SAND2022-5276C

X-ray Heating and Temperature in Multielement Laboratory Photoionized Plasmas at Z

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2022 ZNetUS Workshop

2022-04-22

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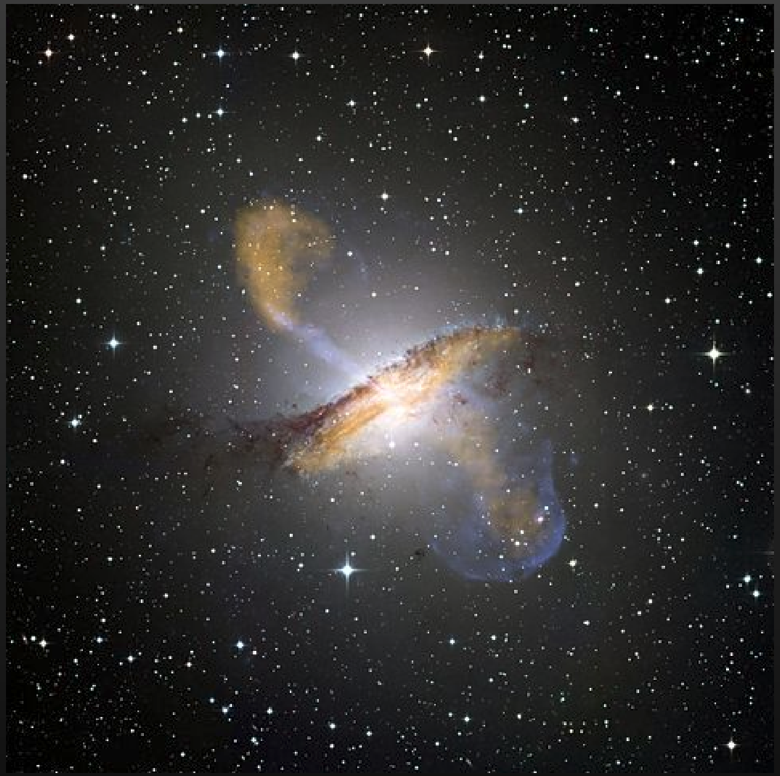
Laboratory plasmas can be used to improve astrophysics theory, modeling, and analysis

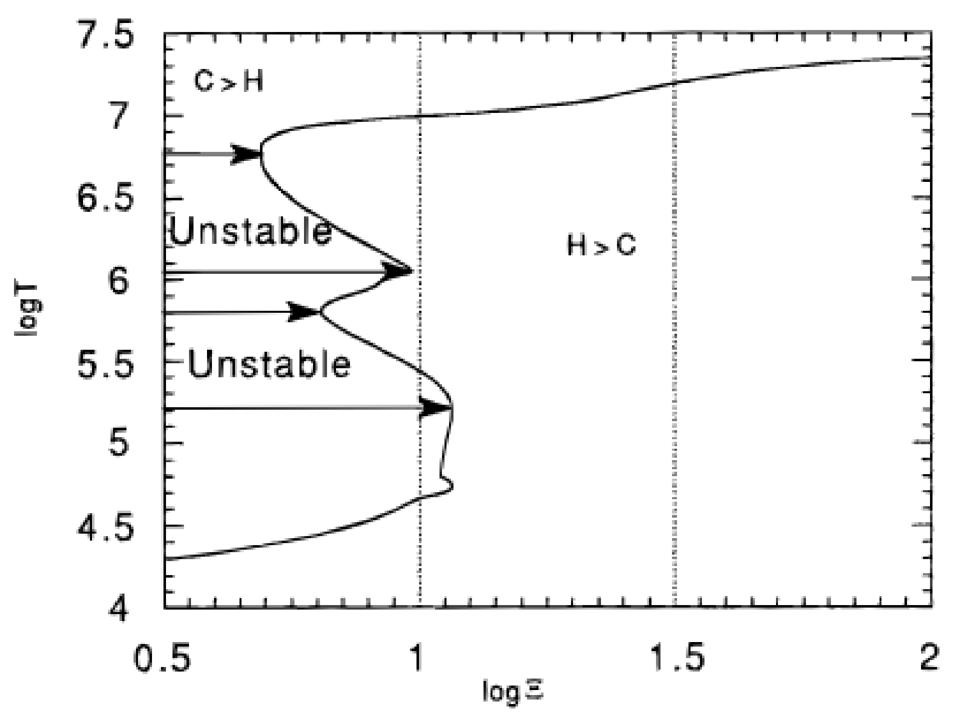
- Historically inaccessible regime now available using the latest HEDP drivers (Z, NIF, OMEGA, etc.)
- Lab plasmas are more reproducible, diagnosable, and variable as compared to astronomical plasmas
- Lab data can serve as benchmarks for untested physics models used in Astro community to interpret observations
- Challenges in astrophysics inform direction of future lab experiments and form a feedback cycle



Composite of Centaurus A
ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

The Thermal Instability problem poses a challenge to modeling astronomical spectra from photoionized systems

- Photoionized (PI) plasmas: photons processes > collisional processes
- Examples: active galactic nuclei, accretions disks, x-ray binaries, quasars
- Under certain conditions, the thermal equilibrium of a PI medium can be unstable
- Thermal instability (TI) in models can contribute to multi-phase structures and element/ion abundances inferred from x-ray spectral observations
- Presence of TI sensitive to initial conditions and computational methods and relies on untested physics of radiation heating and cooling



Phase diagram for photoionized gas with cosmic abundances irradiated by 10 keV bremsstrahlung spectrum[1]

[1]C.J. Hess et al., Astrophysical Journal **478**, 94 (1997)

Photoionized plasmas can be created at parameter in the lab to test physics of radiation heating and cooling

Our Platform: Photoionized Plasma Gas Cell Experiment at Z

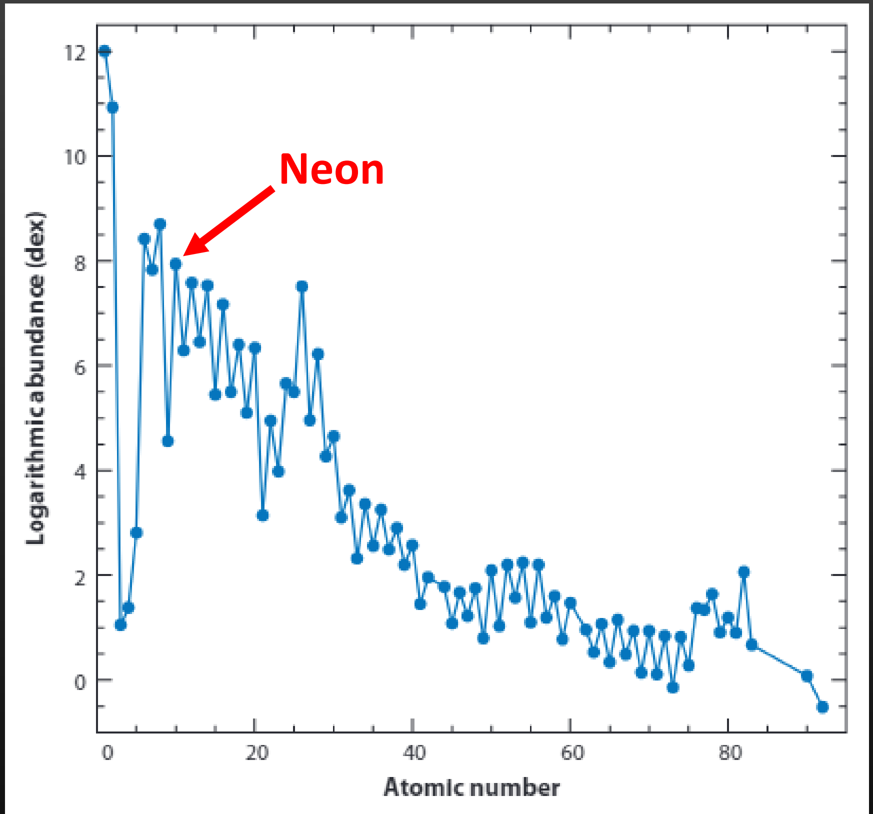
- Can access **plasmas at parameter** ($\Xi \approx 0.5 - 1, \mathrm{k_B T} \approx 15 - 30\ eV$) for testing astrophysical models of photoionized plasmas
  - X-ray Source: $\sim 10^{12}\ W/cm^{-2}$
  - Gas: $\sim 10^{17} - 10^{18}\ cm^{-3}$ of Ne, H, Ar, or others at **cm-scale volumes**
- Can **measure electron temperature** independent of atomic kinetics via absorption spectroscopy[2]
  - Temperature depends primarily on radiation heating and cooling
- Can use astro codes (CLOUDY, XSTAR) and lab codes (HELIOS-CR) to model our experiment and compare results

[2]R.C. Mancini et al., Phys. Rev. E **101**, 051201 (2020)

Multielement compositions in the lab are needed to better replicate astrophysical plasmas

- Astrophysical compositions are dominated by H and He
- **Question: What is the qualitative and quantitative role of higher-Z elements in photoionized plasmas?**
- Previous experiments have focused on single element PI plasmas
- The gas cell platform allows flexibility of composition using molecular and mixed gases

This talk: Presenting first results from Ne-H mixed gas cell experiments



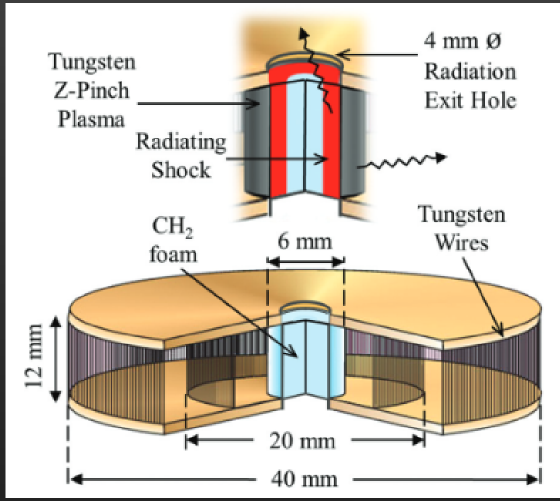
Present-day solar photospheric elemental abundances as a function of atomic number[3]

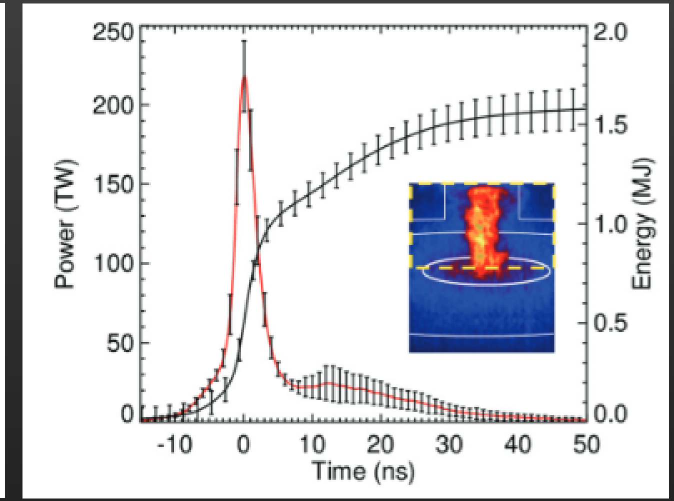
[3]M. Asplund et al., Annual Review of Astronomy and Astrophysics **47**, 481 (2009)

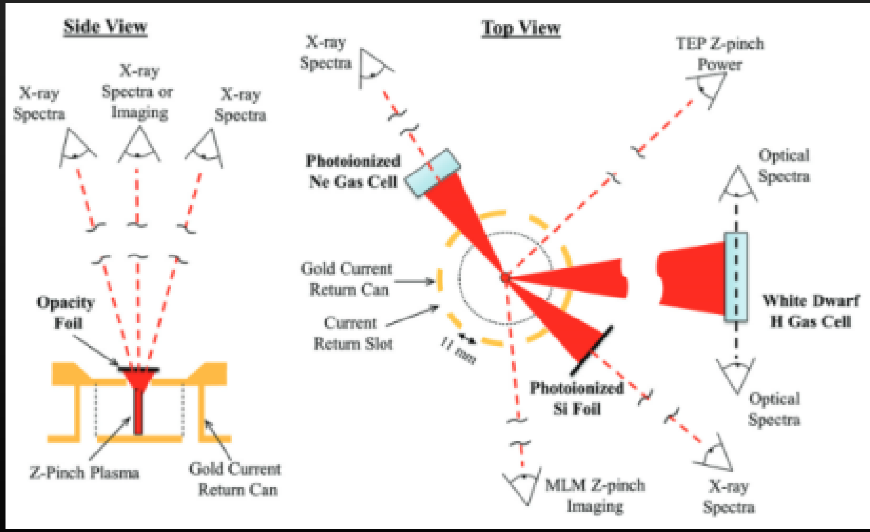
Our experiments are conducted as part of the ZAPP collaboration at the Sandia National Labs Z Machine

ZAPP: the Z Astrophysical Plasma Properties collaboration[4]

- Source: Z-Pinch Dynamic Hohlraum
  - Input: ~26 MA to W wire array + foam
  - Output: ~ 200 eV Planckian, 1.6 MJ, 220 TW, < 10 ns duration
- Multiple samples and diagnostics fielded at the same time, with emphasis on spectroscopy
- Topics of study: Stellar opacity, photoionized plasmas, white dwarf atmospheres, photoionization fronts
- Participation from UNR, UT, UM, and SNL



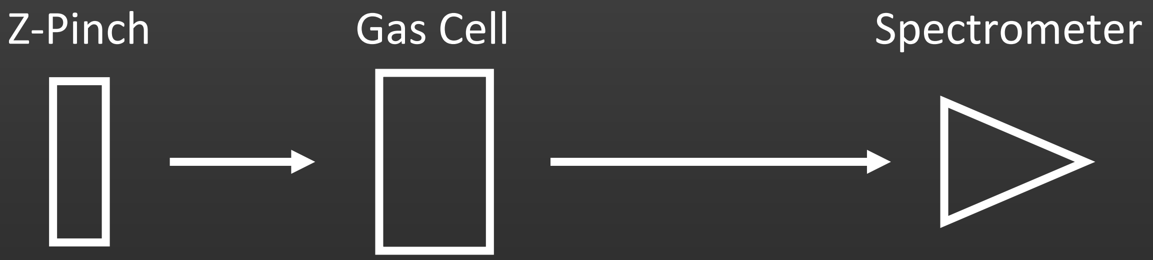


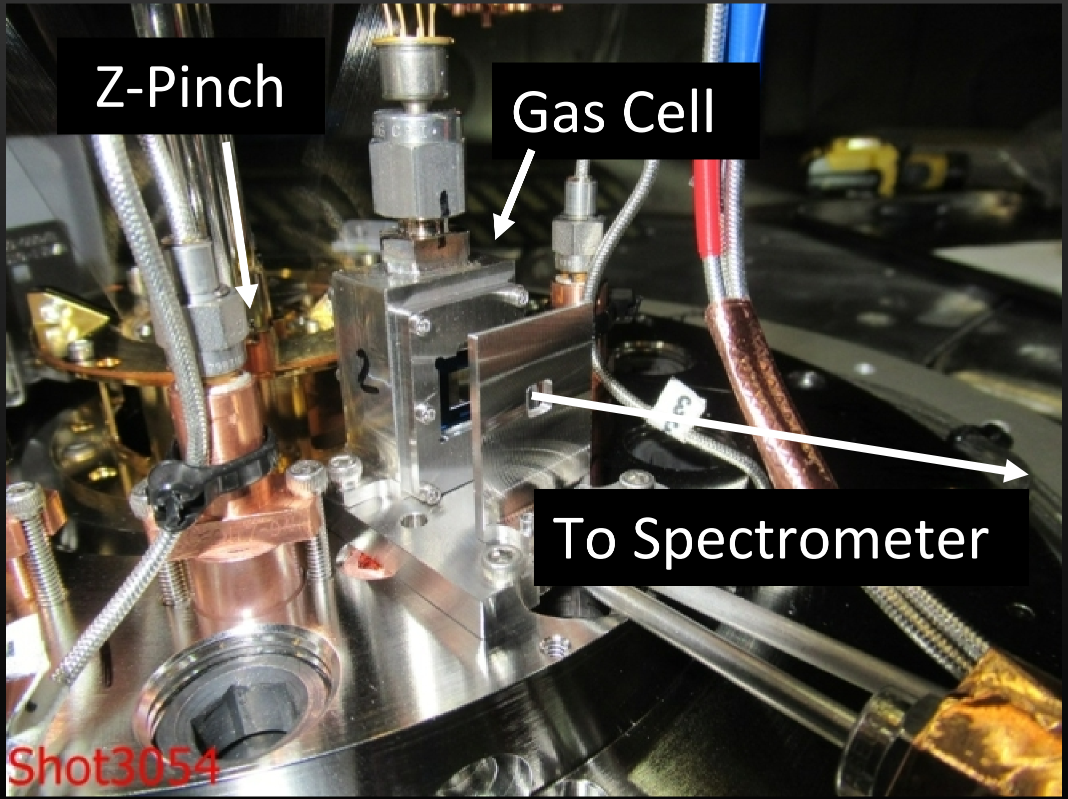


[4]G.A. Rochau et al., Phys. Plasmas **21**, 056308 (2014)

The z-pinch drives gas in the cell and simultaneously backlights it for absorption spectroscopy[5]

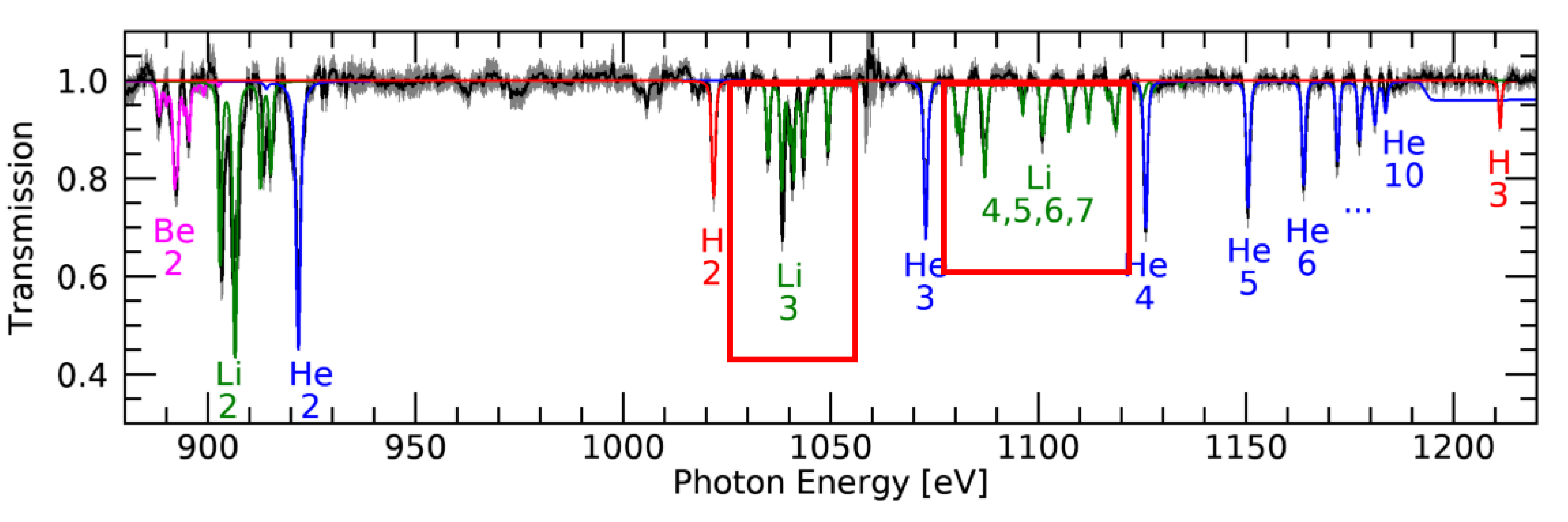
- 2.0 x 1.0 x 1.15 cm internal volume filled with gas at various pressures
- Two positions: 4.3 and 5.9 cm from pinch
- Thin ($\leq 1.5\ \mu m$) mylar or Si_3N_4 windows in front and back
- Position/window/pressure combo controls ionization parameter
- Fitted with gas fill tubes and *in-situ* pressure sensor
- TREX spectrometer[6] records Ne K-shell spectra time-integrated and/or resolved





[5]I.M. Hall et al., Phys. Plasmas **21**, 031203 (2014); [6]P.W. Lake et al., Rev. Sci. Instrum. **77**, 10F315 (2006)

Absorption spectra are processed to transmission and analyzed using a synthetic spectra model fitting procedure



- Transmission spectra are time-integrated and averaged from multiple images
- The synthetic spectrum is fit to the data by a weighted least squares minimization procedure
- Individual ion areal densities are determined from the fit to the data[7]
- Temperature is extracted from the Li-like Ne features[2]

[7]D.C. Mayes et al., Phys. Rev. E **104**, 035202 (2021); [2]R.C. Mancini et al., Phys. Rev. E **101**, 051201 (2020)

Electron temperature is extracted from a Li-like Ne population ratio interpreted with a Boltzmann factor[2]

Assumptions

- Population ratio equivalent to ion areal density ratio
- Population ratio < 3
- Relative populations dominated by electron collisions
- Population ratio remains close to the Boltzmann value
- $k_B T_e \sim \Delta E$
- Plasma electrons are in thermal equilibrium
- Overall CSD is NLTE

Li-like Ne configs: $1s^2 2s$, $1s^2 2p$

$$R = \frac{N_p}{N_s} = g e^{-\frac{\Delta E}{k_\mathrm{B} T_e}}$$

$$k_\mathrm{B} T_e = \frac{\Delta E}{\ln(g/R)}$$

$$\Delta E \approx 16.2\ eV, g = \frac{g_p}{g_s} = \frac{6}{2} = 3$$

$$\delta(T_e)/T_e = [(k_B T_e)/\Delta E]\,[\delta R/R]$$

[2]R.C. Mancini et al., Phys. Rev. E **101**, 051201 (2020)

First Ne-H experiments were performed across multiple parameters and electron temperature was extracted

Shot #	Pressure (Torr)	Ne %	Ne PP (Torr)	H PP (Torr)	Distance (cm)	T_e (eV)
Z2389	75	20%	15	60	4.3	23.6 ± 3.9
Z2410	93	10%	9	84	4.3	15.8 ± 1.6
Z2411	46.5	10%	4.5	42	4.3	14.6 ± 1.9
Z2412	46.5	10%	4.5	42	5.9	16.3 ± 3.2
Z2413	37.5	20%	7.5	30	5.9	15.8 ± 1.4

Remarks

- All shots used Gen2 style cells with 5x5 mm Si_3N_4 windows
- No repeated conditions
- Weak signal from z2411 and z2412

Comparison of Ne-H data to pure Ne data show dominant role of Ne for electron temperature

Ne-H Mix (single-shot)

$P\ (Torr)$	$X\ (cm)$	$n_e\ (cm^{-3})$	$T_e\ (eV)$
75 (20% Ne, 15)	4.3	8E+18	23.6 ± 3.9
37.5 (20% Ne, 7.5)	5.9	4E+18	15.8 ± 1.4

Pure Ne (multi-shot averages)[8]

$P\ (Torr)$	$X\ (cm)$	$n_e\ (cm^{-3})$	$T_e\ (eV)$
15	4.3	4E+18	$26.9^{+6.4}_{-7.1}$
7.5	5.9	2E+18	$17.7^{+3.1}_{-3.8}$

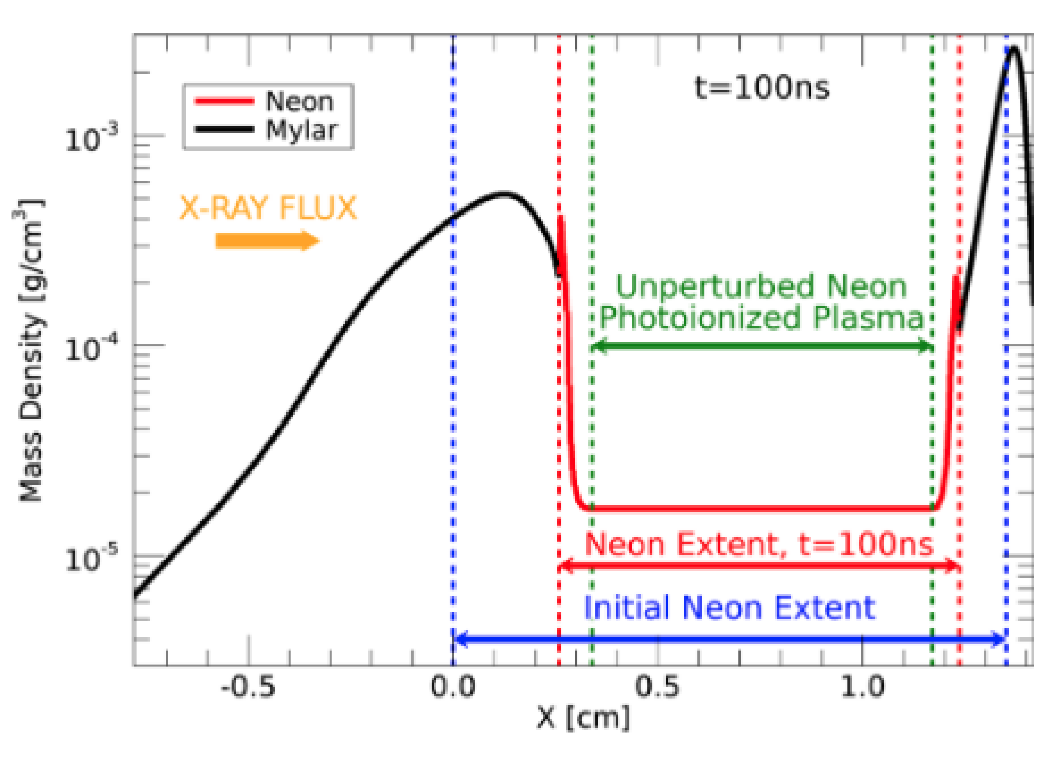
- Important parameters: electron and Ne number density
- Temperature similar for shots w/ same Ne PP despite different electron density and total pressure
- Additional experiments are ongoing to expand the data set and establish trends

[8]D.C. Mayes, University of Nevada, Reno, ProQuest Dissertations Publishing, 28262596, (2020)

We use the lab code HELIOS-CR to simulate our experiments and improve the interpretation of results

HELIOS-CR[9]: a 1D Rad-MHD code with inline atomic kinetics

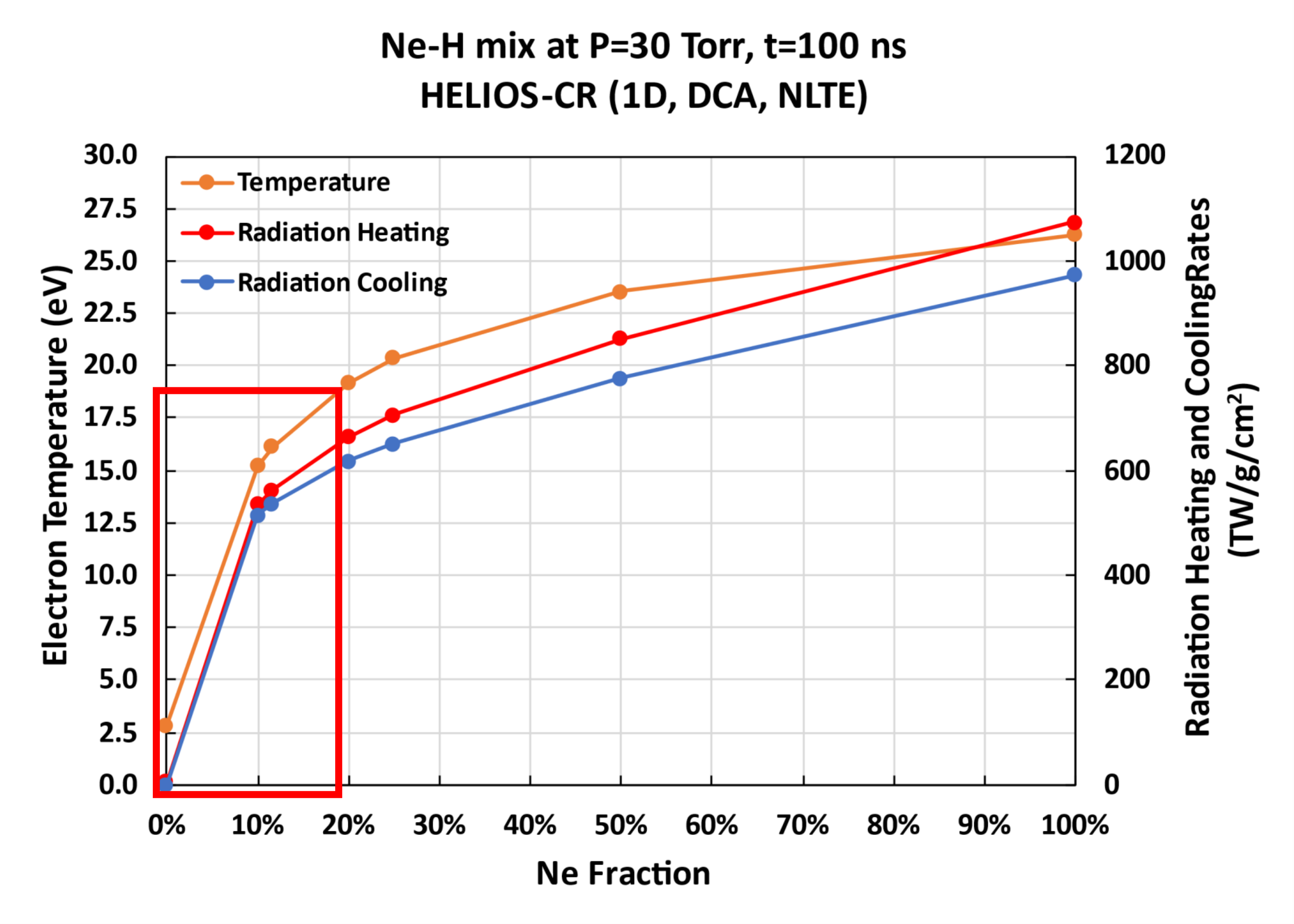
- Model includes gas and windows
- Model uses data constrained model of x-ray flux time history applied at front window to drive the plasma
- Simulations run with detailed configuration accounting (DCA) for the gas material only
- Simulation run with non-local thermal equilibrium (NLTE) atomic kinetics



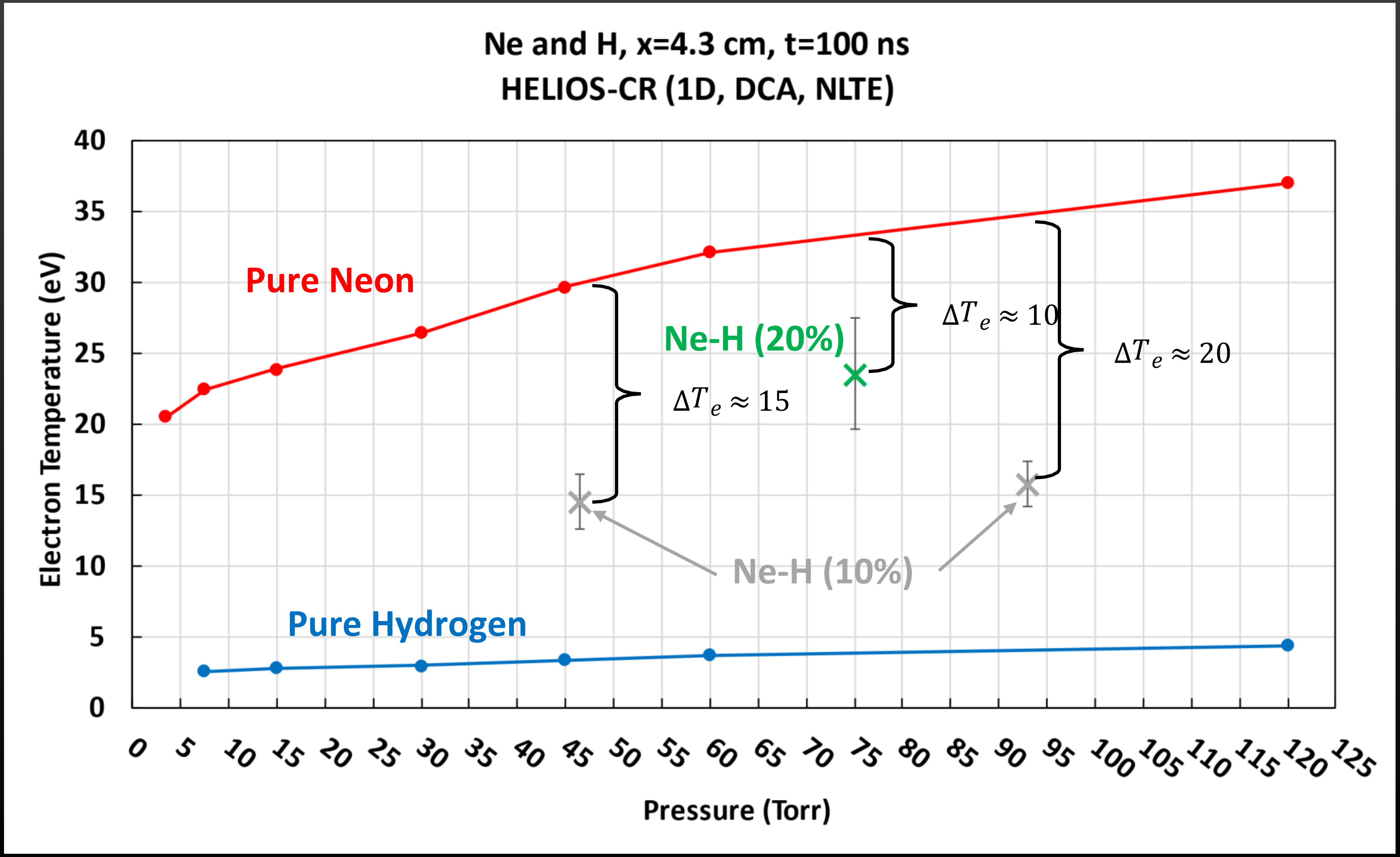
Snapshot of the mass density from the simulation at peak x-ray drive (t=100ns) with labels indicating different plasma regions[7]

[9]J.J. MacFarlane et al., J. Quant. Spec. Rad. Tran. **99**, 381 (2006); [7]D.C. Mayes et al., Phys. Rev. E **104**, 035202 (2021)

Simulations suggest strong influence of Ne on electron temperature and radiation heating



Simulations of pure Ne at same total pressure as Ne-H mix show significantly higher temperature



Conclusion

Summary

- Successfully measured electron temperature from Ne-H mixed photoionized plasmas at various parameters
- Analysis indicates Ne plays dominant role in temperature and x-ray heating vs H, supported by HELIOS simulations

Future Work

- Extract charged state distribution from data
- More Ne-H experiments to expand data set
- Use CLOUDY and XSTAR to model experiment and compare (in progress)

Acknowledgments

This work is sponsored in part by US DOE NNSA Grant No. DE-NA0003875, US DOE OFES Grant No. DE-SC0014451, the Wootton Center for Astrophysical Plasma Properties under US DOE Cooperative Agreement No. DE-NA0003843, and the Z Facility Fundamental Science Program of Sandia National Laboratories. Sandia National Laboratories is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Thank You

Questions?

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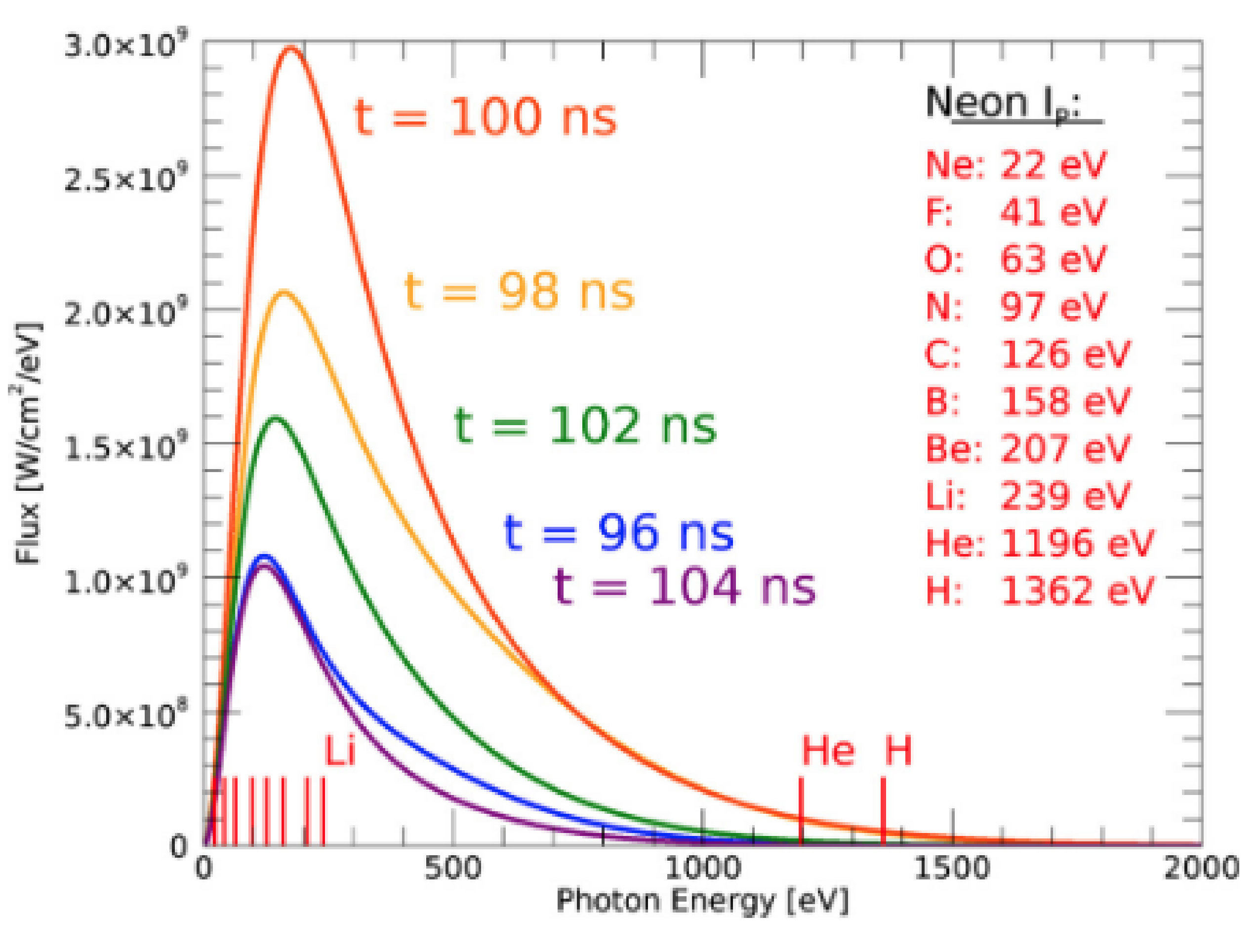
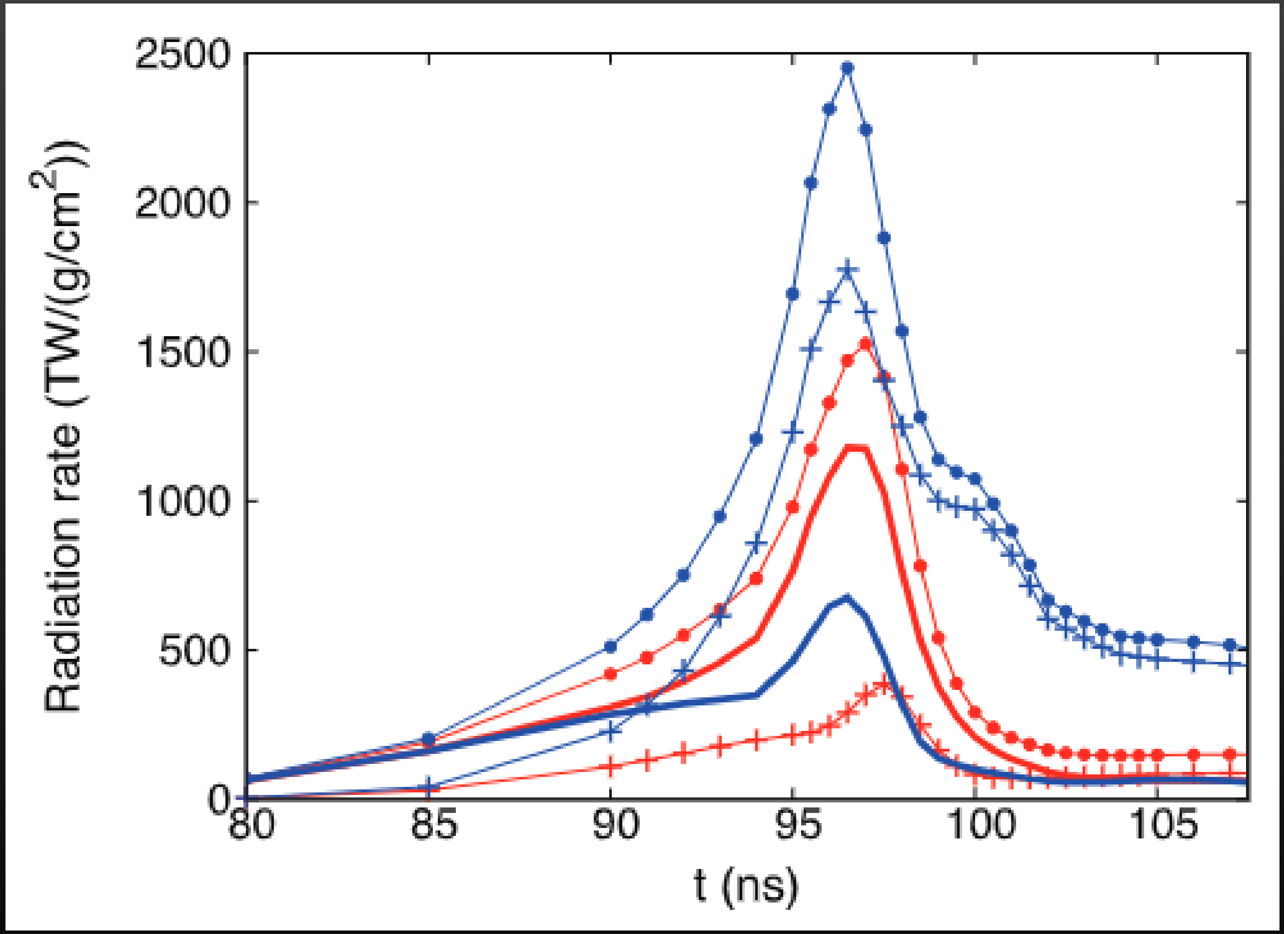
3. M. Asplund et al., Annual Review of Astronomy and Astrophysics **47**, 481 (2009)
4. G.A. Rochau et al., Phys. Plasmas **21**, 056308 (2014)
5. I.M. Hall et al., Phys. Plasmas **21**, 031203 (2014)
6. P.W. Lake et al., Rev. Sci. Instrum. **77**, 10F315 (2006)
7. D.C. Mayes et al., Phys. Rev. E **104**, 035202 (2021)
8. D.C. Mayes, University of Nevada, Reno, ProQuest Dissertations Publishing, 28262596, (2020)
9. J.J. MacFarlane et al., J. Quant. Spec. Rad. Tran. **99**, 381 (2006)

ZPDH X-Ray Drive Model energy resolved time-history with Neon ionization potentials[7]



[7]D.C. Mayes et al., Phys. Rev. E **104**, 035202 (2021)

Radiation heating and cooling rate time-history from HELIOS-CR for pure Ne at 30 Torr[2]



[2]R.C. Mancini et al., Phys. Rev. E **101**, 051201 (2020)