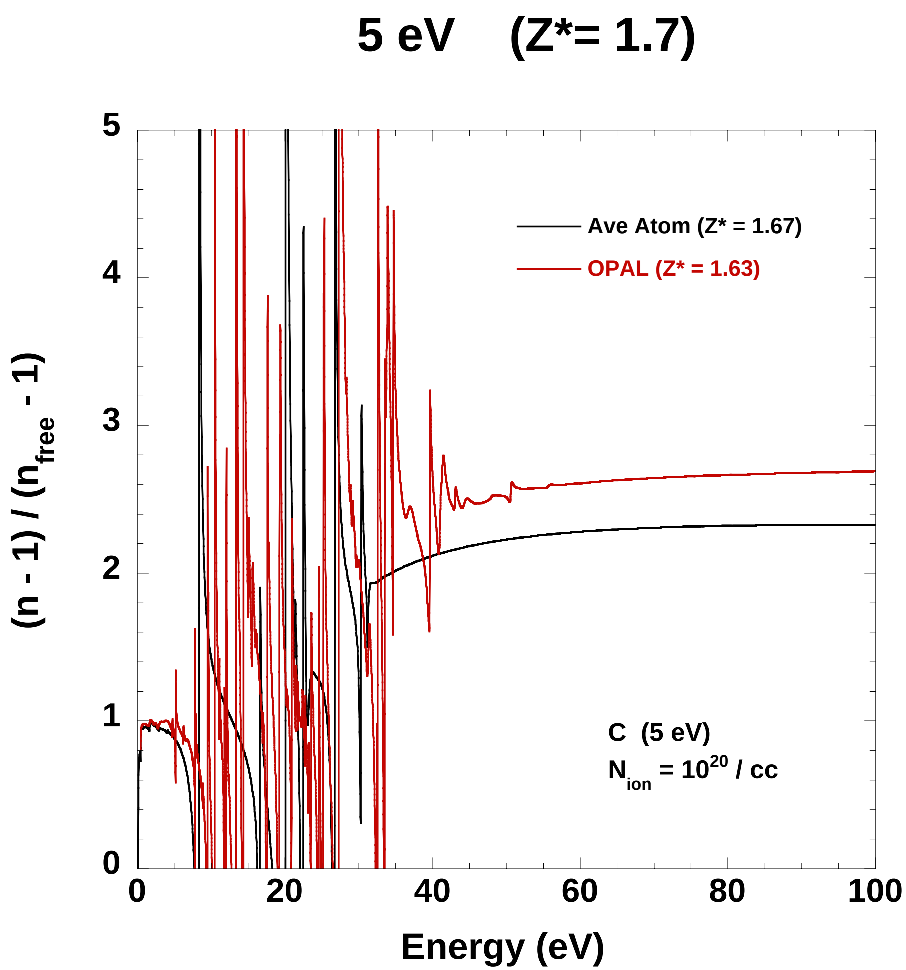
Images taken using Ar XRL at 46.9 nm (26.44 eV)



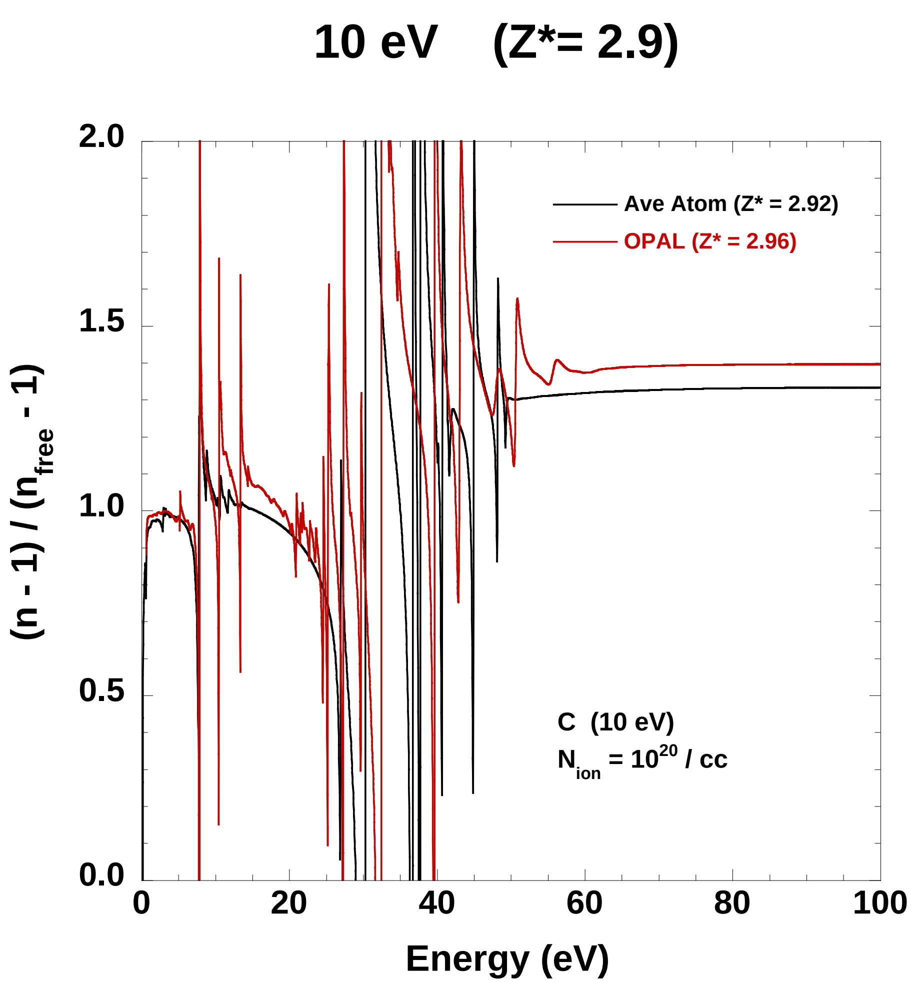


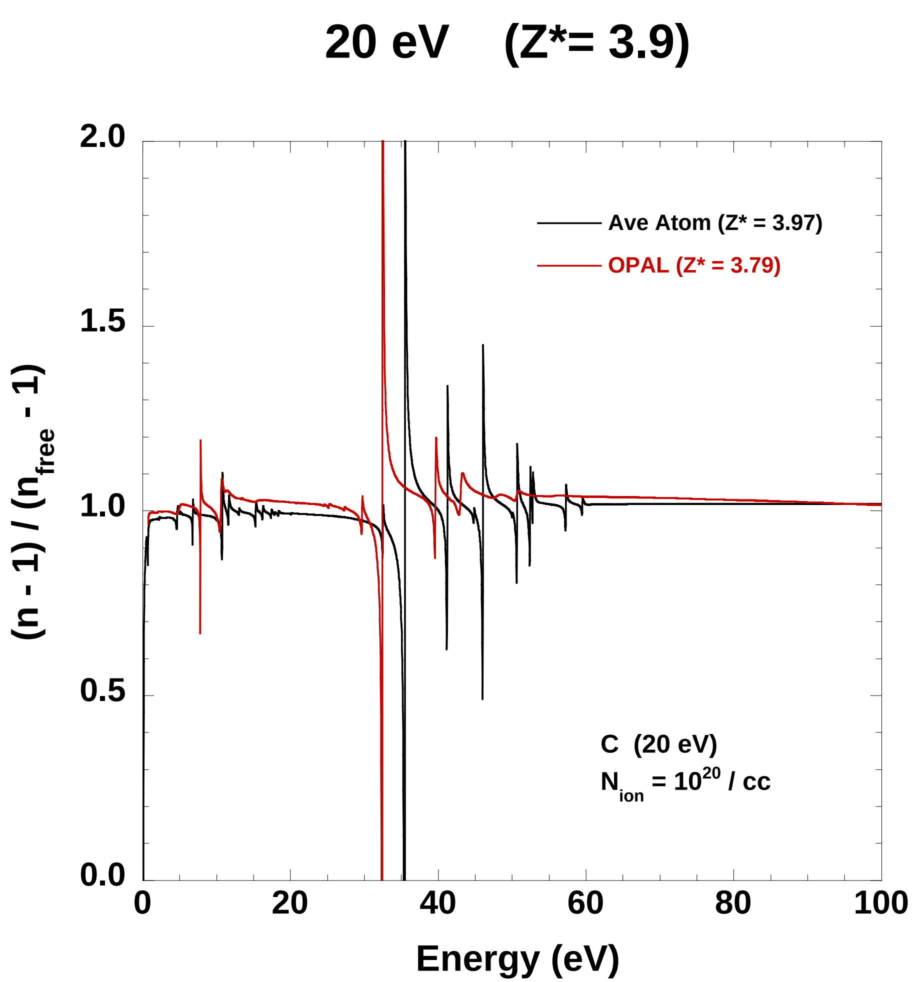
Singly and doubly- ionized carbon plasma looks very complicated below 40 eV



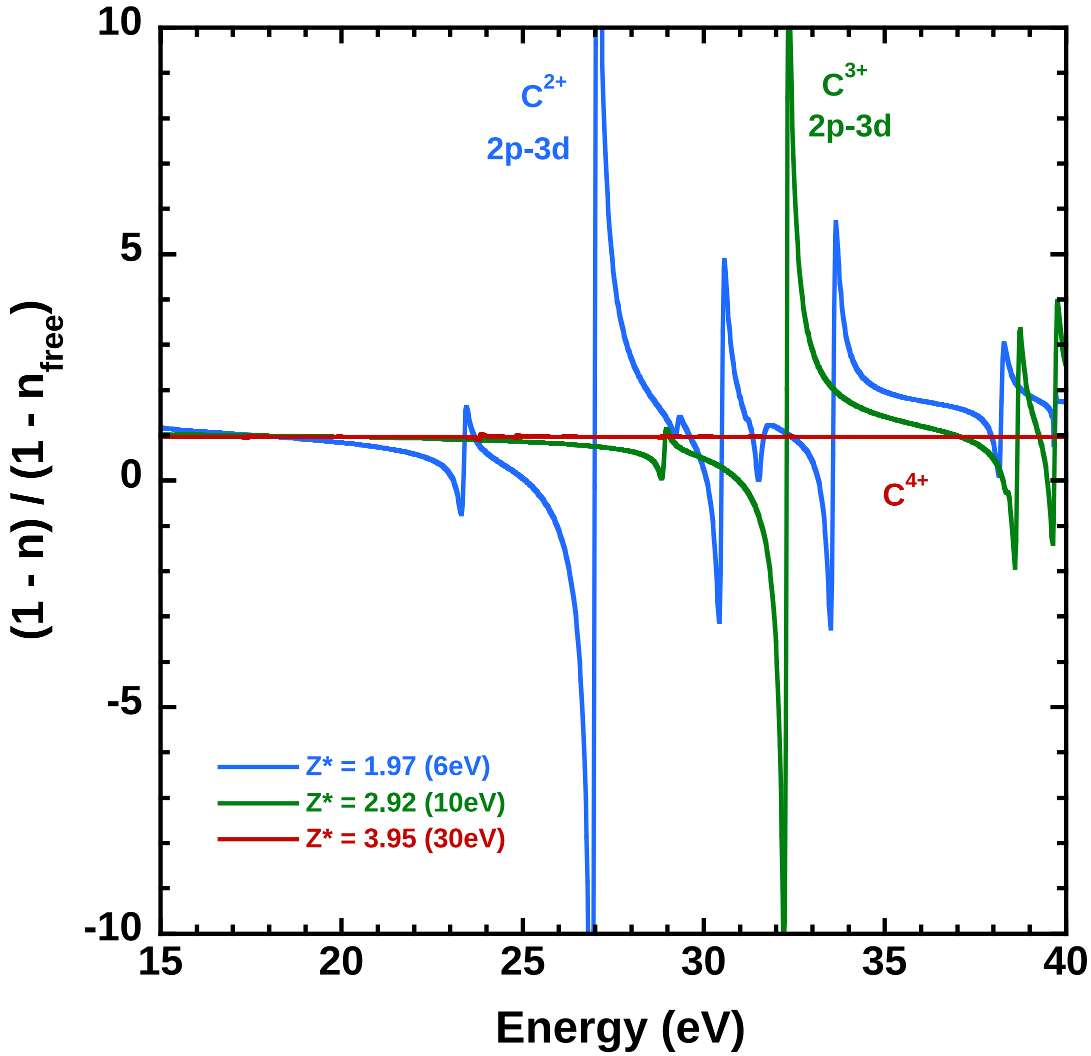


As carbon is sufficiently ionized (Z* about 4) the free electron approximation becomes valid





Average Atom code predicts the change in the index of refraction as the plasma is heated



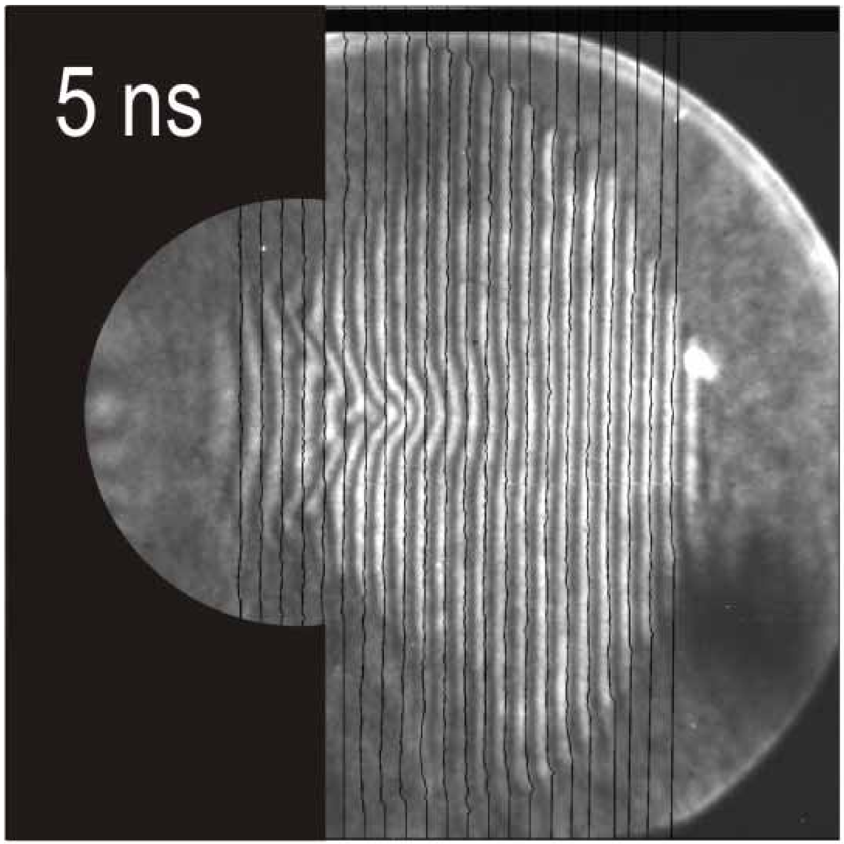
Use experimental data to
shift C^{2+} by 4.21 eV
shift C^{3+} by 1.95 eV
shift C^{4+} by 12.3 eV

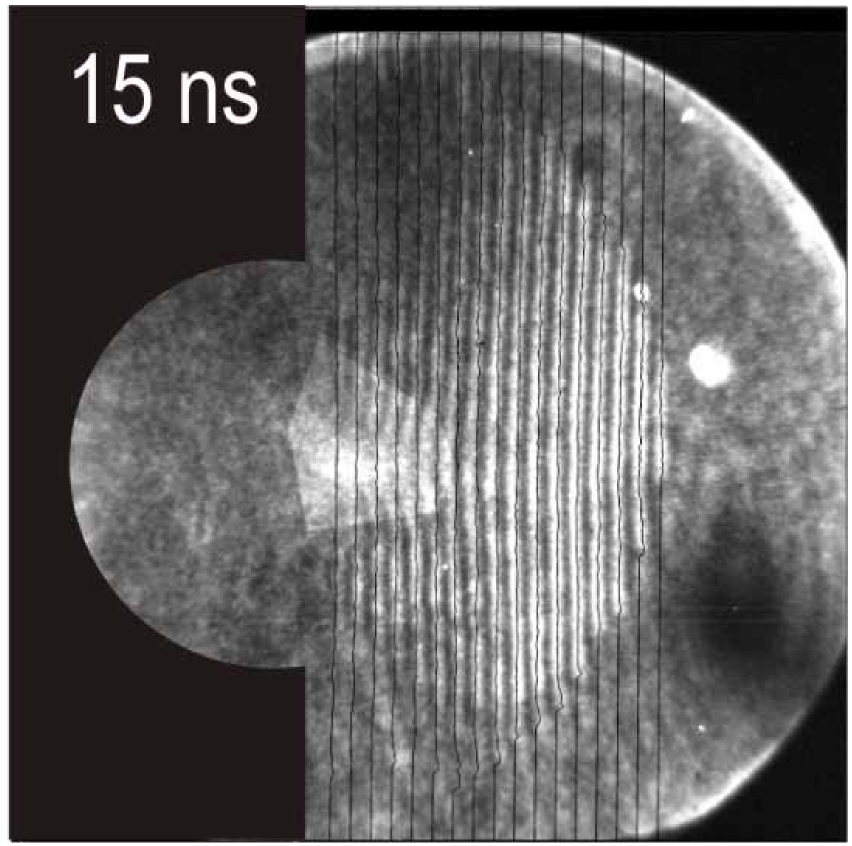
Ionization Potential
C^{0+} = 11.26 eV
C^{1+} = 24.38 eV
C^{2+} = 47.89 eV
C^{3+} = 64.49 eV
C^{4+} = 392 eV

Interferograms of C plasma show index of refraction greater than one in regions where plasma near C^{2+}

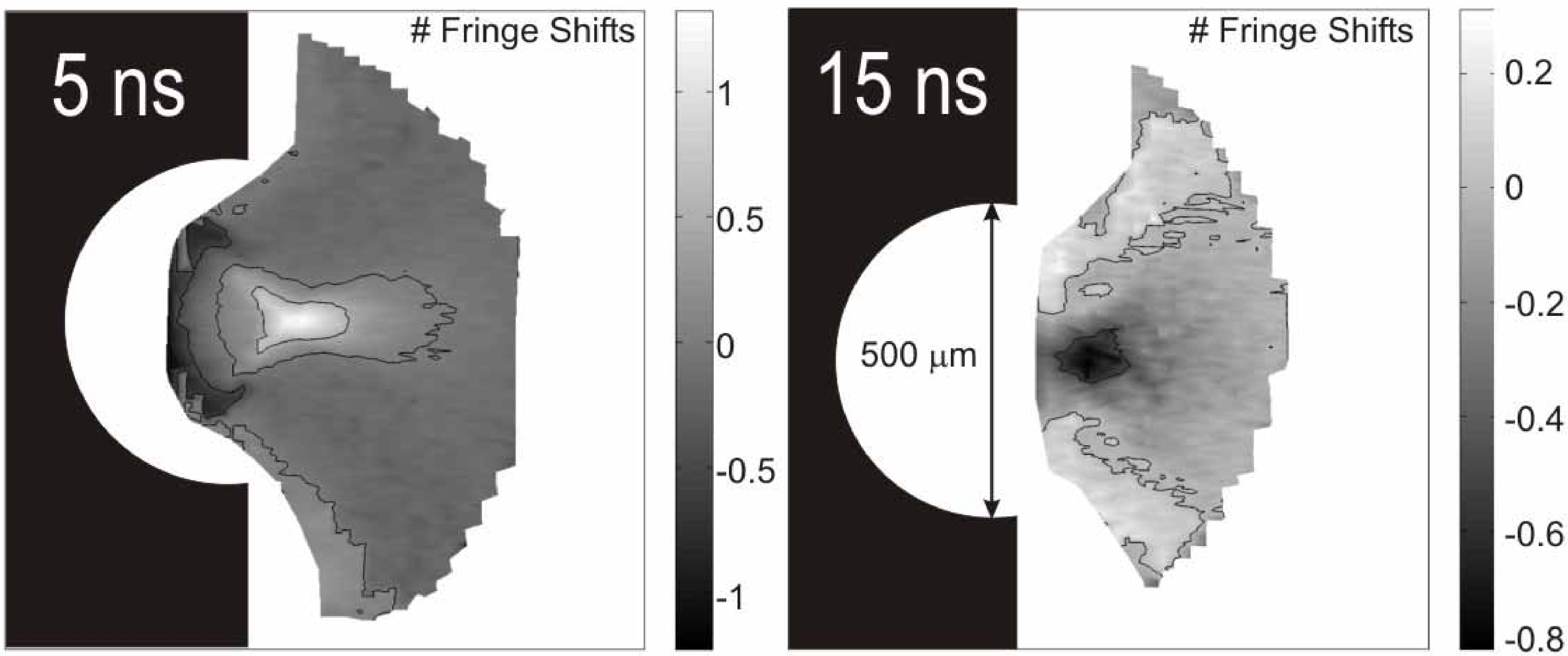
Ionization Potential
C^{0+} = 11.26 eV
C^{1+} = 24.38 eV
C^{2+} = 47.89 eV

Images taken using Ar XRL at 46.9 nm (26.44 eV)

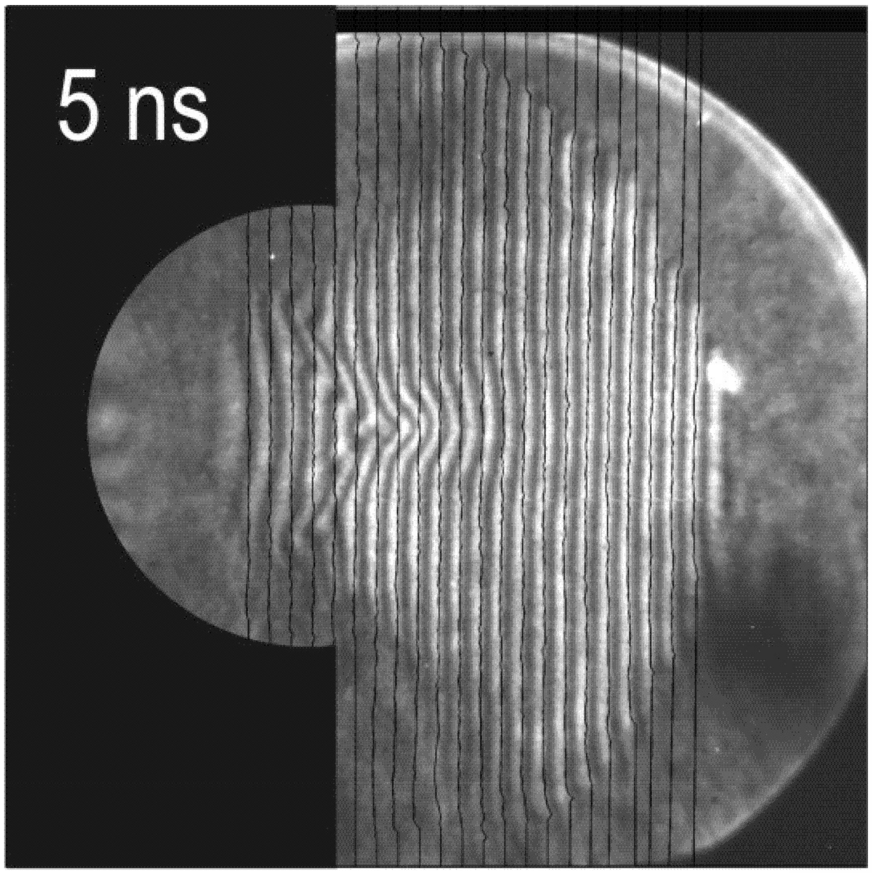


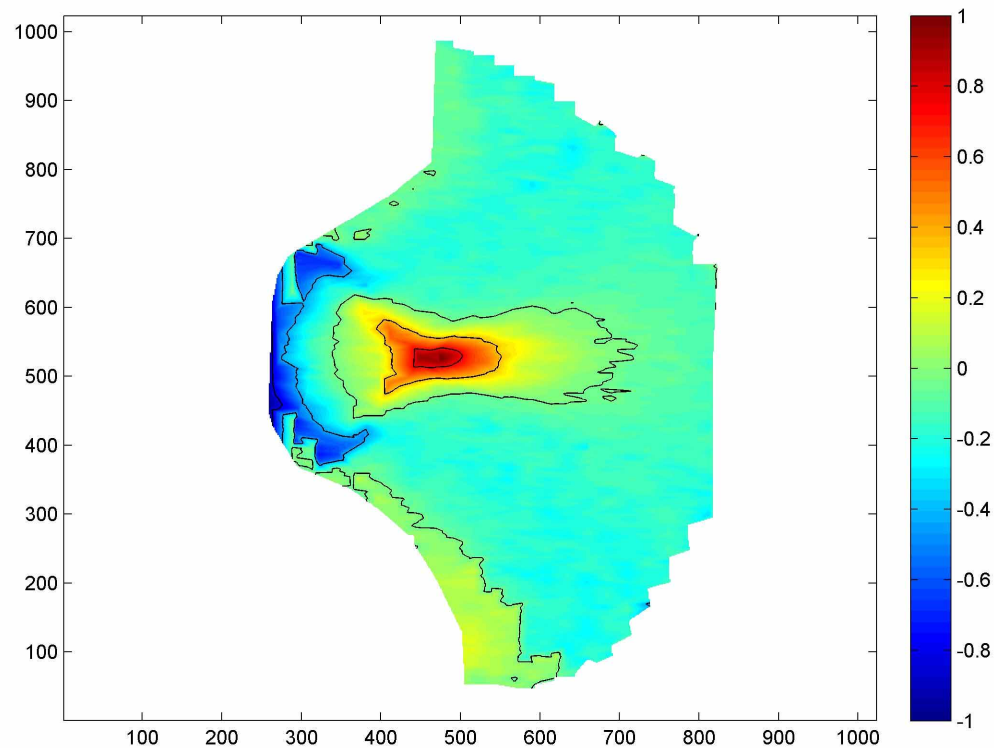


Interferograms of C plasma show negative fringe shifts where plasma is C^{2+}

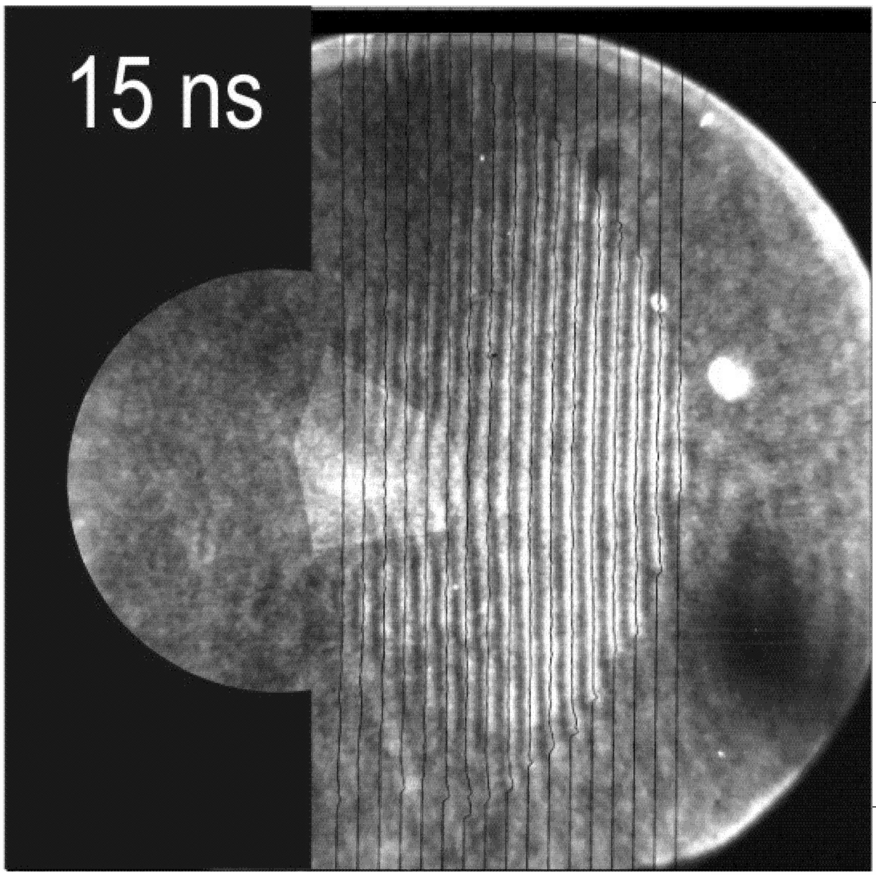


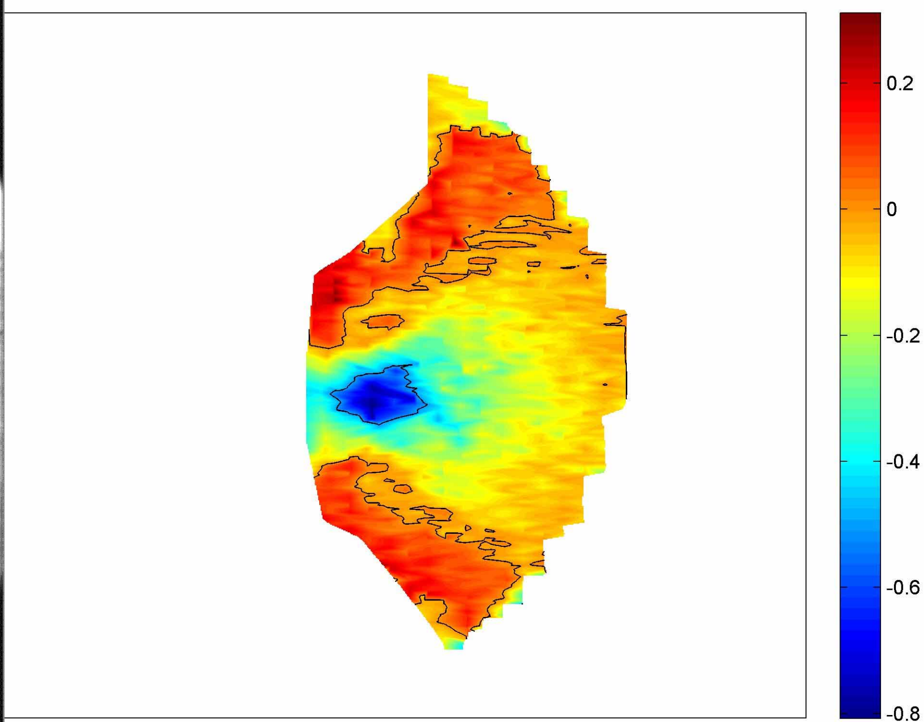
Interferogram of C plasma at 5 ns shows negative fringe shifts near surface where plasma is C^{2+}



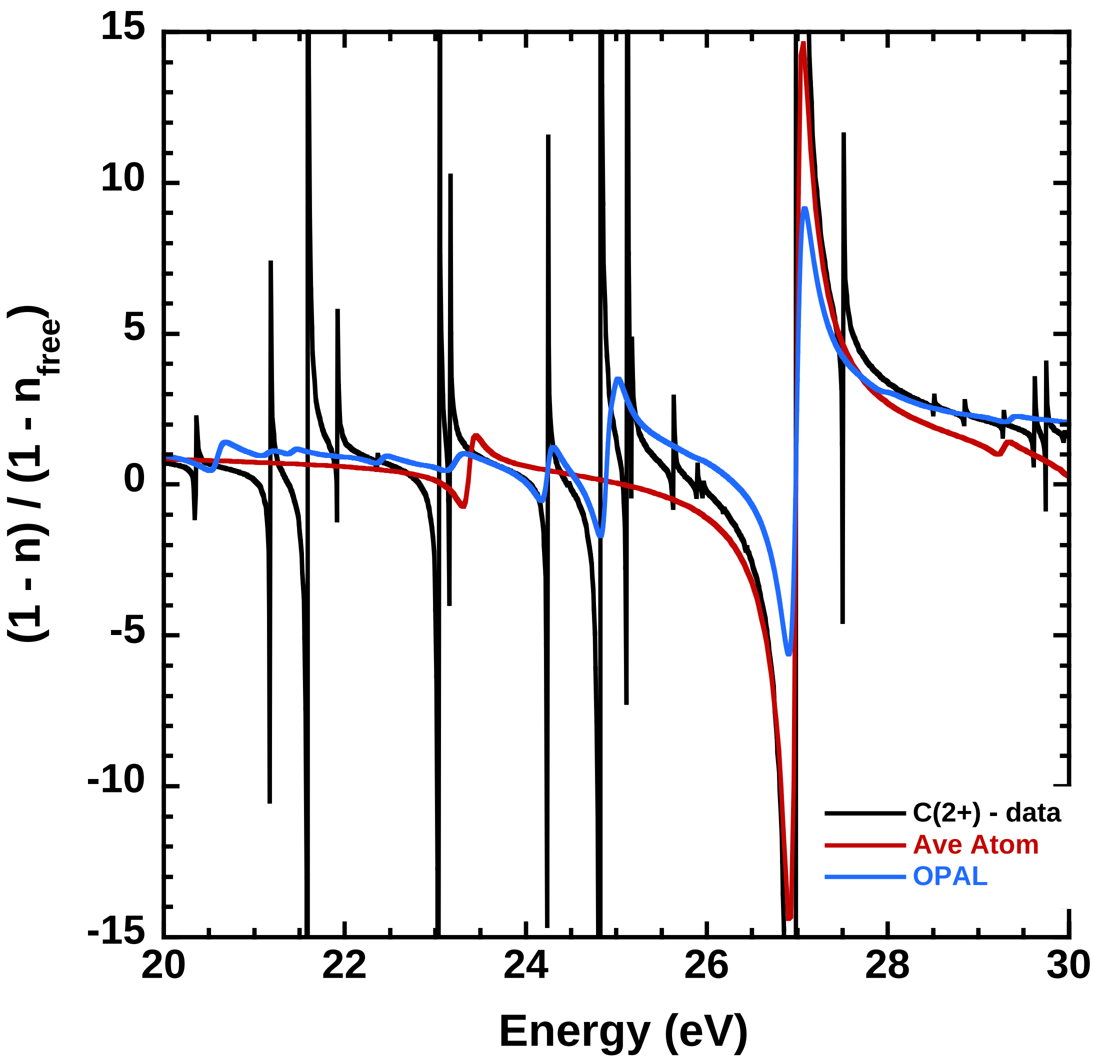


Interferogram of C plasma at 15 ns shows negative fringe shifts in center of plasma where plasma is C^{2+}





Average Atom code is validated against other methods to show anomalous effects for C^{2+}



Use experimental data to shift Ave Atom by 4.21 eV shift OPAL by -0.35 eV

Ratio = -2.1 Exp
Ratio = -2.8 Ave Atom
Ratio = -0.4 OPAL

Lines with fosc=0.6
2s2p(3P)-2s3d(3D) 26.98 eV
2p2p(3P)-2p3d(3D) 24.82 eV
2s2p(1P)-2s3d(1D) 21.59 eV
Line with fosc=0.3
2p2p(1D)-2p3d(1F) 24.24 eV

Average Atom code has simply spectrum as compared with OPAL and Experiments for C^{2+}

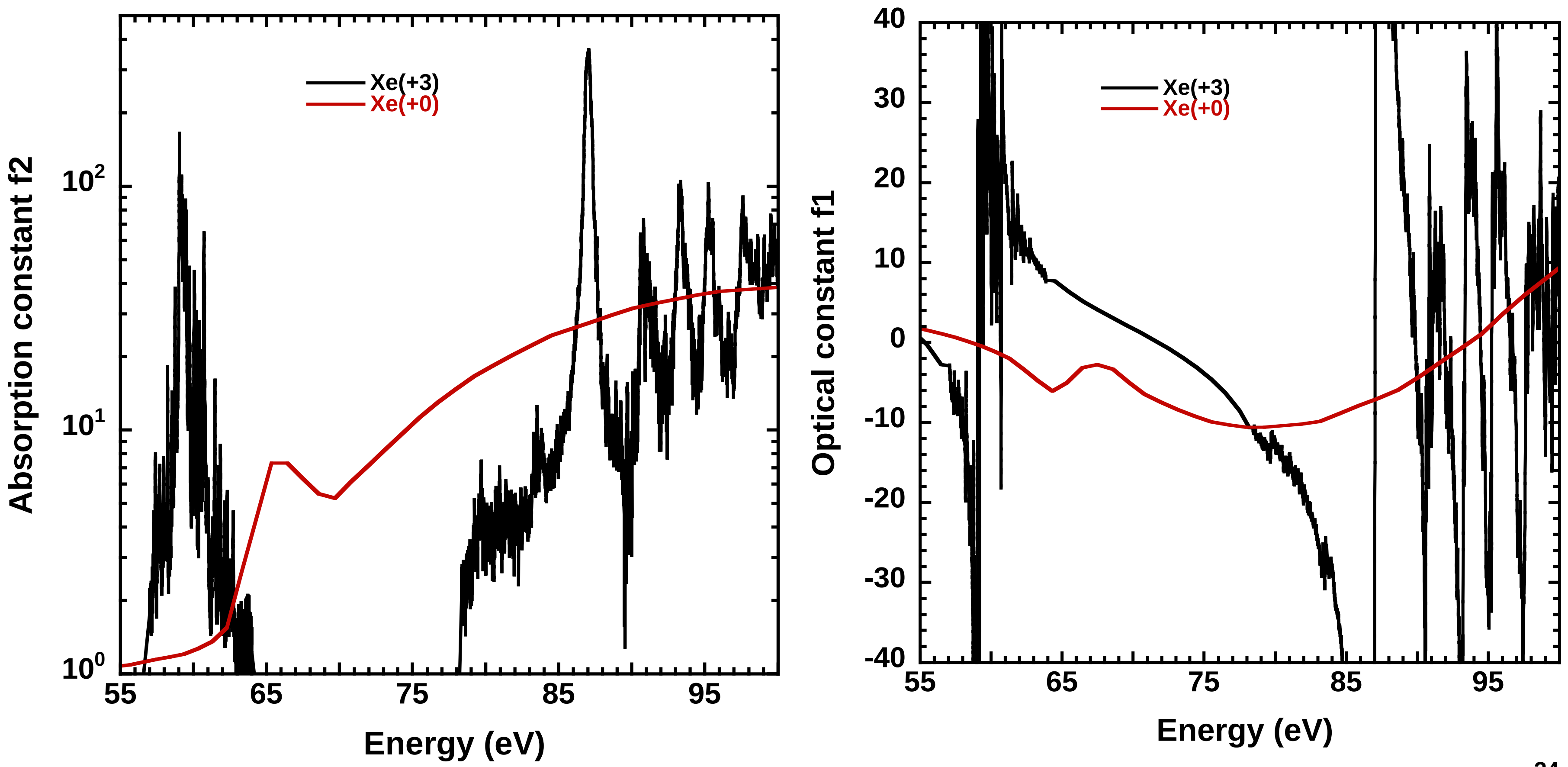
Average Atom has single 2p - 3d line

OPAL and Experimental data have many terms

> **2s2p(3P)-2s3d(3D) 26.98 eV**
> **2s2p(1P)-2s3d(1D) 21.59 eV**
> **2p2p(3P)-2p3d(3D) 24.82 eV**
> **2p2p(3P)-2p3d(3P) 25.12 eV**
> **2p2p(1D)-2p3d(1F) 24.24 eV**
> **2p2p(1S)-2p3d(1P) 20.36 eV**
> **2p2p(1D)-2p3d(1P) 24.90 eV**
> **2p2p(1D)-2p3d(1D) 23.16 eV**

Xe^{3+} has strong absorption line (4d-4f) at 87.05 eV that makes f1 less than zero and index of refraction greater than one from 72 to 87 eV

Absorption data measured at LBL ALS with high resolution from 57 to 117 eV
Data courtesy of Erik Emmons from Phys. Rev. A 71, 042704 (April 2005)



Observe index of refraction greater than one in many plasmas at 26.44 eV energy of Ar X-ray laser

- Free electron approximation for index of refraction is not always valid
- Bound electron can contribute significantly to the index of refraction over a wide range of photon energies
- All partially ionized ions can have lines and edges that affect the index
- Analysis of XRL interferometer experiments require some modeling to estimate contributions from bound electrons and range of validity
- Utilized a new tool, Average Atom code, developed at Notre Dame to calculate index of refraction of many plasmas
- Validated the Average Atom code against OPAL and experiments for low Z plasmas
- Predicted plasmas with anomalous index of refraction greater than one
- Showed interferograms of plasmas (doubly-ionized Ag, Sn, and C) that exhibit index of refraction larger than one at X-ray laser energy of 26.44 eV