Laboratory photoionized plasma experiments relevant for astrophysics

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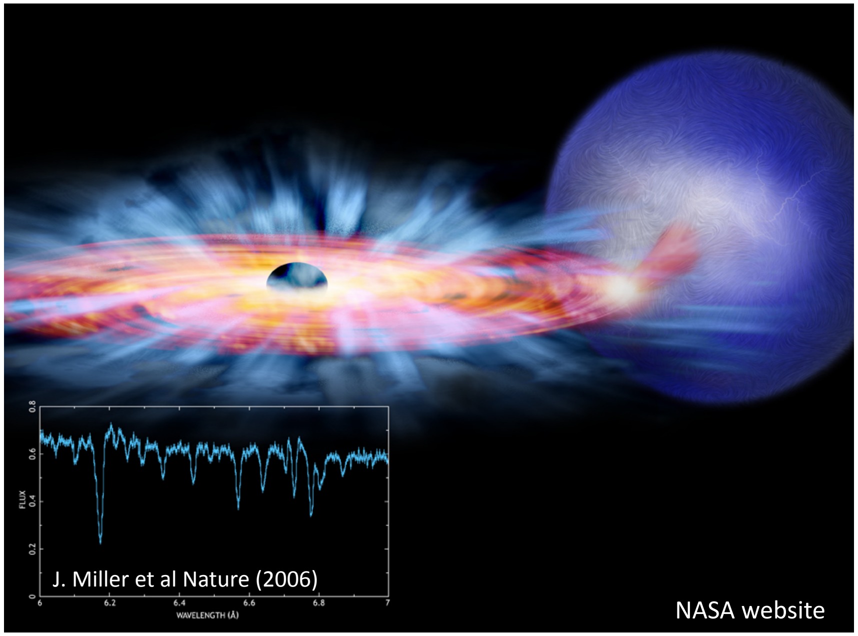
Photoionized Plasmas

- Widespread in space – active galactic nuclei, accretion discs around black holes
- Plasma is driven by an intense source of X-rays
- Unlike collisional plasmas, photo-ionisation and photo-excitation dominate atomic kinetics
- The complexity of the astrophysical environment makes the spectral analysis challenging ⟶ laboratory experiments are important[1]

Relevance to astrophysics

- Perform well-characterized laboratory photoionized plasma experiments to benchmark modeling codes developed only from theory
- Address specific problems: e.g. effect of resonant Auger destruction on radiative properties of accreting disks



J. Miller et al Nature (2006)

NASA website

Artists impression of binary system GRO J1655-40, 11,000 lights years away in scorpius constellation

1. R. C. Mancini et al, Phys. Plasmas **16**, 041001 (2009)

Laboratory experiment requirements

- Plasma ionization driven by a distribution of photons through photoionization
- Large value of the ionization parameter ξ: up to 1000 erg cm / s
- Uniform plasma: minimize spatial structure/gradients, approximate the ideal "0-D" case of a single temperature and density point
- Steady-state photoionization equilibirum: photoionization counterbalanced by radiative and dielectronic recombination (i.e. two body processes)

- Plasma needs to be well characterized
- X-ray flux producing the plasma needs to be known: measure color (T_C) and brightness (T_B) temperatures
- Plasma electron temperature (T_e) and particle number density (N) need to be diagnosed independently
- Record absorption and emission spectra

- Benchmark: given T_B, T_C, T_e and N theory/modeling code can be run to compute plasma ionization and spectral properties to compare with data

- The standard is high and challenging, but not unusual for benchmarking

Considerations and challenges

- Laboratory plasmas are short-lived: steady-state is difficult to achieve
- Time scales associated with photoionization rates are in the range of few ns to tens of ns
- Long-duration drivers for high-energy density laboratory plasmas can typically last from a few ns up to 10ns
- OMEGA-EP long-pulse ~4ns, NIF ~10ns, Z ~5ns

- Laboratory plasmas are smaller and denser that astrophysical plasmas but column/areal-densities and line optical depths can be comparable
- Low densities are important to achieve high ionization parameters but this can compromise achieving steady-state
- Large plasma sizes can help with "hydrodynamic isolation" of the plasma but can also compromise uniformity
- Locating plasma close to radiation source maximizes ionization parameter but can compromise uniformity as well

Laboratory photoionized plasma experiments

- Each one represent a different approach to producing and studying laboratory photoionized plasmas

- Differences in driver, target design and experimental configuration

- Photoionized iron plasma experiment performed at Z: z-pinch radiation driving a tamped, expanding iron foil

- Photoionized nitrogen plasma experiment performed at GEKKO XII: nitrogen gas-filled hohlraum driven by high-power laser beams

- Photoionized silicon plasma experiment performed at GEKKO XII: x-rays from shell implosion driving a preformed, warm silicon plasma

- Photoionized neon plasma experiment at Z, ongoing project: z-pinch radiation driving a gas cell filled with neon

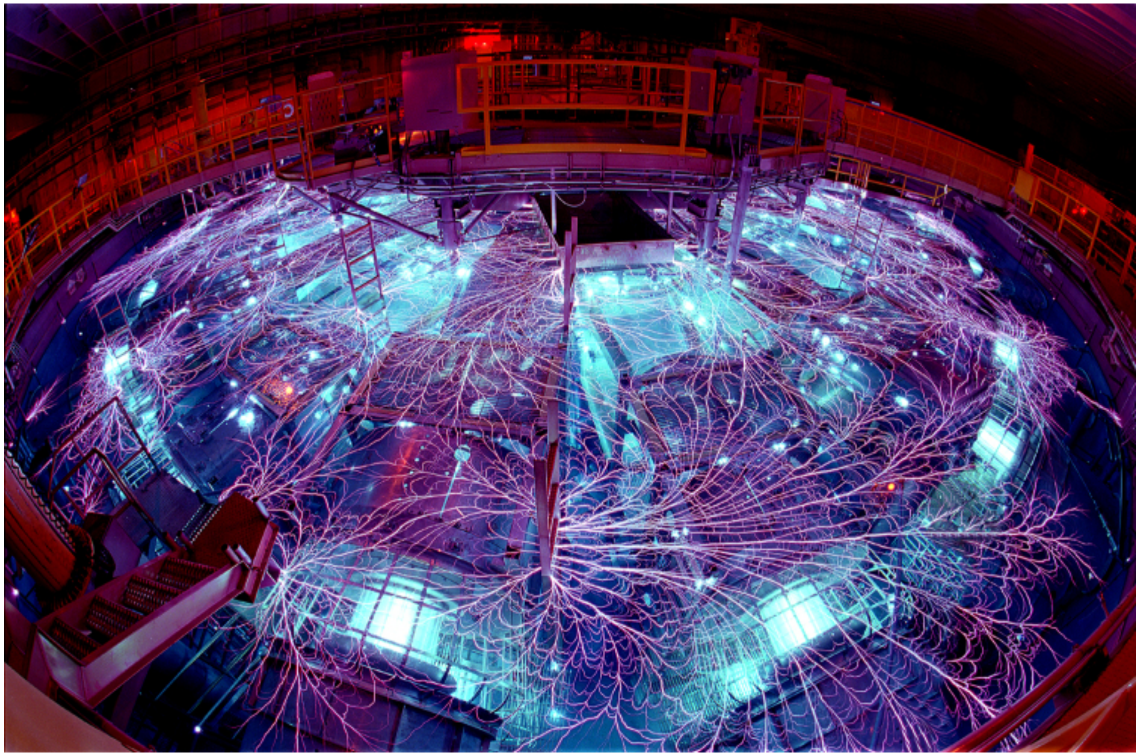
Tamped foil driven by z-pinch radiation[1-5]

- Photoionized iron plasma experiment performed at Z: wire-array z-pinch radiation driving a tamped foil located at 1.5cm from z-pinch axis
- Slab target: 500 – 750 Å thick Fe/NaF foils overcoated on each side with 1000 Å of lexan to help maintain uniform conditions during expansion
- Boron-coated Z hardware to minimize re-radiation effect on x-ray drive
- Bright x-ray flux from z-pinch stagnation phase drives photoionize plasma
- Edge-on self-emission imaging of the foil measures expansion: density
- Estimated electron density N_e of $2\text{x}10^{19}\text{cm}^{-3}$
- Electron temperature T_e from modeling of 150eV
- Narrow-band x-ray flux also used to record absorption spectrum
- No measurement of self-emission spectrum
- Few ns estimated to reach steady-state: assumed at 3ns after drive peak
- Ionization parameter ξ of 20 – 25 erg cm / s
- Data attracted significant attention and motivated many comparisons with atomic kinetics codes

1. R. F. Heeter et al, RSI **72**, 1224 (2001); 2. M. E. Foord et al, PRL **93**, 055002 (2004); 3. S. J. Rose et al, JPB **37**, L337 (2004)
4. P. A. M. Van Hoof et al, ApSS **298**, 147 (2005); 5. M. E. Foord et al, JQSRT **99**, 712 (2006)

Sandia National Laboratories Z facility

- The dearth of laboratory photoionised plasma data is due to inadequate x-ray radiation source energy.
- Today, Z experiments can fill this gap.
- Idea: use broad-band Z-pinch X-ray emission as ionising source to produce a photoionised plasma, and a narrow-band portion of it to probe the plasma.



- Produces ~1—2MJ of X-ray energy in a ~10ns burst, up to 200TW of peak power.
- Planckian distribution with $T_r \approx 220$ eV.
- Well characterised and reproducible source of X-rays.

M. Foord et al, PRL **93**, 055002 (2004): time-integrated transmission

Fe was photoionized to the L-shell, and F and Na to the K-shell

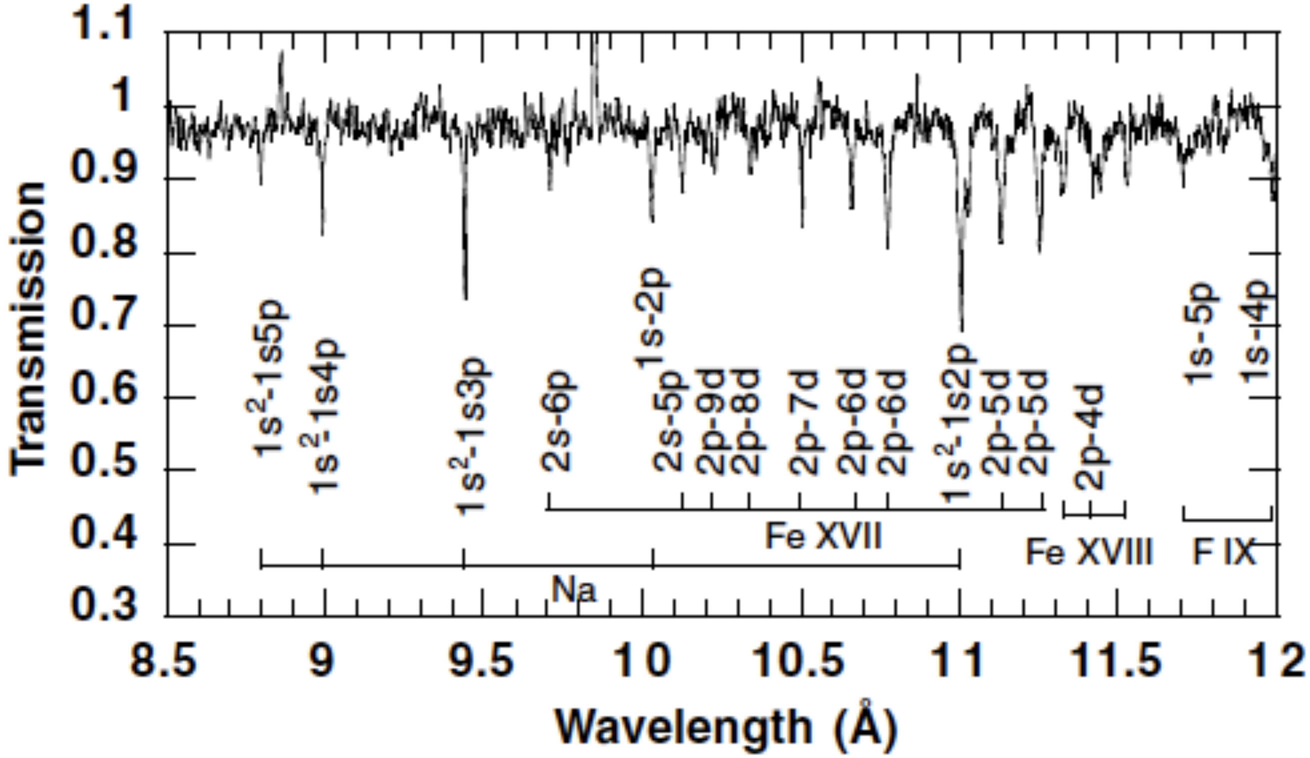


FIG. 2. Absorption spectrum of *L*-shell iron and *K*-shell sodium and fluorine lines. Unidentified peaks at 8.8 and 9.8 Å are due to film defects.

M. Foord et al, PRL **93**, 055002 (2004): data-theory comparison

Electron temperature T_e estimated from fits to the Fe charge state distribution

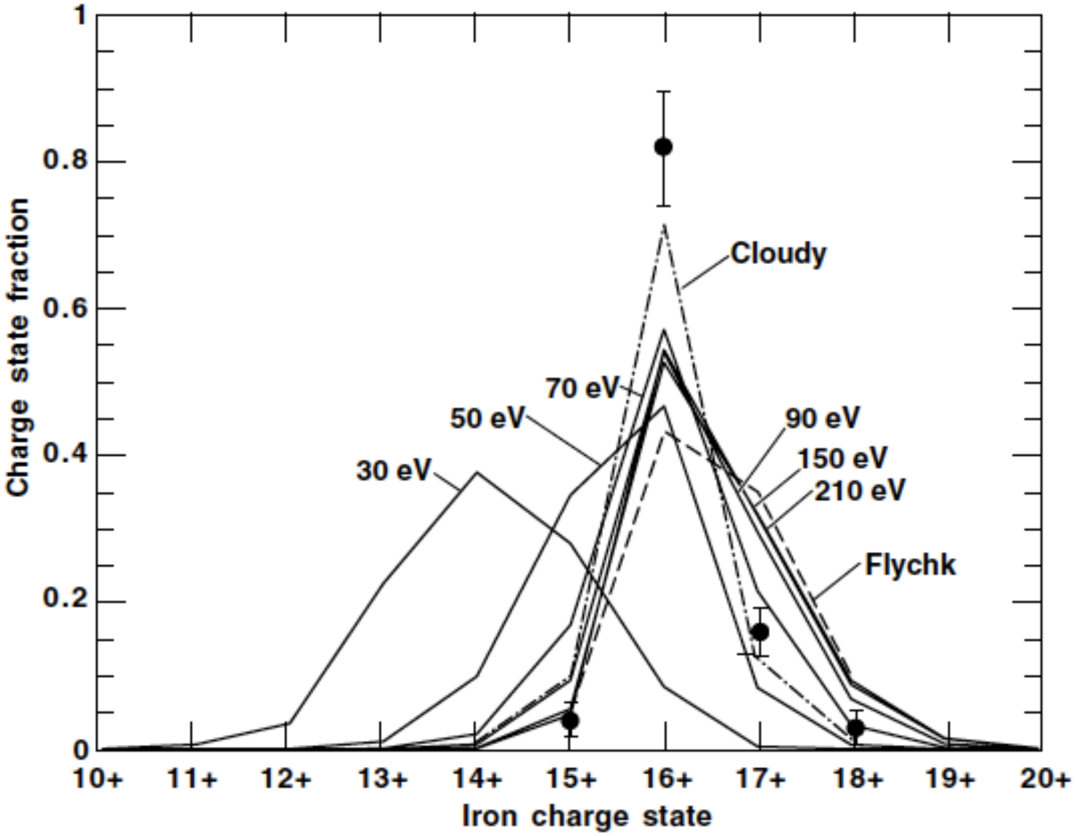


FIG. 4. Iron charge state distribution (solid dots) and comparisons with photoionization code GALAXY for T_e = 30–210 eV (solid lines). Also shown are results from the code FLYCHK at T_e = 150 eV (dashed line) and CLOUDY (dash-dotted line).

- Charged state distribution is relatively insensitive to Te in the 90eV to 210eV range
- Photoionization of L-shell ions dominates over collisional ionization
- Cloudy heating calculation yielded T_e of 150eV and an average charge state of 16

M. Foord et al, JQSRT **99**, 712 (2006): data-theory comparison

Relative population of ground and low-excited states is insensitive to T_e

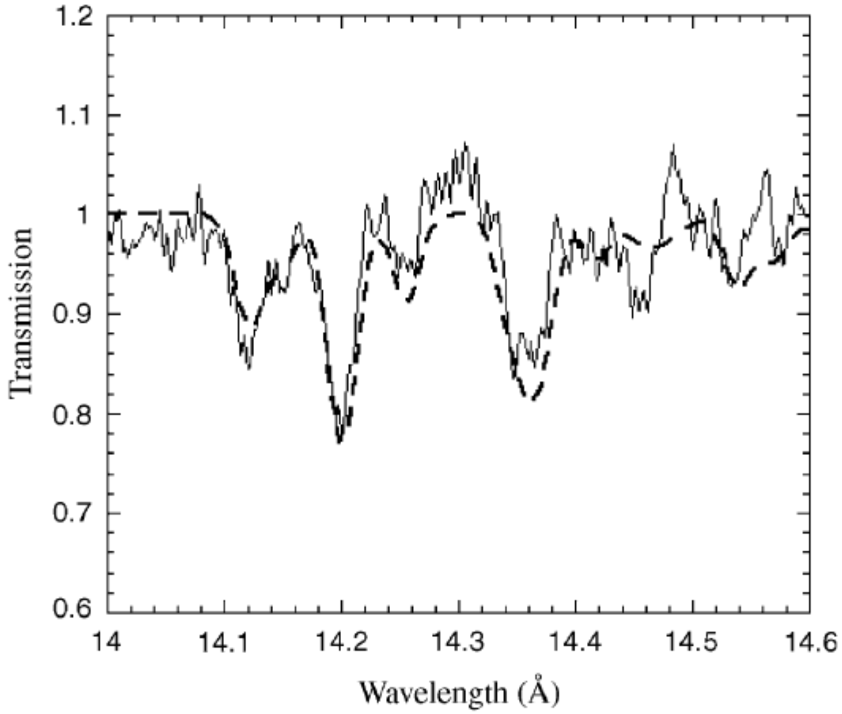


Fig. 6. $\mathrm{Fe}^{+17} 2s^2 2p^5 - 2s^2 2p^4 3d$ absorption spectrum (solid) and multiple line fit (dashed) used to determine the Fe^{+17} abundance.

M. Foord et al, JQSRT **99**, 712 (2006): data-theory comparison

Need of x-ray drive tested with many codes including and average-ion model[35]

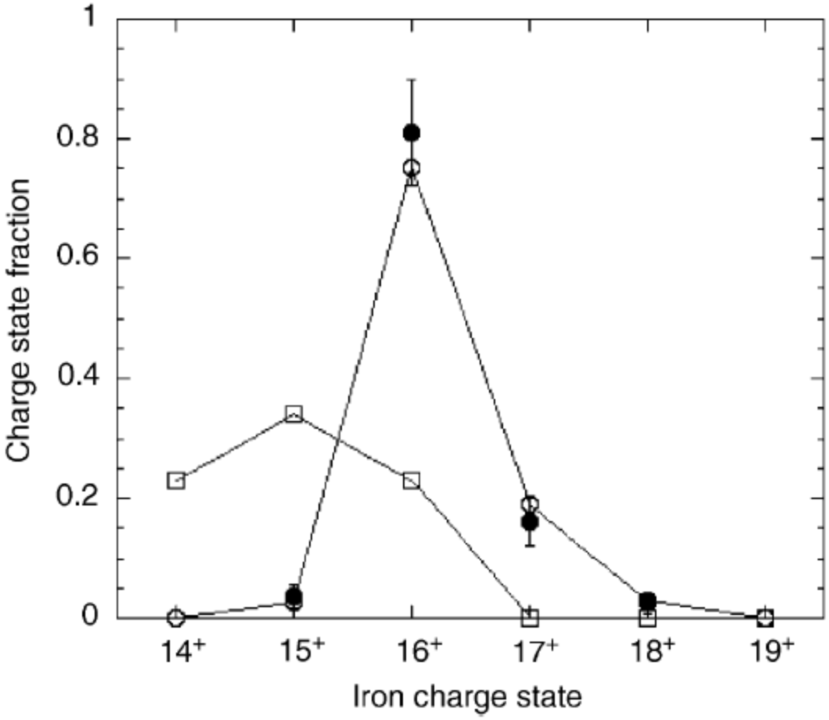


Fig. 8. Measured Fe charge-state distribution (solid dots) and comparisons with the average atom code, Nimp (open dots). Results from Nimp with no radiation field are also shown (open squares) (from Ref. [35]).

35. S. J. Rose et al, J. Phys. B **37**, L337 (2004)

Laser-driven gas-filled hohlraum[1]

- Photoionized nitrogen plasma experiment performed at GEKKO XII: gas-filled hohlraum driven by high-power laser beams
- Green light laser beams heat a gold-coated hohlraum cavity producing a Planckian radiation field of T_r=80eV: x-ray drive
- Gaussian laser pulses of 0.5ns FWHM
- Two diagnostic windows: x-ray drive and self-emission spectrum
- Nitrogen atom number density of $1.4\text{x}10^{19}\text{cm}^{-3}$
- K-shell line emission spectrum of the plasma was observed and used to diagnose the plasma conditions
- Photoionized nature of the plasma is inferred from spectral line ratios
- Transient effects: time-dependent modeling of the photoionized plasma suggests an electron temperature in the 20 – 30 eV range
- Ionization parameter $\xi \sim 10$ erg cm / s

1. Fei-lu Wang et al, Phys. Plasmas **15**, 073108 (2008)

Fei-lu Wang et al, PoP **15**, 073108 (2008): experiment concept

“Dog-bone” hohlraum cavity

T_r = 80eV

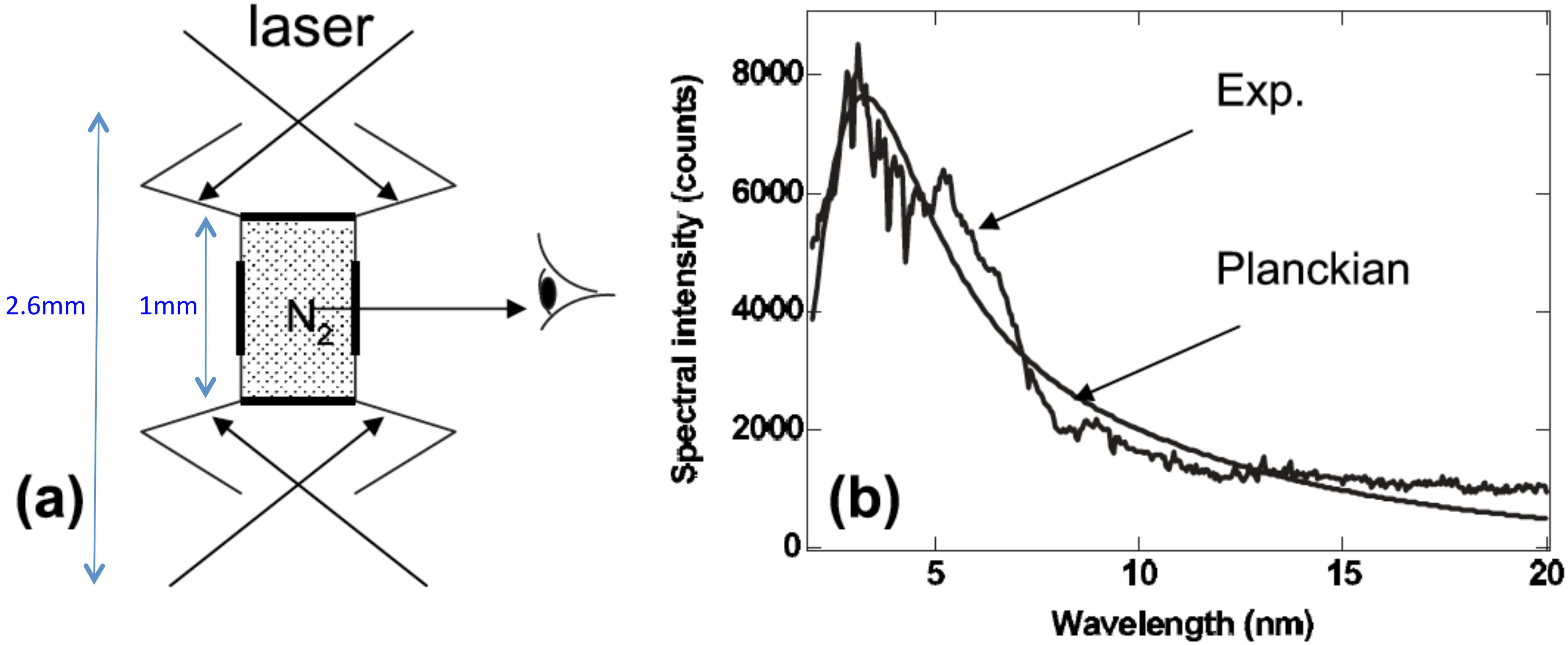


FIG. 1. (a) Experimental setup of photoionized nitrogen plasma. (b) X-ray spectral emission of the thermal radiation through one of the observation windows measured at peak power with transmission grating spectrometer. Also shown is the Planck spectrum corresponding to a radiation temperature of 80 eV.

Silicon plasma driven by shell implosion emission[1]

- Photoionized silicon plasma experiment performed at GEKKO XII: x-rays from shell implosion driving a preformed, warm silicon plasma
- Low intensity, infrared laser pulse ($5x10^{10}Wcm^{-2}$) irradiates a Si slab creating a warm plasma blow-off of $N_e=7.5x10^{19}cm^{-3}$ and $T_e=28eV$, that was diagnosed by UV spectroscopy
- Planckian source of x-rays produced by the implosion of a shell driven by the GEKKO XII high-power laser photoionizes the preformed Si plasma
- Planckian is characterized by $T_r=480eV$ and a duration of 0.16ns
- Again, transient effects are important
- Silicon photoionized plasma is diagnosed via emission spectroscopy
- Spectrum shows emission from K-shell silicon ions
- Ionization parameter $\xi \sim 6$ erg cm / s
- Data interpretation and analysis by Hill and Rose[2]

1. S. Fujioka et al, Nature Physics **5**, 821 (2009)
2. E. Hill and S. Rose, PoP **17**, 103301 (2010)

S. Funjioka et al, Nature Physics **5**, 821 (2009): experiment concept

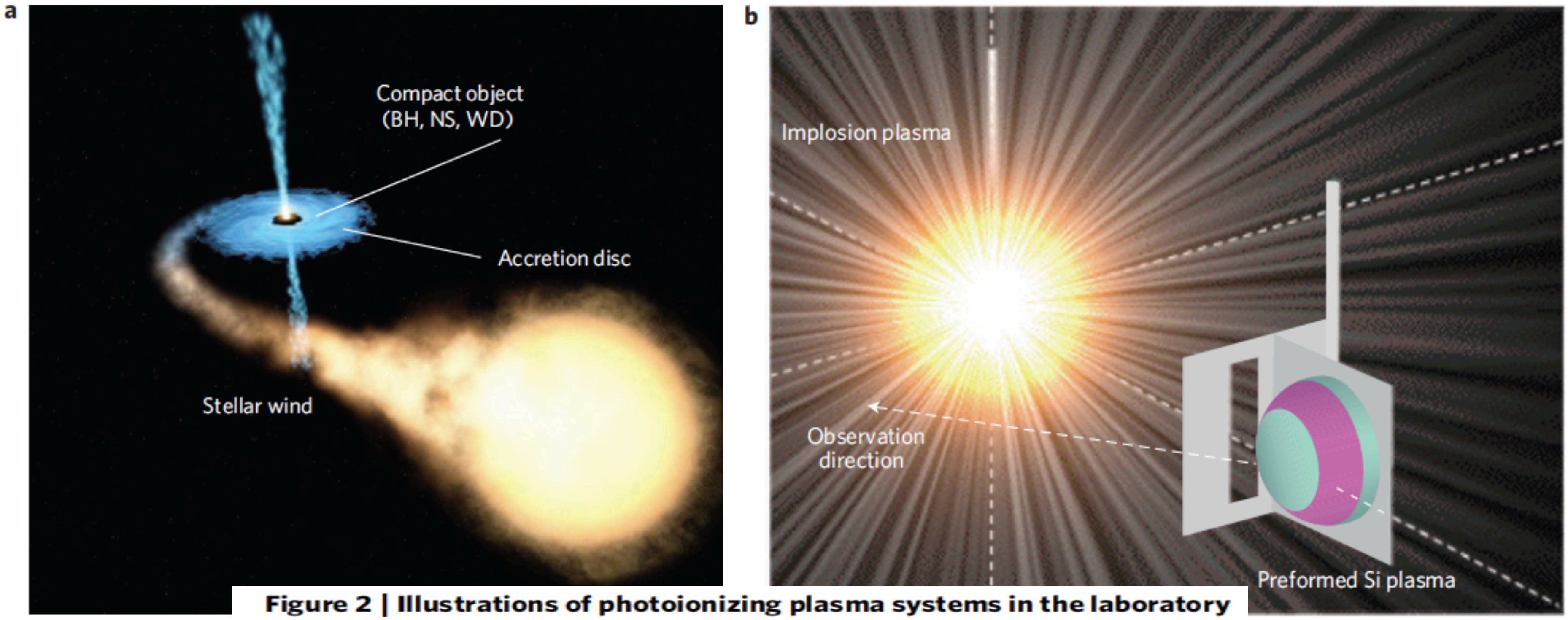


Figure 2 | Illustrations of photoionizing plasma systems in the laboratory experiment and astronomy. a, A schematic diagram of a binary system consisting of a black hole and a companion star. Ambient gases are photoionized by strong radiation emitted from the accretion disc. (These images were created for the European Space Agency by the Hubble European Space Agency Information Centre and for NASA by STScI under Contract NAS5-26555.) BH: black hole, WD: white dwarf, NS: neutron star. **b**, Schematic view of the photoionized plasma experiment. A spherical hollow plastic shell is imploded with 12 laser beams from the GEKKO-XII facility. The resulting core plasma simulates X-rays from a compact object, a Planckian X-ray radiator with a radiation temperature of 480 ± 20 eV. Silicon plasma with a 30 eV temperature was produced in the vicinity of the Planckian radiator. The angle between the line of sight of the X-ray spectrometer and the target normal is 25°.

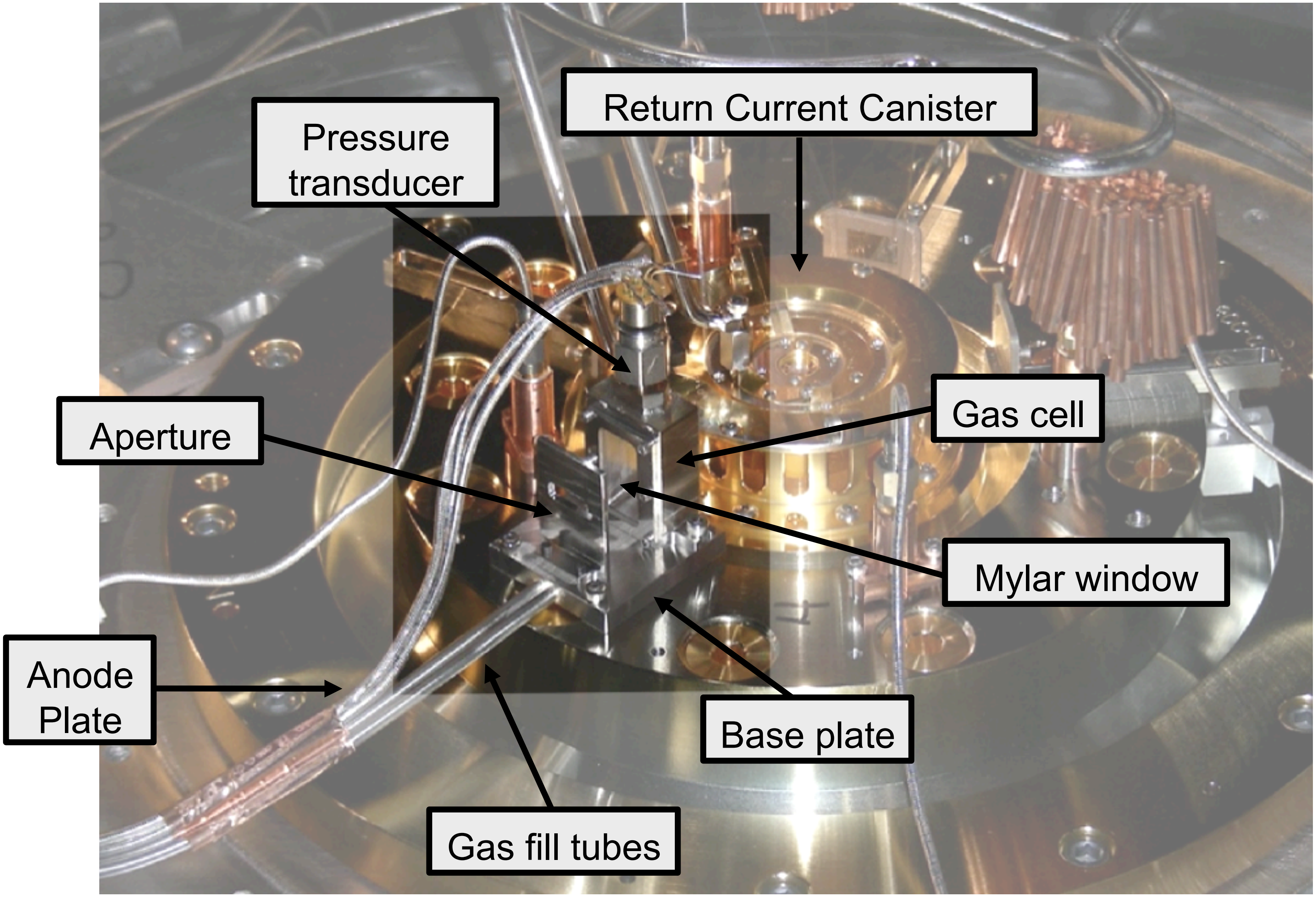
Gas cell driven by z-pinch radiation[1-5]

- Ongoing project: photoionized neon plasma experiment at Z, z-pinch x-ray flux drives a gas cell
- X-ray drive both produces and backlights the plasma
- Analysis of transmission spectrum is used to diagnose the plasma
- Gas cell located at several distances from the z-pinch: different x-ray drives
- Different filling pressures: different plasma densities
- Filling pressure measurement yields total atom number density
- Charge distribution extracted with a method independent of atomic kinetics calculations
- Electron temperature estimated from a Li-like ion population ratio
- X-ray drive characterized with view-factor calculations that take into account set up geometry and power measurements
- No self-emission measurement yet

1. J. E. Bailey et al, JQSRT **71**, 157 (2001); 2. D. H. Cohen et al, RSI **74**, 1962 (2003); 3. I. M. Hall et al, ApSS **322**, 117 (2009);
4. I. M. Hall et al, RSI **81**, 10E324 (2010); 5. I. M. Hall et al, ApSS **336**, 189 (2011)

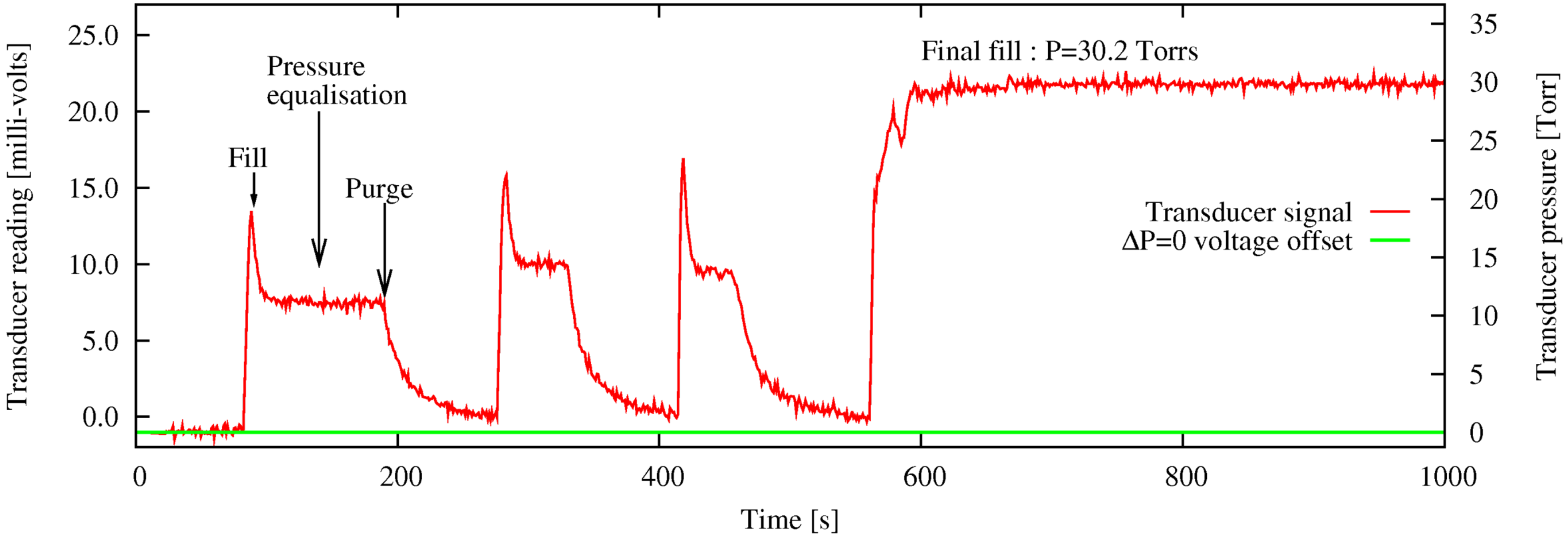
Experimental setup at Z

Experiments performed for filling pressures of neon in the range: 3.5 - 30 Torrs



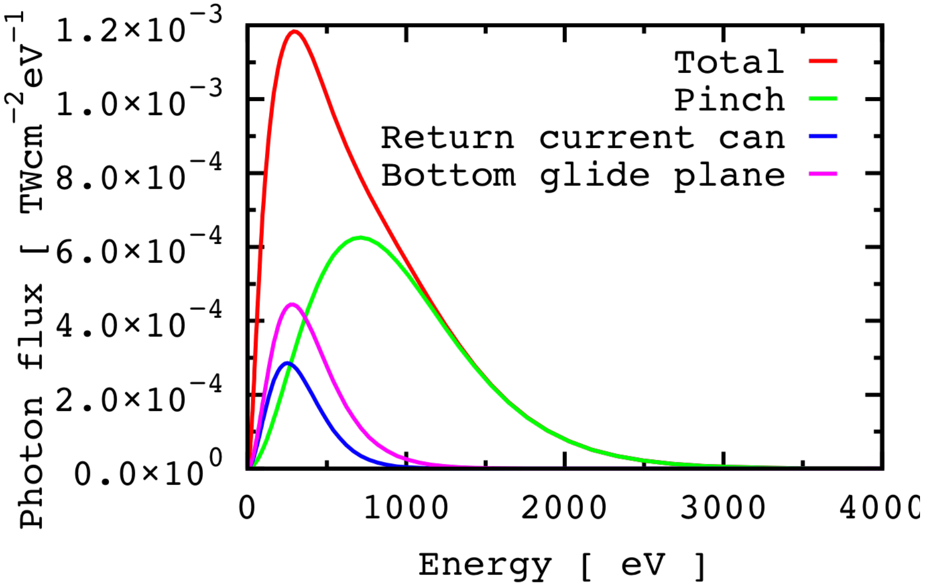
Filling pressure measurement

- Gas fill pressure is carefully monitored *in situ* all the way to shot time using a gas cell mounted pressure transducer
- This provides a measurement of the gas particle number density
- Experiments have been done with gas fill pressures of 30, 15, 7.5 and 3.5 Torrs., which correspond to atom number densities of 10^{18} , $5\text{x}10^{17}$, $2.5\text{x}10^{17}$ and $1.2\text{x}10^{17}\text{cm}^{-3}$



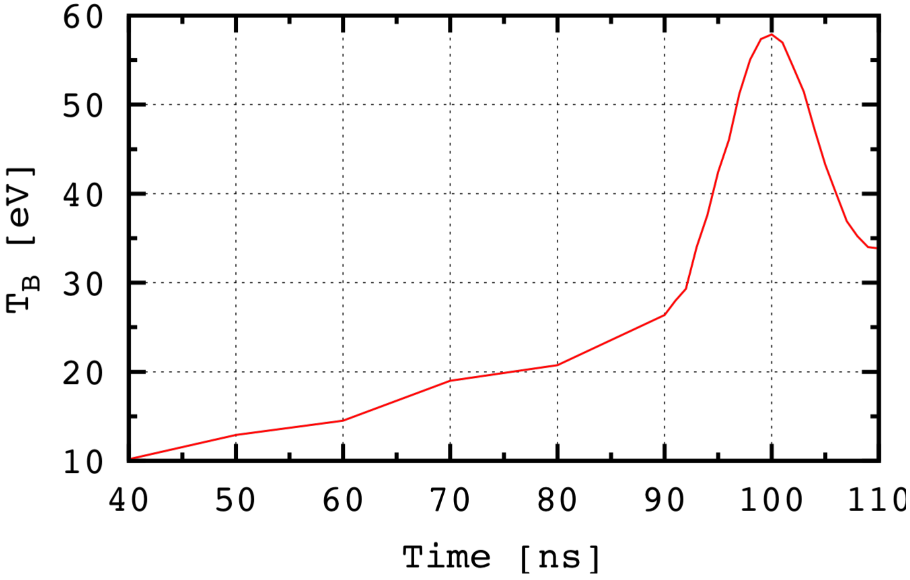
X-ray drive model calculations

Breakdown of contributions at peak of X-ray drive



$$x_{Max} = \frac{h\nu_{Max}}{kT_C}$$

Geometry dilution effect results in $T_B < T_C$

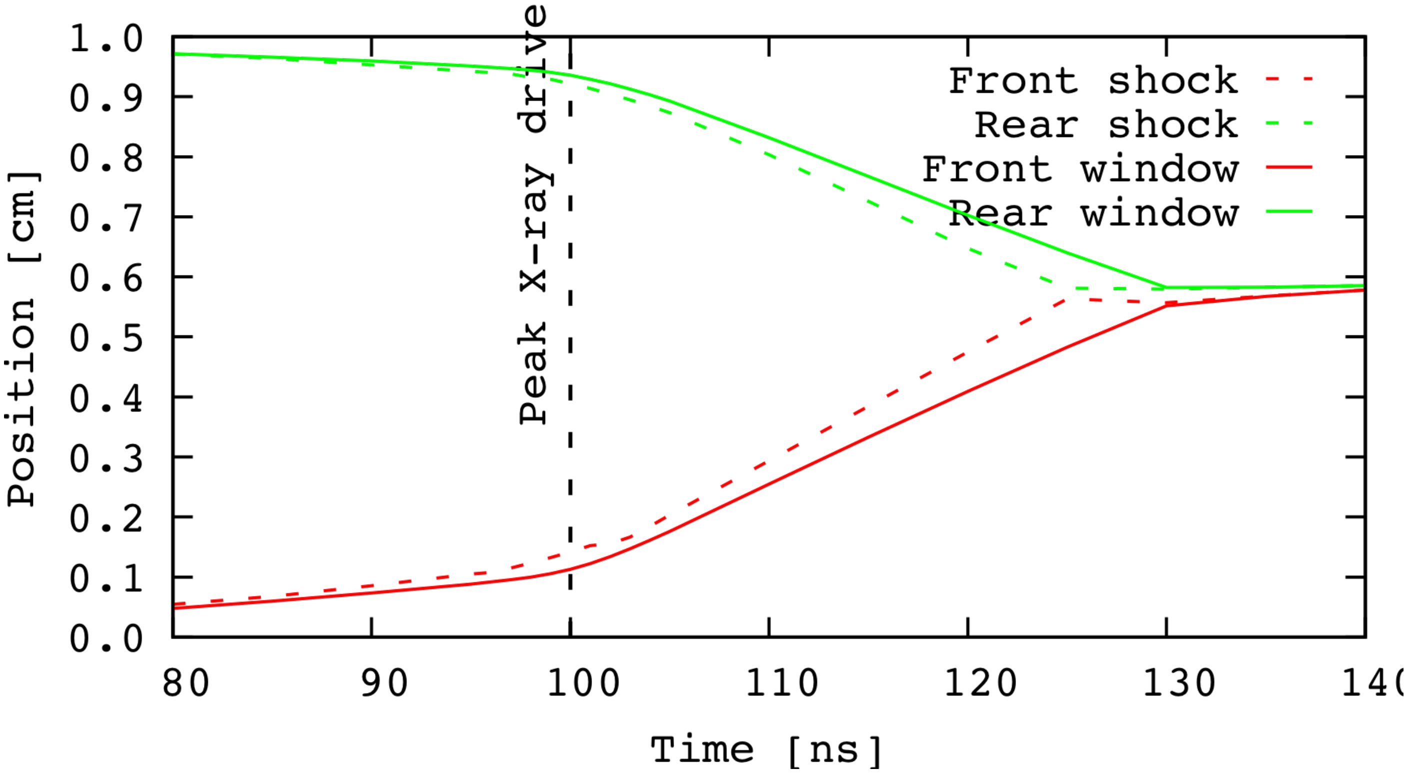


$$F = \sigma T_B{}^4$$

- X-ray drive characterization is now being improved by G. Loisel using x-ray power measurements as well as gated, x-ray narrow-band images of the z-pinch

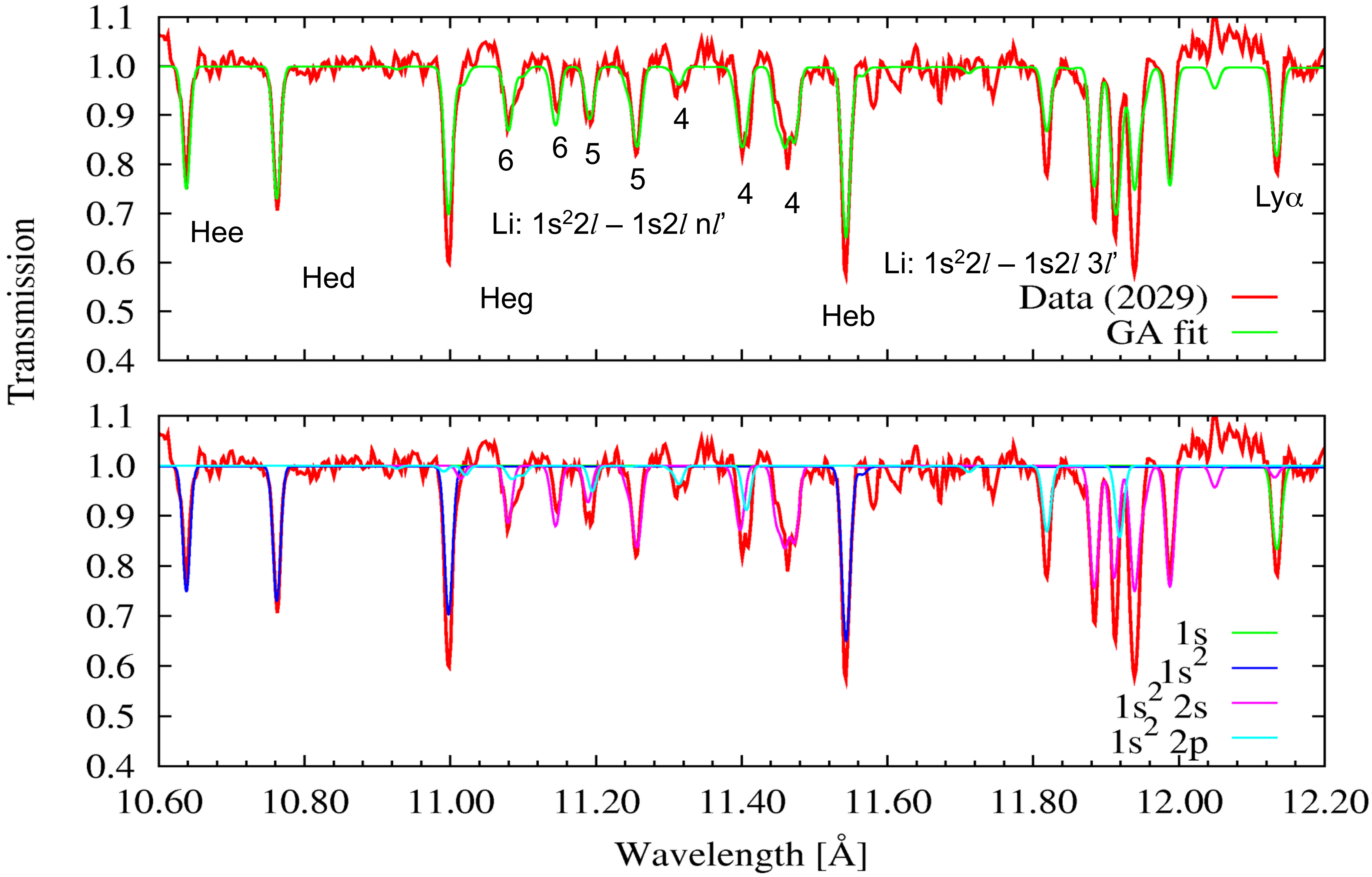
Radiation-hydrodynamic simulation

Most of the neon gas is hydrodynamically unperturbed at peak of x-ray drive



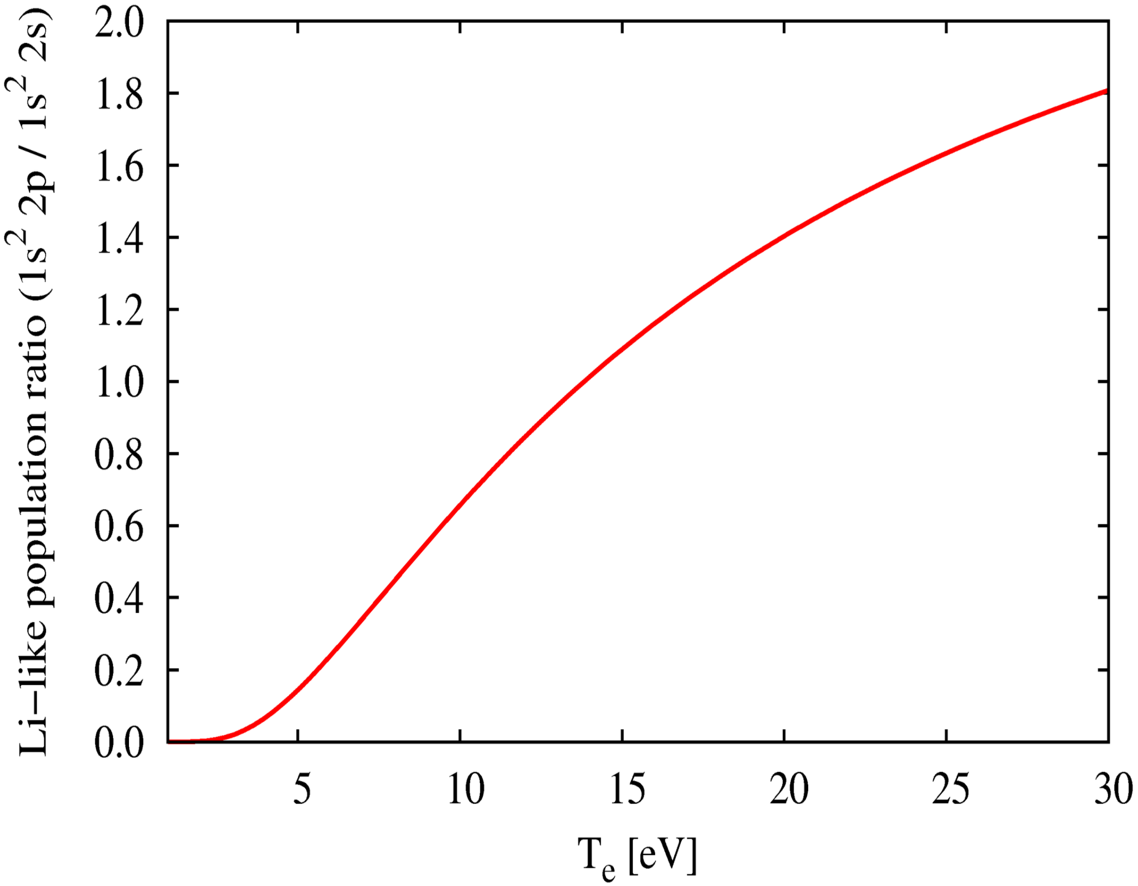
Short wavelength range transmission

Total transmission fit and contribution breakdown



Li-like neon population ratio $1s^2\,2p/1s^2\,2s$ is very close to LTE

This ratio can be used to determine T_e



$$R = g e^{-\frac{\Delta E}{kT_e}}$$

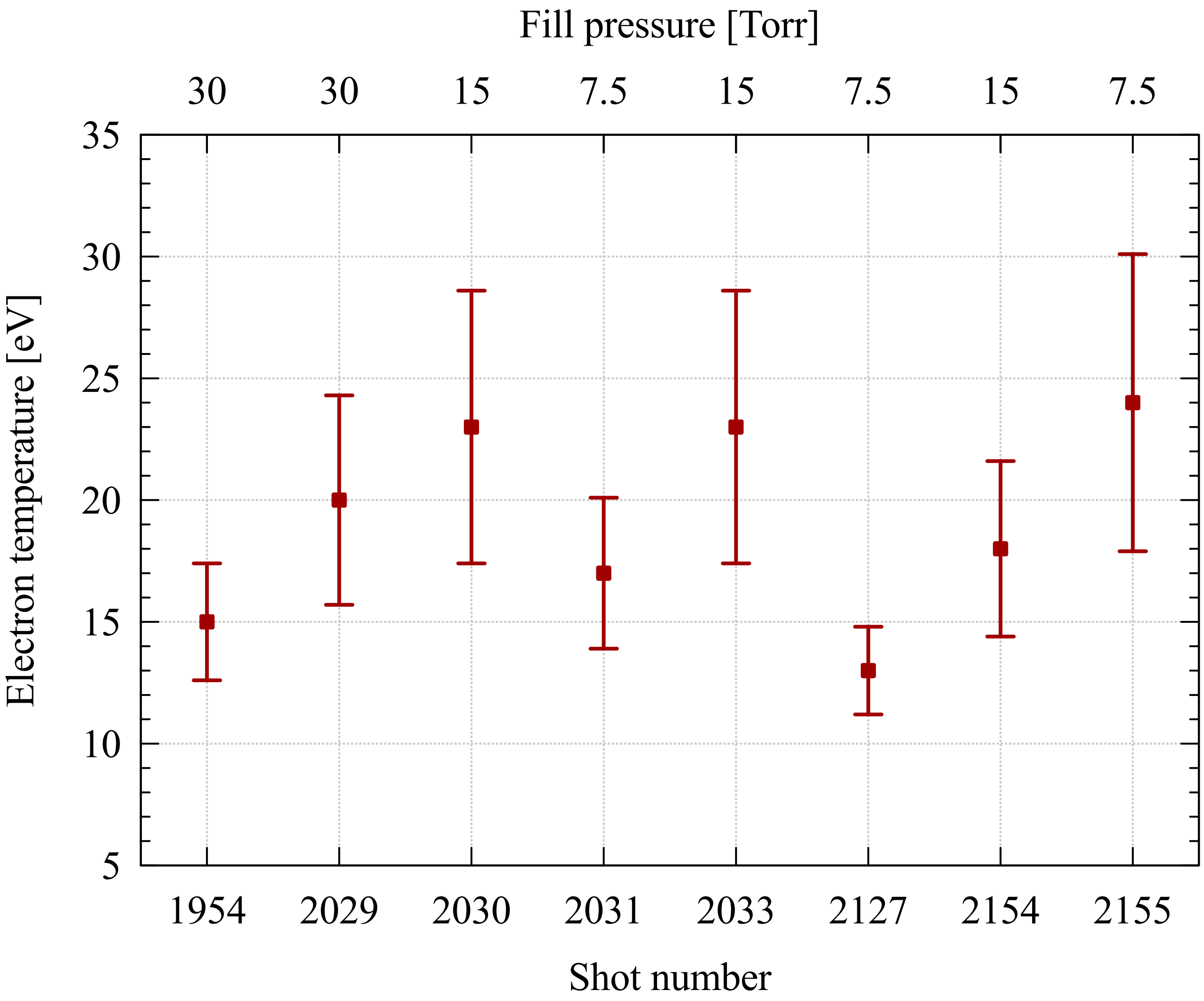
$$g = 3$$

$$\Delta E = 16 eV$$

$$\frac{\delta T_e}{T_e} = \left(\frac{kT_e}{\Delta E}\right)\frac{\delta R}{R}$$

Te from Li-like neon population ratio, d=4.7cm

Trend is qualitatively similar to code result but quantitatively different



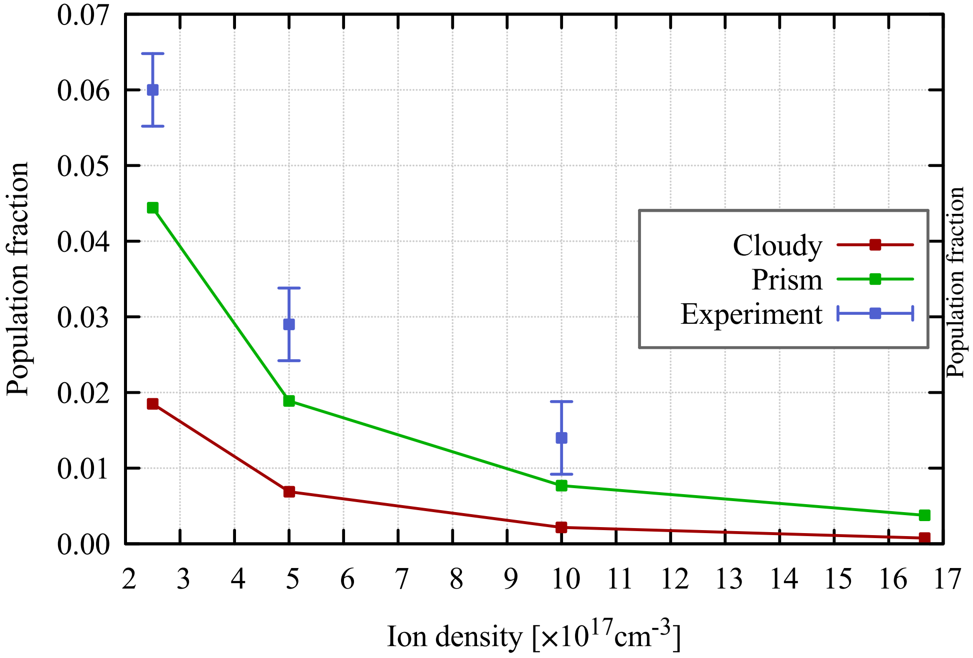
P (Torrs)	<Te> (eV)
30	18+/-3
15	21+/-3
7.5	18+/-4

$\langle Te\rangle_{\text{all Pressures}}$=19+/-2eV

Populations show similar trends but different values

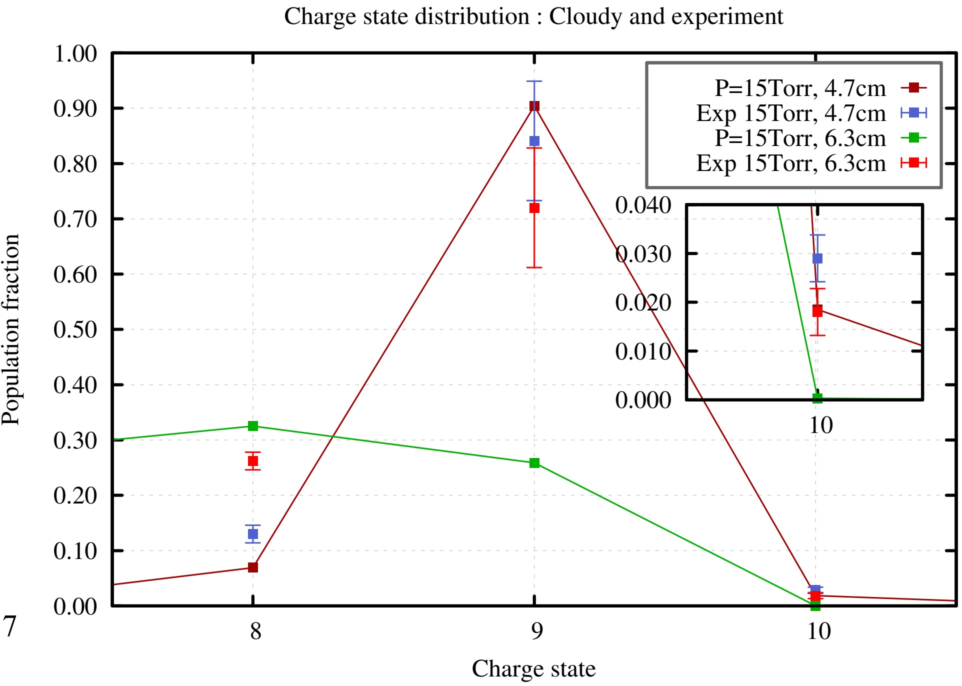
Different filling pressures, same x-ray drive

Data from (z1954, z2029), (z2030, z2033, z2154), and (z2031, z2127, z2155)



Different x-ray drives, same filling pressure

Data from (z2030, z2033, z2154), and (z2129)



Summary and future opportunities

- During the last decade a variety of photoionized plasma experiments have been performed using high-power laser and pulsed-power facilities
- Experiments so far have not met all requirements of the “single-point” photoionized plasma equilibrium
- They have produced for the first time though relevant datasets to test atomic kinetics codes in photoionized plasmas
- And, they are beginning to address specific issues such as RAD
- Recent gas cell experiments at Z have produced ξ of up to 100 erg cm / s

- A top gas cell design for Z could achieve ξ of 500 erg cm / s
- Future opportunities at the National Ignition Facility can potentially produce x-ray drives long enough to achieve photoionization equilibrium with ξ of order 1000 erg cm / s
- Yet, new ideas on how to produce and study photoionized plasmas are being proposed, next talk by E. Hill

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