Experiments and Modeling of Photoionized Plasmas at Z

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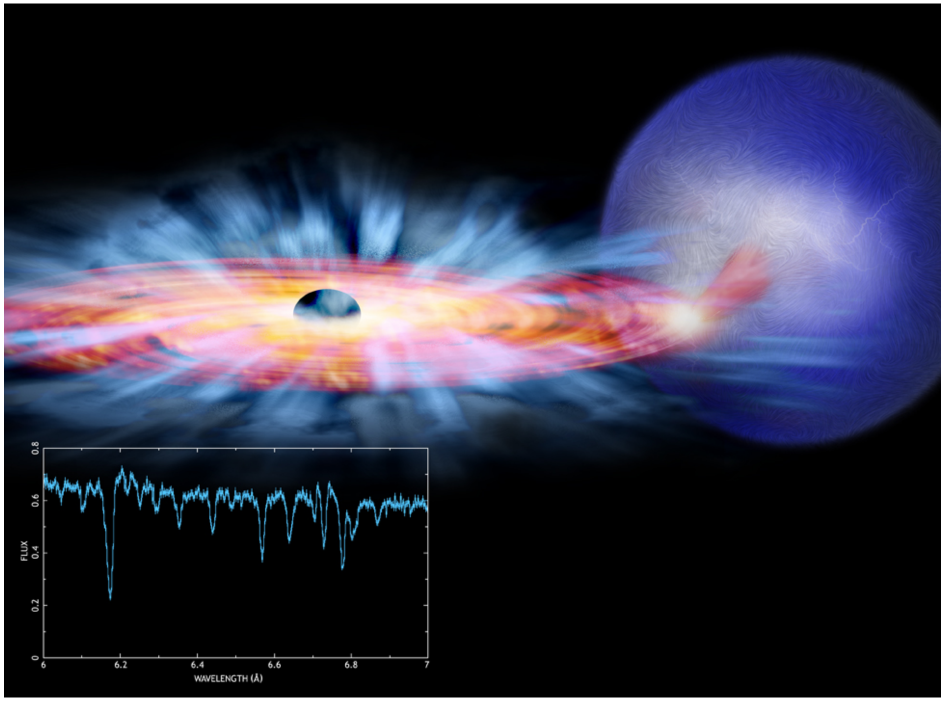
Astrophysical Photoionised Plasmas

Widespread in space – active galactic nuclei, accretion discs around black holes.
Gas is photoionised by an intense source of X-rays; unlike collisional plasmas, photo-ionisation and excitation dominate the atomic kinetic behaviour.

The complexity of the astrophysical environment makes the spectral analysis challenging.

Basic Science at Z

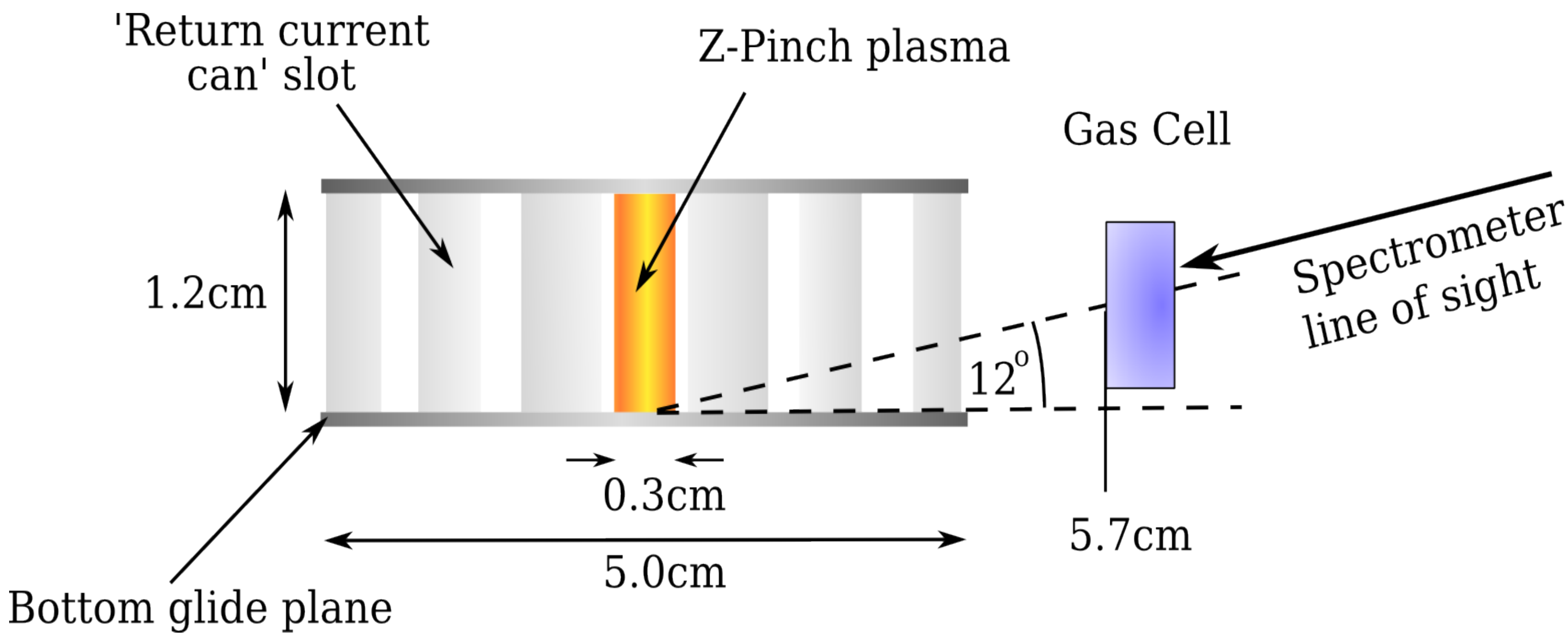
We can do high-energy density laboratory astrophysics while cutting into a new and relatively unexplored laboratory plasma regime.[1]



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

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

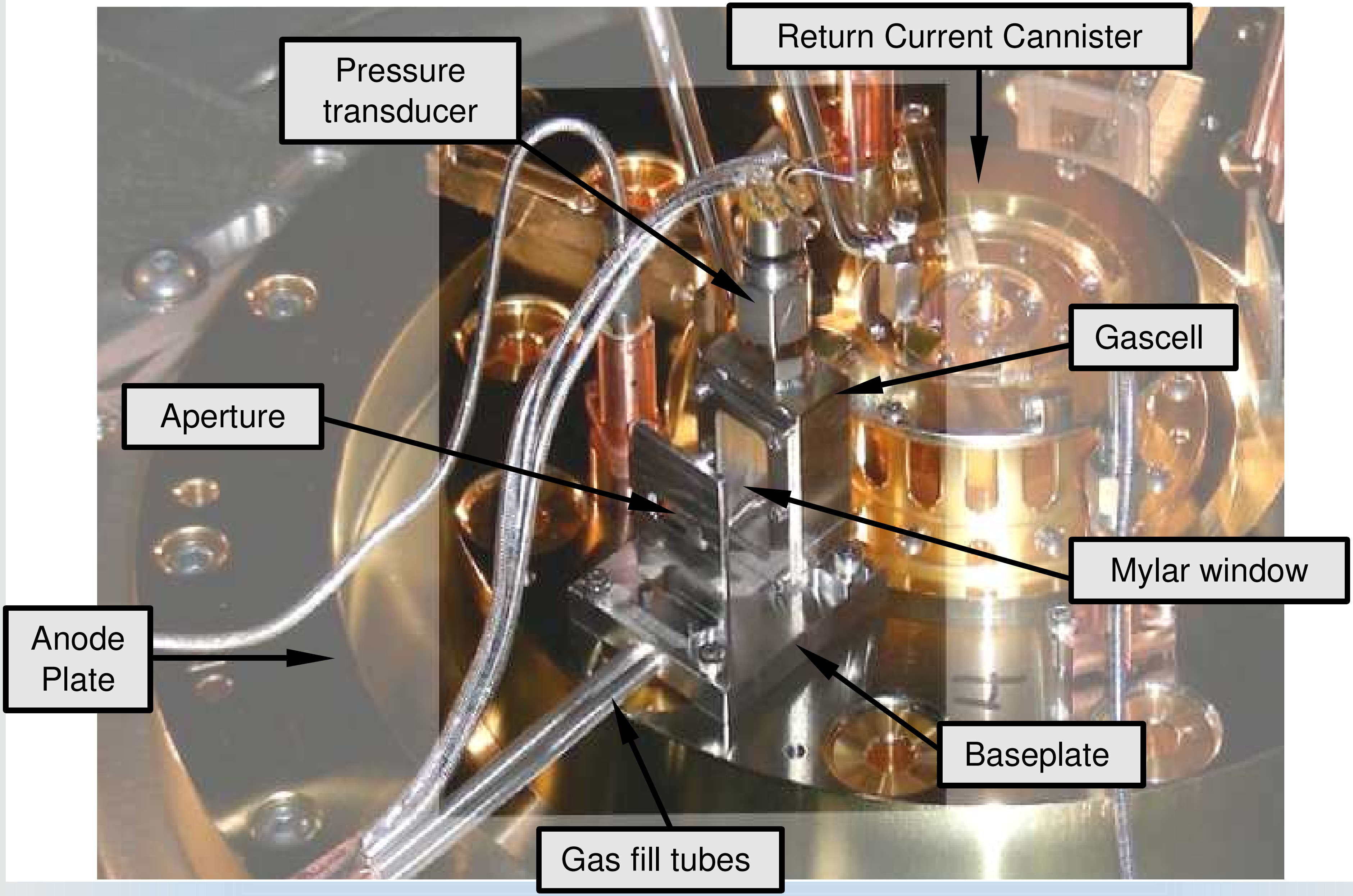
Experimental setup: schematic figure[1]



- Z pinch parameters : ~22-25MA load current,
  ~160TW total X-ray power with ~Planckian energy distribution
  Color temperature ~200eV.
- X-rays from collapsing Z-pinch photoionise **Neon** contained in gascell
- Re-radiated X-ray emission contributes to total flux at gascell.
- Would like to maximise X-ray flux at gas cell→ high ionisation parameter

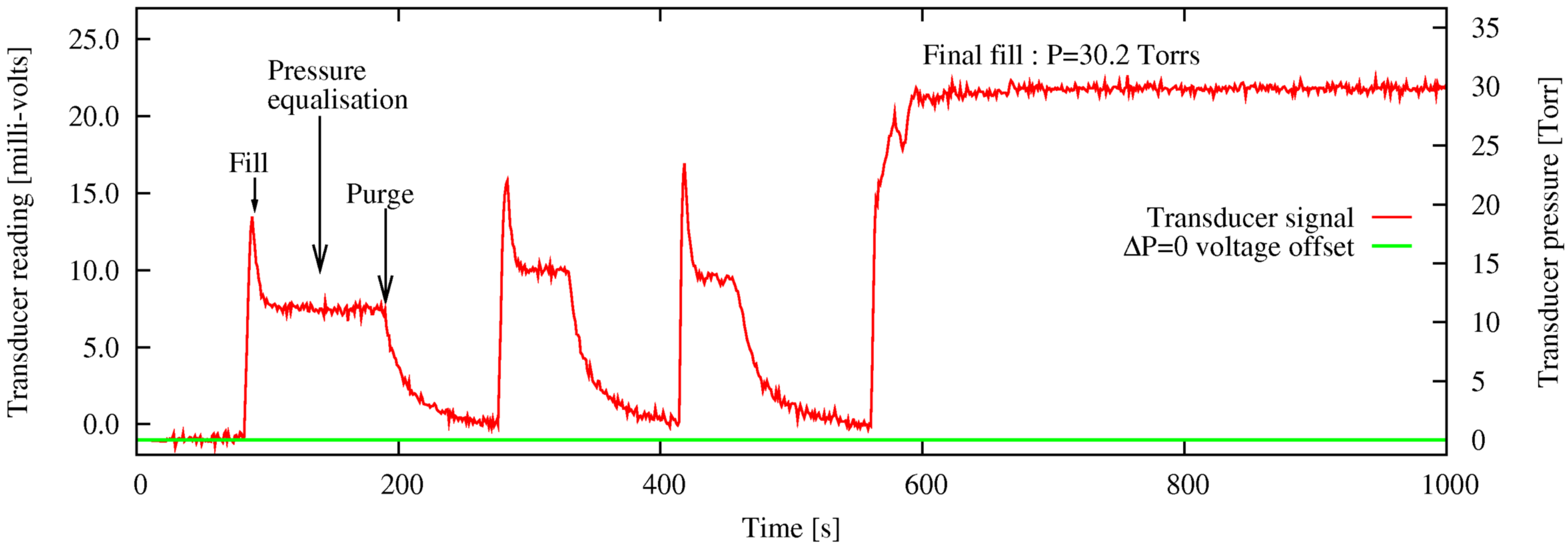
1. I. M. Hall et al., *Astrophysics and Space Science* **322**, 117 (2009)

Experimental setup: gascell details



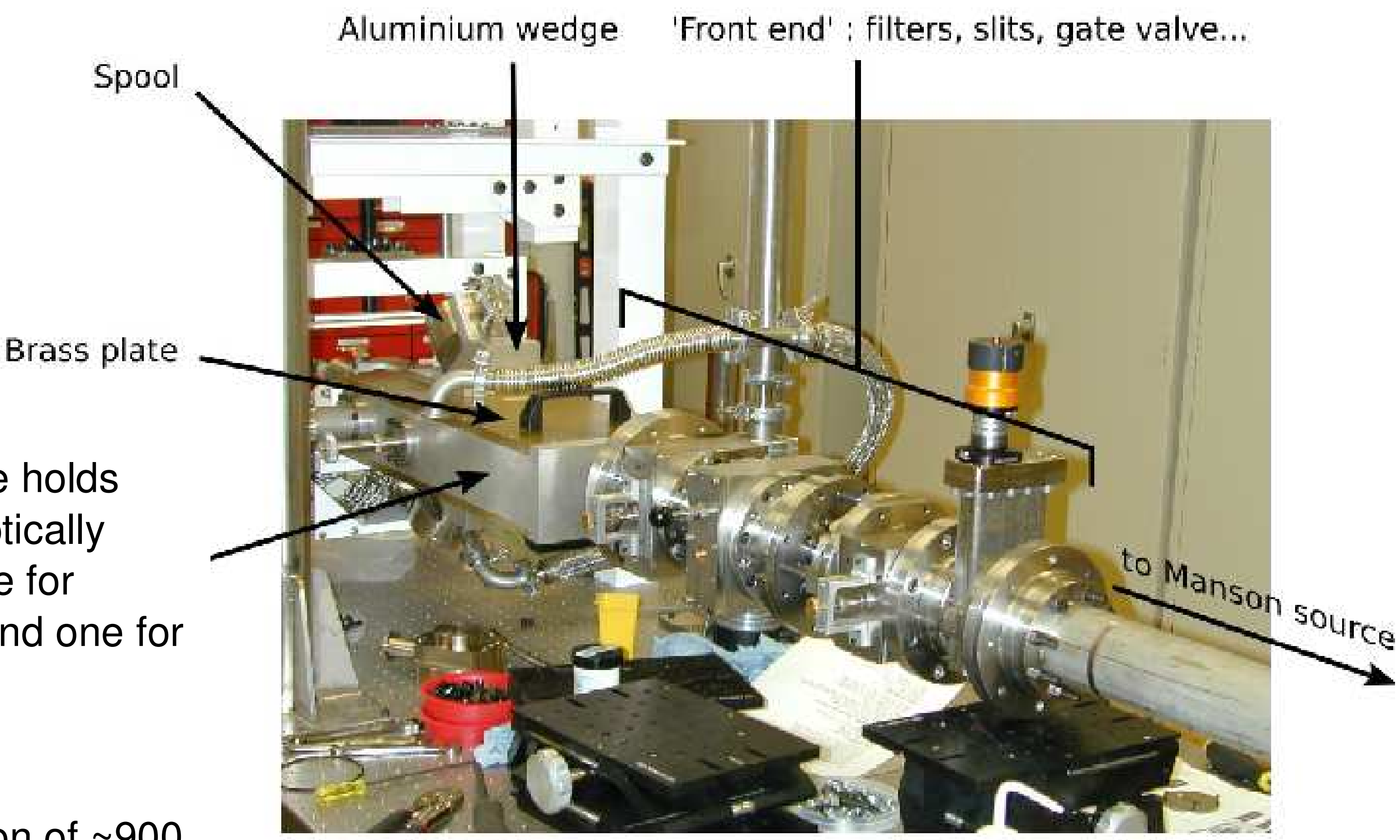
Experimental setup: pressure measurement

- Gas fill pressure is carefully monitored *in situ* all the way to shot time using a gascell 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 Torrs., which correspond to atom number densities of 10^{18} , $5x10^{17}$, $2.5x10^{17}$ cm^{-3}.



Time-integrated and gated spectra recorded with TREX[1,2]

Two sets of brass plates, aluminum wedges and steel spools were fabricated at the UNR Physics machine shop for customised KAP crystals.



Crystal enclosure holds two identical elliptically bent crystals: one for time integrated and one for time resolved measurements

Spectral resolution of ~900

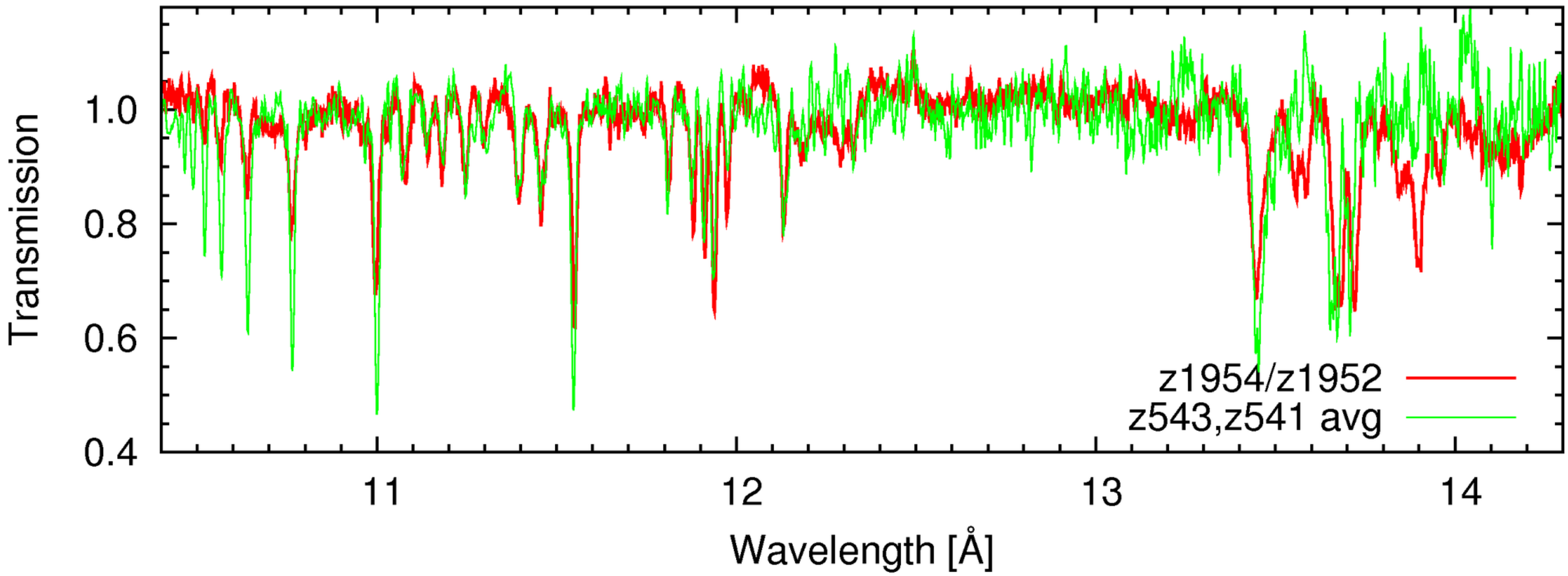
1. P.W. Lake, J.E. Bailey et al, RSI, **75**, 3690 (2004);
2. P.W. Lake, J.E. Bailey et al, RSI. **77**, 10F315 (2006)

Some of the “knobs” in the experiment are:

- Different type of gases
- Ionization parameter ξ is proportional to x-ray flux / density
- Changing the filling pressure makes the plasma more (or less) collisional which, in turn, changes the ionization parameter
- Moving the gas cell out reduces the x-ray flux which, in turn, also changes the ionization parameter
- Moving the gas cell out and changing the filling pressure simultaneously permits the study of photoionized plasmas of the same ionization parameter but different densities
- Including front apertures mitigates the re-radiation effect of Z hardware components

Experimental Transmission

Averaged transmission spectra from pilot experiments in 2001[1] and current results[2]



Spectra from the two experiments show similar spectral features.
Photoionised plasma experiment capability has been re-established and improved.

We analyse the transmission data in detail to :

- Identify spectral features
- Extract ion density and charge state distribution of the plasma

1. J. E. Bailey et al., JQSRT **71**,157 (2001)

2. I. M. Hall et al, RSI (2010)

Charge State Analysis : Method[1]

Absorption spectra has contributions from four different ionisation stages of Neon : H, He, Li and Be-like.

1. For each ion stage, compute *total cross section* σ_ν for fine structure transitions from the low lying energy level(s) :

$$\sigma_\upsilon^i = \frac{\pi e^2}{mc} \sum_{j>i} f_{ij} \phi_{ij}$$

2. For each ion compute the absorption coefficent κ_ν :

$$\kappa_\nu^{ion} = \sum_i N_i^{ion} \sigma_\nu^i$$

3. Sum together contributions due to all ions :

$$\kappa_\nu^{total} = \sum_{ion} \kappa_\nu^{ion}$$

4. Compute the total optical depth τ_ν and transmission T_ν :

$$\tau_\nu^{total} = L \kappa_\nu^{total}$$

$$T_\nu = \exp(-\tau_\nu^{total})$$

Use a ***Genetic Algorithm*** to drive the search for population number densities N_i^{ion} that produce the best fit to the experimental data.

1. I. M. Hall et al, in preparation for publication

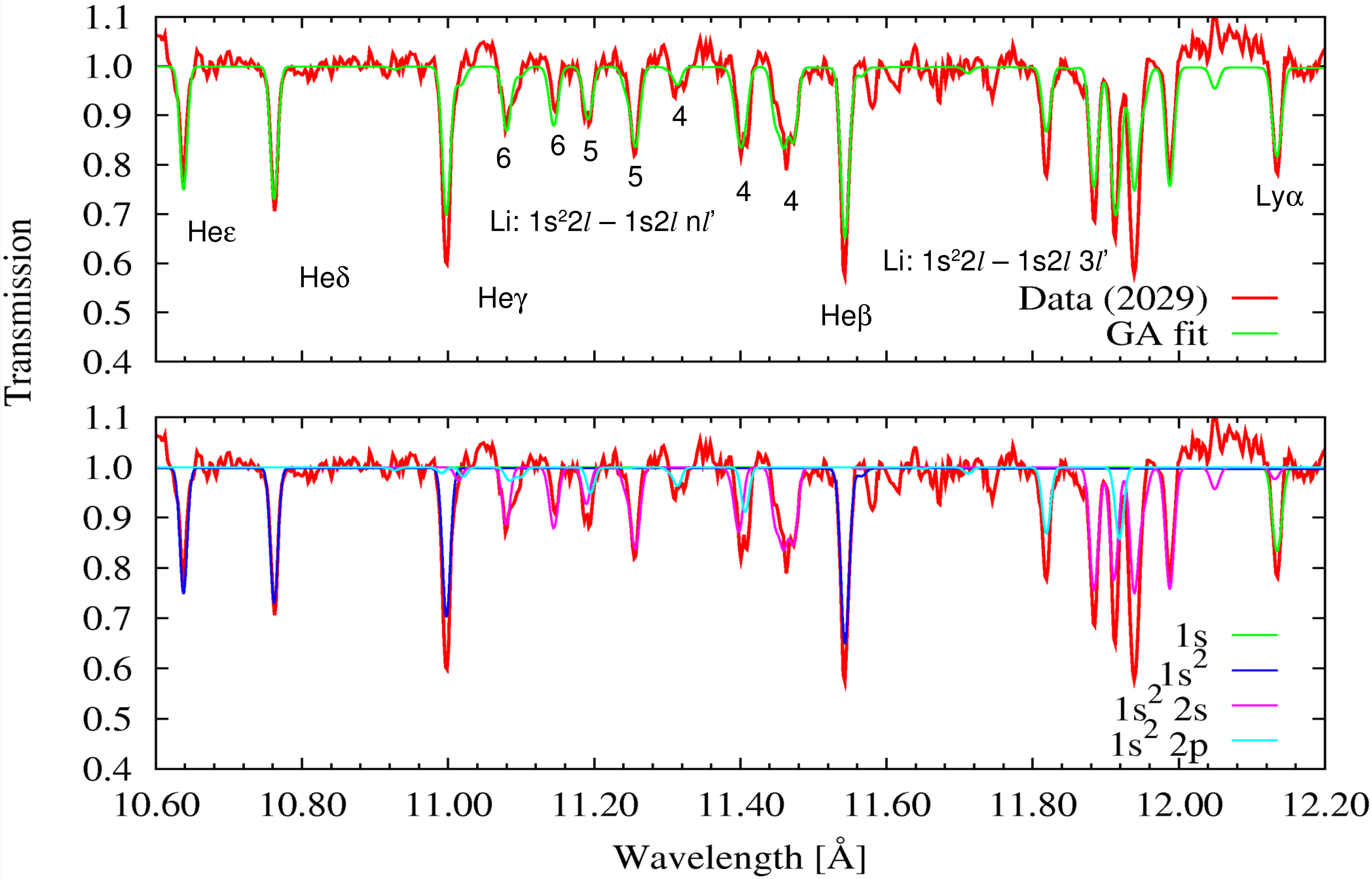
Charge State Analysis: Line transitions

- Absorption line transitions are observed in 4 charge states of Neon from H to Be-like.
- Transitions from low lying energy levels in each charge state are included in the photo-excitation cross section.

H-like	1s	→	2p	**2**	Lyα line
He-like	$1s^2$	→	1s np	**18**	Heα, β, γ... lines (up to n=10)
Li-like	$1s^2$ 2s $1s^2$ 2p	→	1s 2s nl 1s 2p nl	**1285**	Satellites to Heα, Heβ, Heγ … (up to n=7)
Be-like	$1s^2$ $2s^2$ $1s^2$ 2s2p $1s^2$ $2p^2$	→	1s $2s^2$ 2p 1s $2s2p^2$ 1s $2p^3$	**93**	Satellites to Li-like transitions

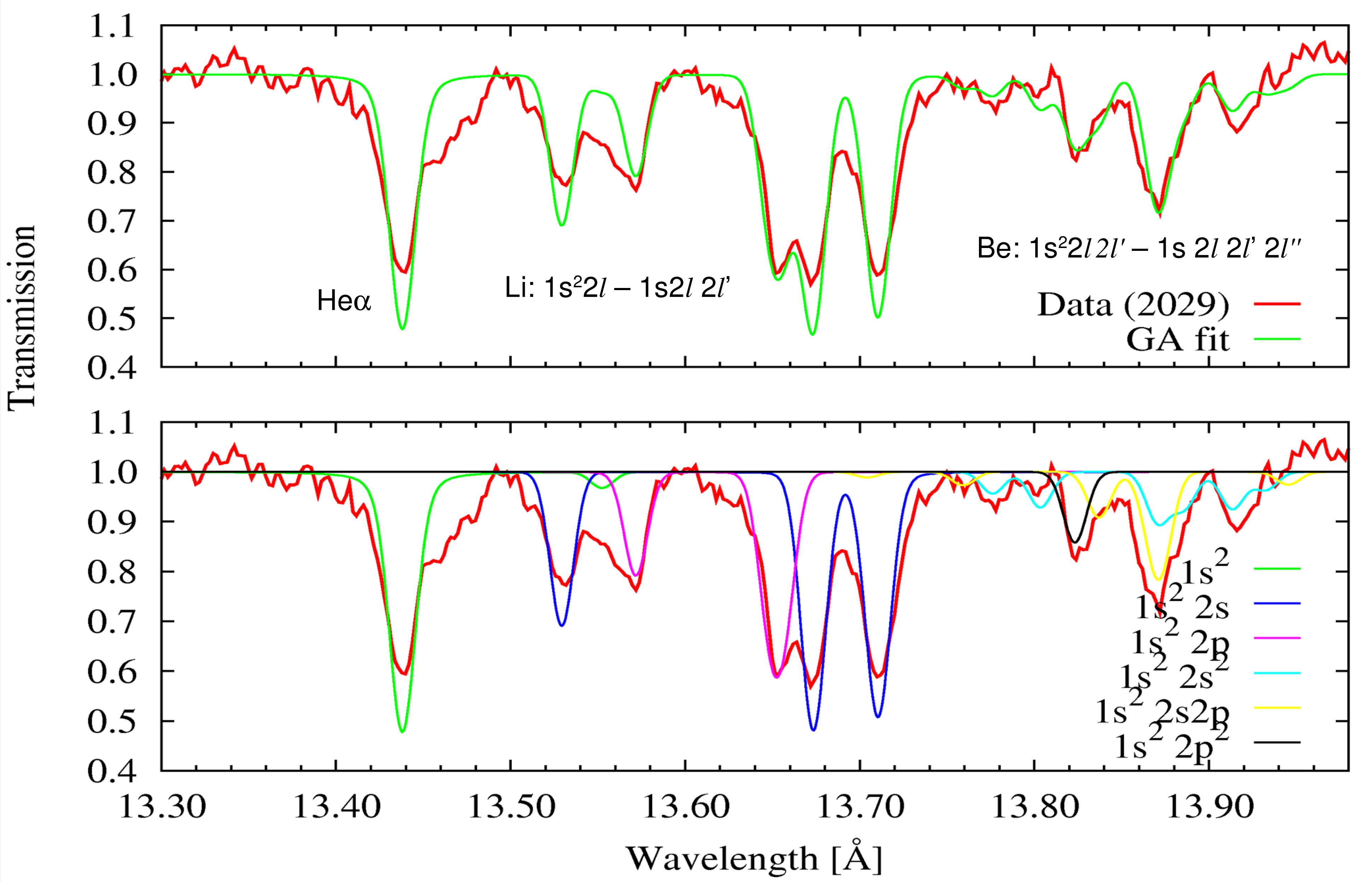
Experimental transmission analysis

total transmission fit and contribution breakdown



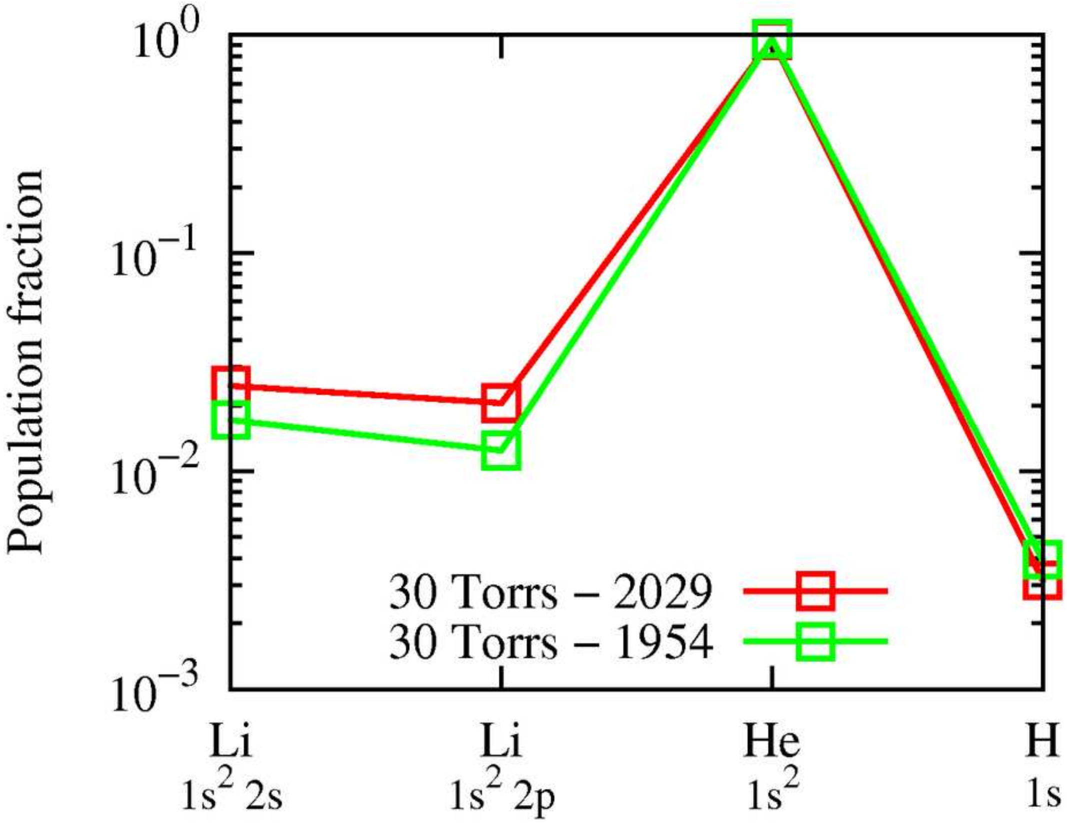
Experimental transmission analysis

total transmission fit and contribution breakdown



Charge State Analysis : Results

Population fractions from charge state analyis



- An effort has been made to establish reliable platform for photoionisation experiments
- Good reproducibility between two series of shots: z1954 (July2009), z2029 (December 2009)
- Dominant He-like population fraction: ~0.95.

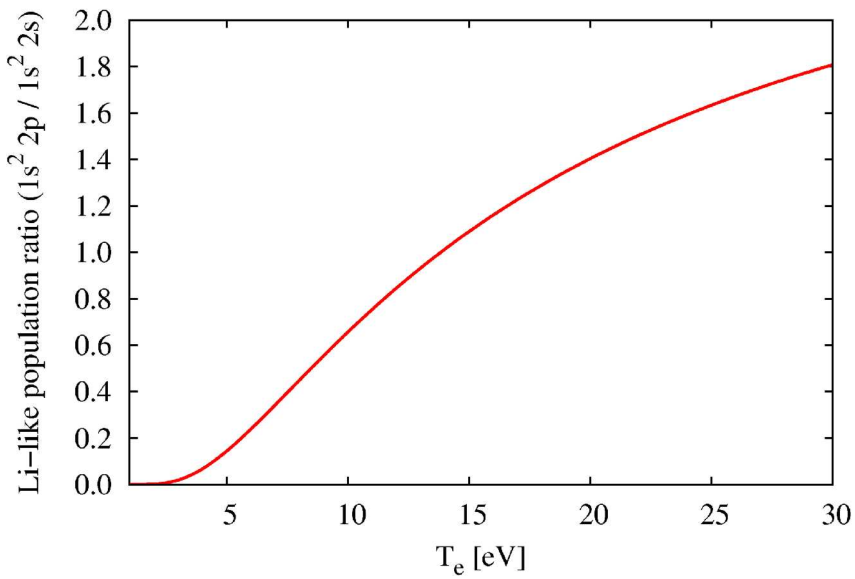
Electron temperature estimation

The GA driven charge state analysis yields populations of the Li-like neon $1s^2\ 2s$ and $1s^2\ 2p$ energy levels.

For the plasma densities of our experiments the relative population of these two energy levels is dominated by electron collisional excitation and de-excitation.

Population ratio can be interpreted in terms of a Boltzmann factor, which in turn yields the temperature :

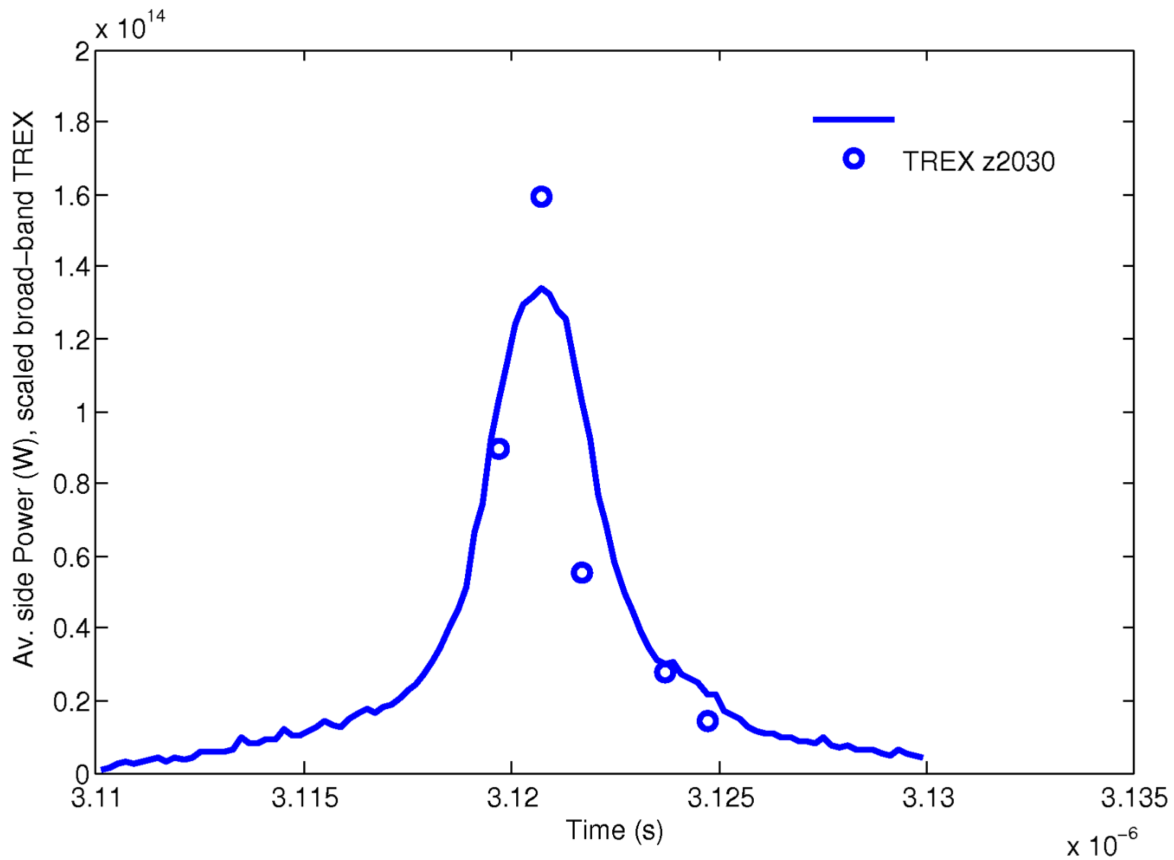
$$k_B T_e = \frac{-\Delta E}{\ln(N_2 g_1 / N_1 g_2)}$$



For our experiments we find temperatures in the **11eV** to **16eV** range.

For this temperature range, the observed charge state distribution is only possible if the plasma is photoionised.

TREX - XRD data time correlation

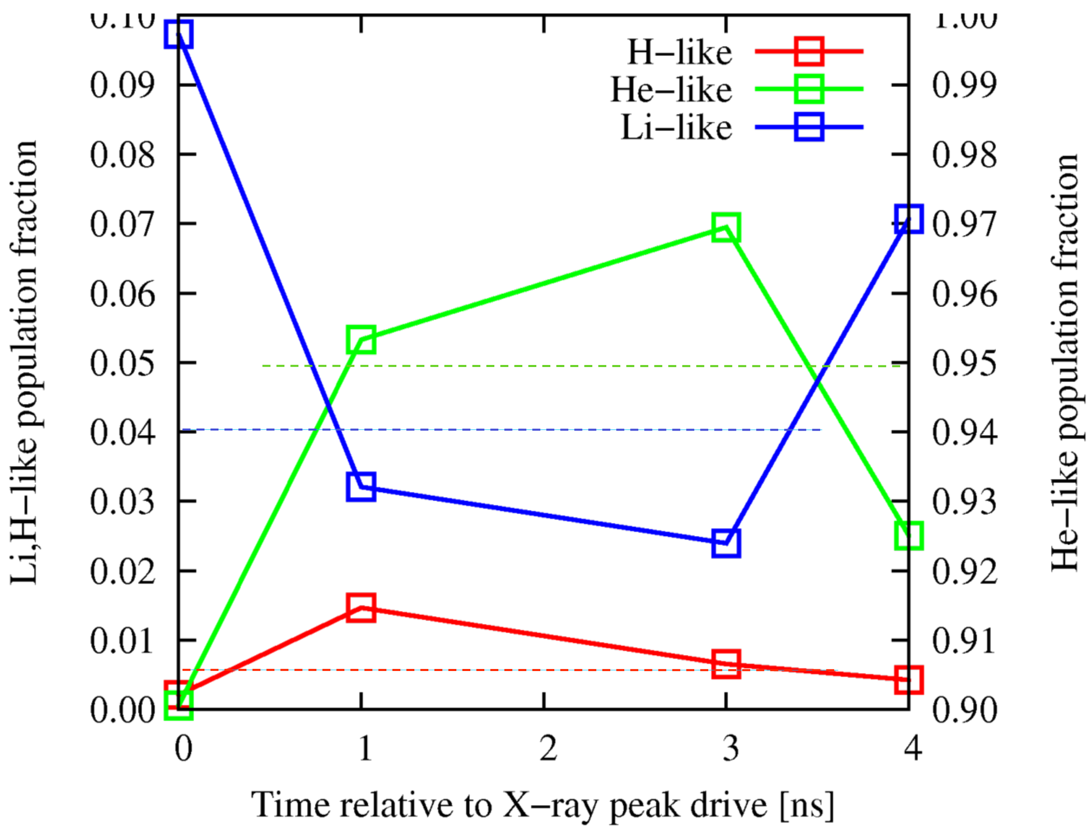


- Time history of side power recorded by XRD is used to place in time the TREX gated data relative to the X-ray drive
- This is accomplished via a time correlation analysis between the XRD and TREX signals

Analysis of gated data is just beginning...

time-dependent data provides a window into photoionised plasma dynamics

Time resolved population fractions for 15 Torr shot (2030)



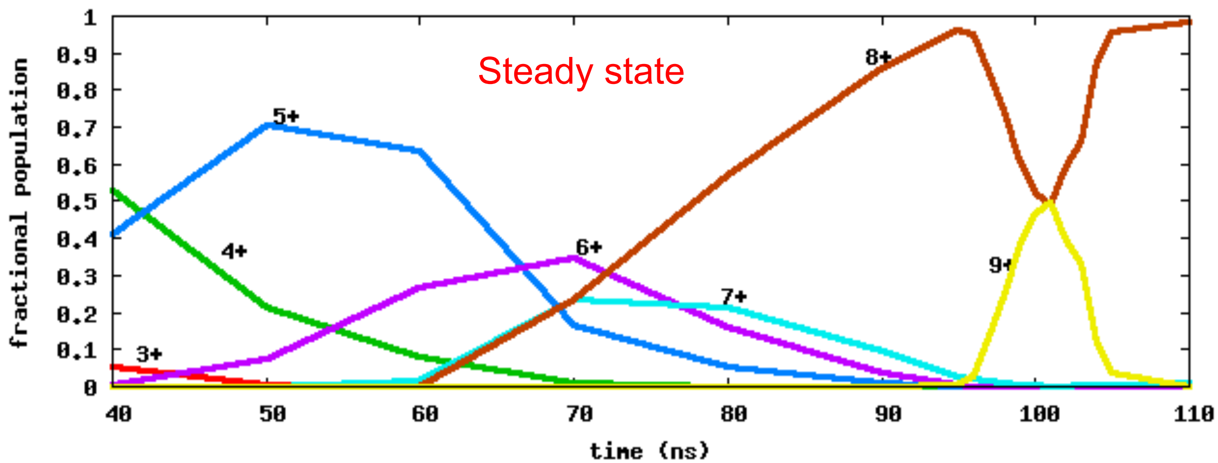
- H-like fraction peaks 1ns after X-ray drive peak; He-like fraction peaks 2ns later
- The increase in Li-like fractions late in time can be interpreted as the beginning of the plasma recombination.

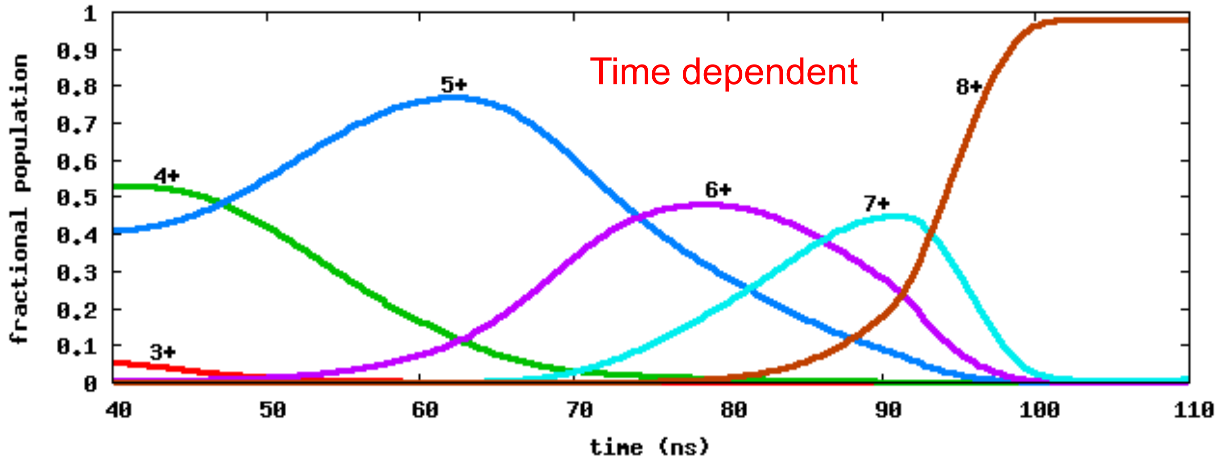
Is the plasma in steady state or not?

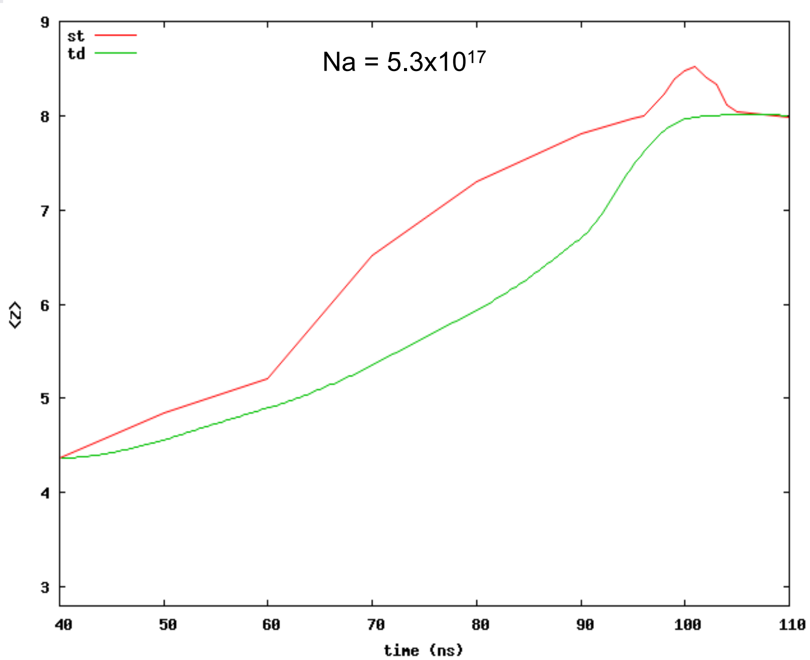
Modeling shows time-dependent effects

P=15Torrs, N_a=5.3x10^{17}cm^{-3}

Atomic kinetics calculations are driven by $T_B(t)$, $T_C(t)$ and $T_e(t)$ for a given N_a.







Summary

- We have established an experimental platform at Z to work on photoionised plasmas relevant to astrophysics while cutting into a new and relatively unexplored laboratory plasma regime.
- Experiments with ξ values in the range from 5 erg cms^{-1} to 20 erg cms^{-1}.
- Particle number density is extracted from pressure measurement.
- Charge state distribution from analysis of transmission spectra using atomic cross sections and novel application of genetic algorithms.
- Method to estimate electron temperature based on suitable population ratio
- We have recorded time-integrated and gated data, for several configurations.

- Work in progress:
  - estimation of uncertainties
  - further analysis of gated data $\longrightarrow$ electron heating in photoionized plasmas
  - better characterization of x-ray drive $\longrightarrow$ TGS measurement
  - electron temperature from Thompson scattering
  - KAP crystal problem sets limitations on the data analysis
  - photoionized plasma self-emission measurement
  - top gascell experiment design: $\xi \sim 500$ erg cms^{-1}.

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