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Interrogation of laboratory produced photoionized plasmas using interferometry on the Z -machine

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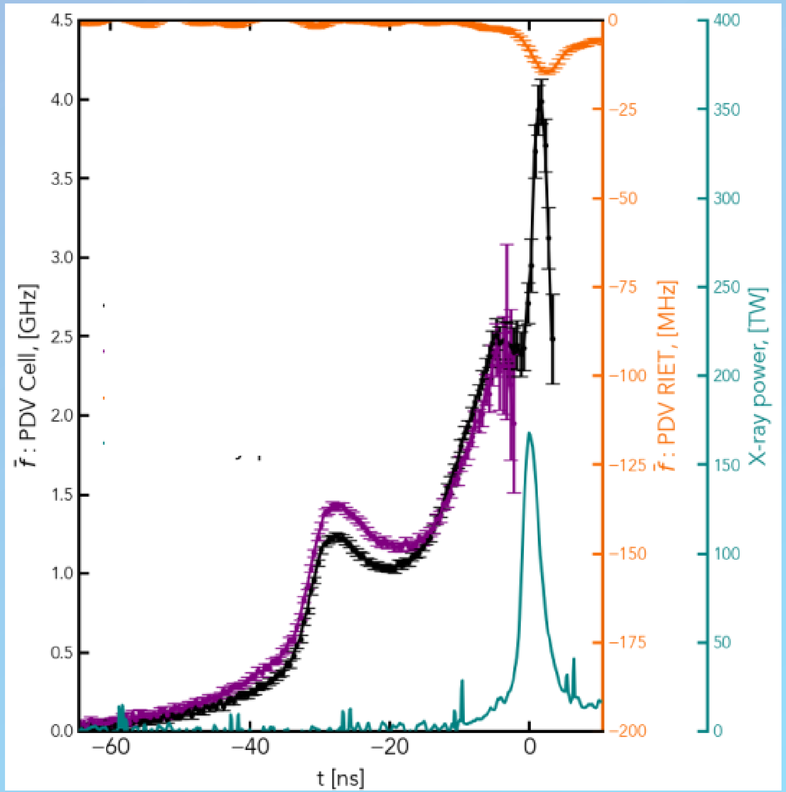
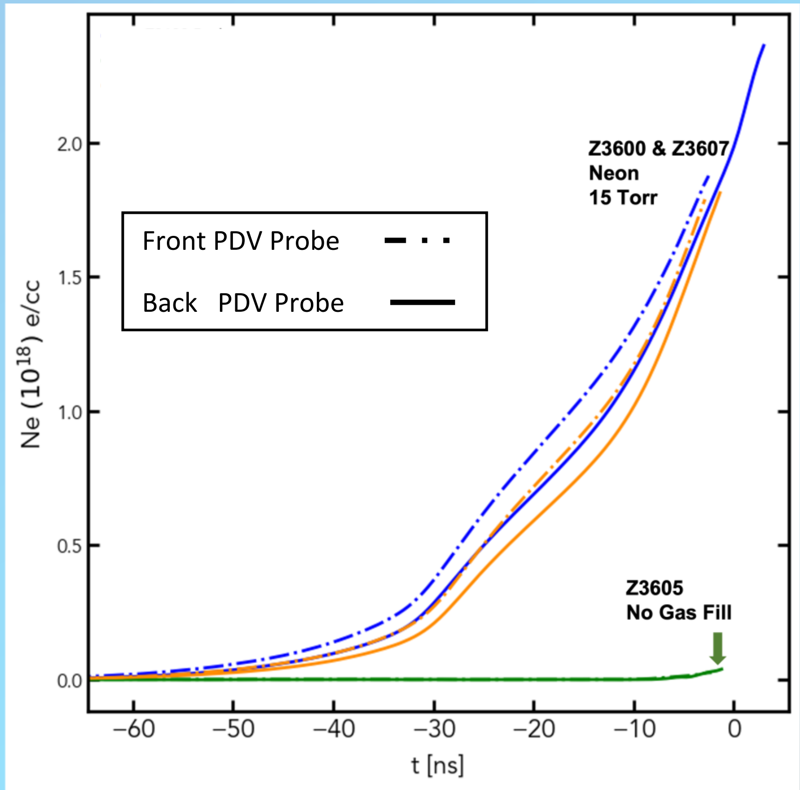
A new interferometric diagnostic in a photoionized plasma gas cell has enabled time resolved electron density measurements for the first time

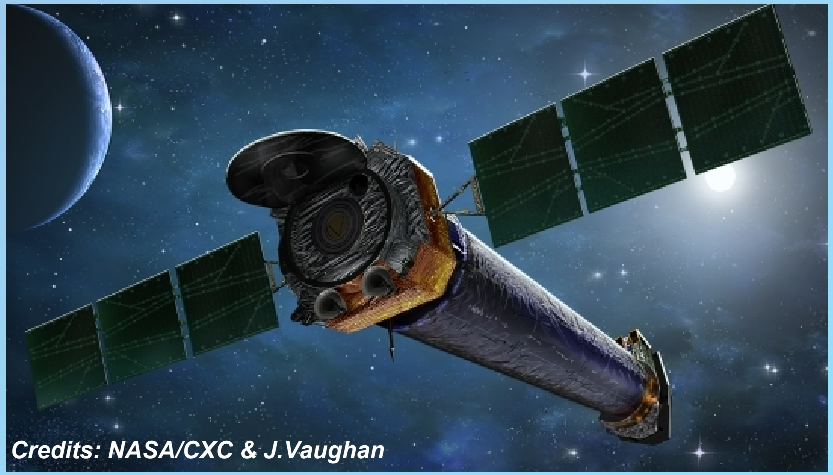
- First fielding of PDV at Z in an experiment driven by a strong x-ray flux close to the pinch
- PDV measurements allowed time resolved density measurements in the gas cell
- Dual PDV probes were used to assess plasma uniformity





We are using the Z-machine to investigate laboratory produced photoionized plasmas

- Photoionized plasmas are ubiquitous throughout space.
  - Ex: Active galactic nuclei, x-ray binary systems, and planetary nebulae



- Observations from orbiting telescopes Chandra and XMM Newton are analyzed with codes, e.g. Cloudy & XStar, developed mainly on a best-theory effort;
  - Testing these codes with laboratory photoionized plasmas is important.[1,2]
- Laboratory produced photoionized plasmas relevant to astrophysics require high intensity broadband x-ray flux.
- This requirement has usually relegated laboratory photoionized plasma work to large scale facilities developed for inertial confinement fusion experiments.[3-7]
- The photoionized gas cell platform on the Z-machine allows investigation of laboratory produced photoionized plasmas.

1) R. C. Mancini et al Phys. Plasmas **16**, 041001 (2009) 2**)** R. C. Mancini et al Phys. Rev. E 101, 051201 (2020) 3**)** M. E. Foord Phys. Rev. Letters **93**, 055002 (2004); 4**)** S. Fujioka et al Nature Physics **5**, 821 (2009); **5)** F. Wang et al, Phys. Plasmas **15**, 073108 (2008); 6**)** I. M. Hall et al, Phys. Plasmas **21**, 031203 (2014); 7**)** G. P. Loisel et al Phys. Rev. Letters **119**, 075001 (2017)

We can control ionization parameters by adjusting gas cell position and fill pressure

Ionization Parameter[1,2]

$$\xi = \frac{4\pi F}{N_e} \quad \left[\frac{erg \cdot cm}{s}\right]$$

A measure of the relative importance of photoionization and collisional ionization

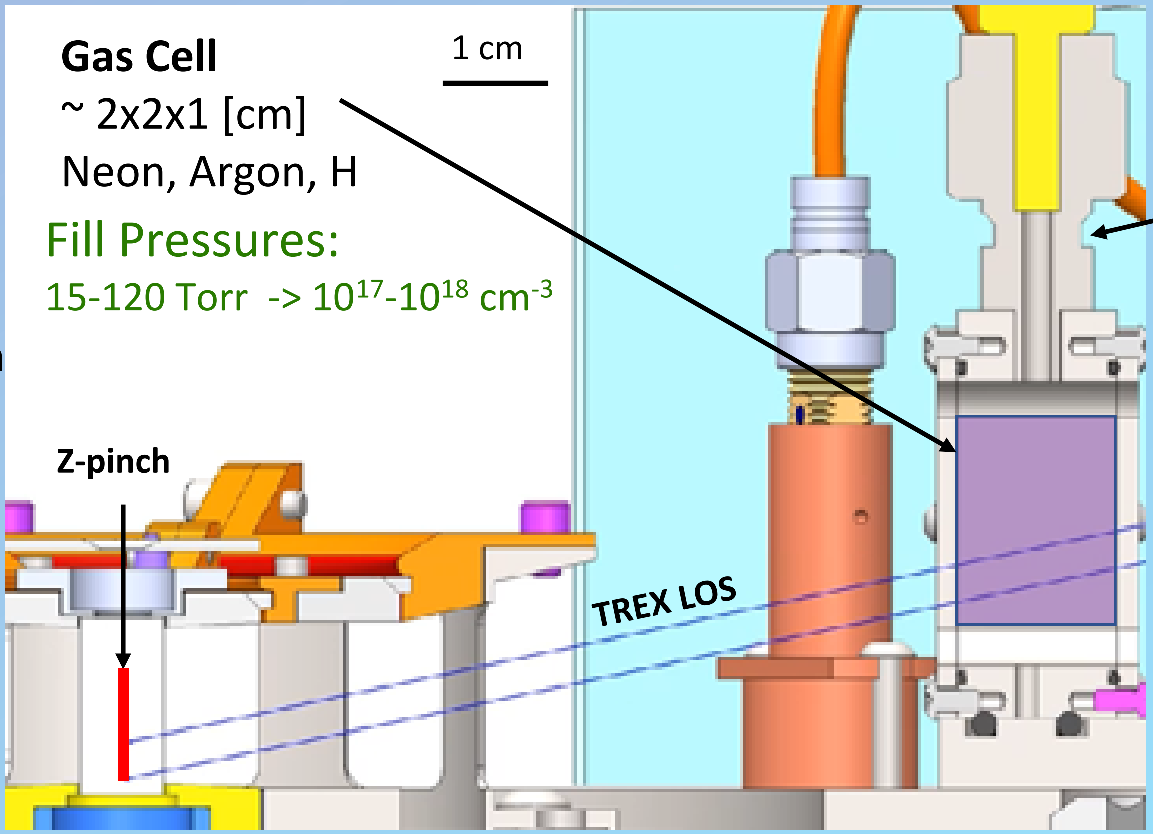
Astrophysically relevant

$$\xi \gg 1$$

Achievable Ionization Parameters[3, 4]

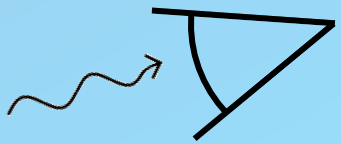
$$\xi \approx 5 - 60$$

Two "knobs"
- Flux
- Density



Pressure sensor
Density up to shot time

TREX Spectrometer[4]



- Observes neon K-shell absorption spectra
- Photon energy range: 860-1230 eV
- Extract charged state distribution and electron temperature

Gas cell positions:

Close Position: 4.3 cm => ~1.3x10^{12} W/ cm^2
Far Position: 5.9 cm => ~0.6x10^{12} W/ cm^2

1) C. B. Tarter, et al. *ApJ*. 1969, 2) J.E. Bailey, et al. *JQSRT*. 2001, 3)R. C. Mancini, et al. PRE 2020 , 4) D. C. Mayes, et al. PRE 2021, 5) P. Lake, et al. RSI 2006

We can control ionization parameters by adjusting gas cell position and fill pressure

Ionization Parameter[1,2]

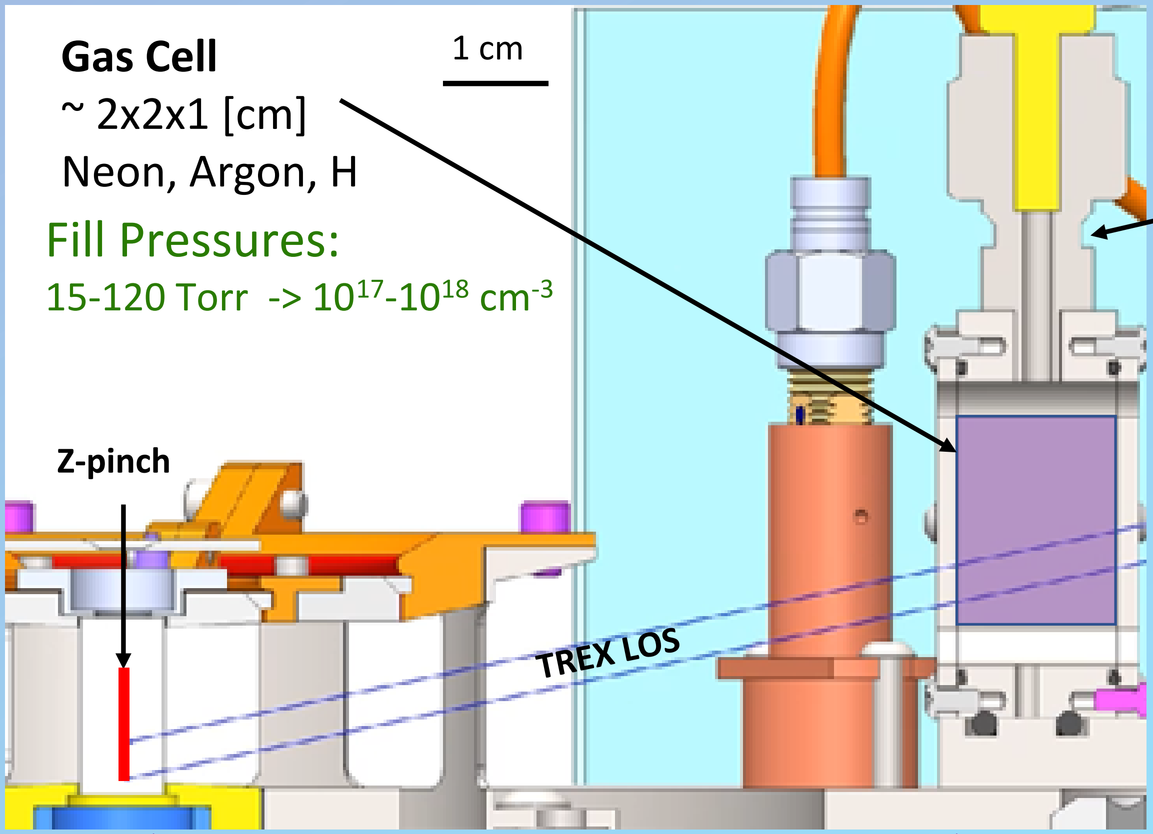
$$\xi = \frac{4\pi F}{N_e} \quad \left[\frac{erg \cdot cm}{s}\right]$$

"A metric for the balance between photoionization and recombination"

Astrophysically relevant

$\xi \gg 1$

Two "knobs" → Flux, Density



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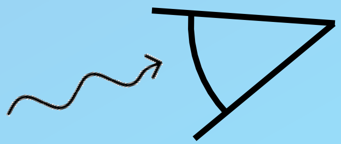
TREX Spectrometer[3]



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Important, to be able to diagnose conditions inside gas cell

1)C.B. Tarter, et al. *ApJ*. 1969, 2) J.E. Bailey, et al. *JQSRT*. 2001, 3) P. Lake et al. RSI 2006

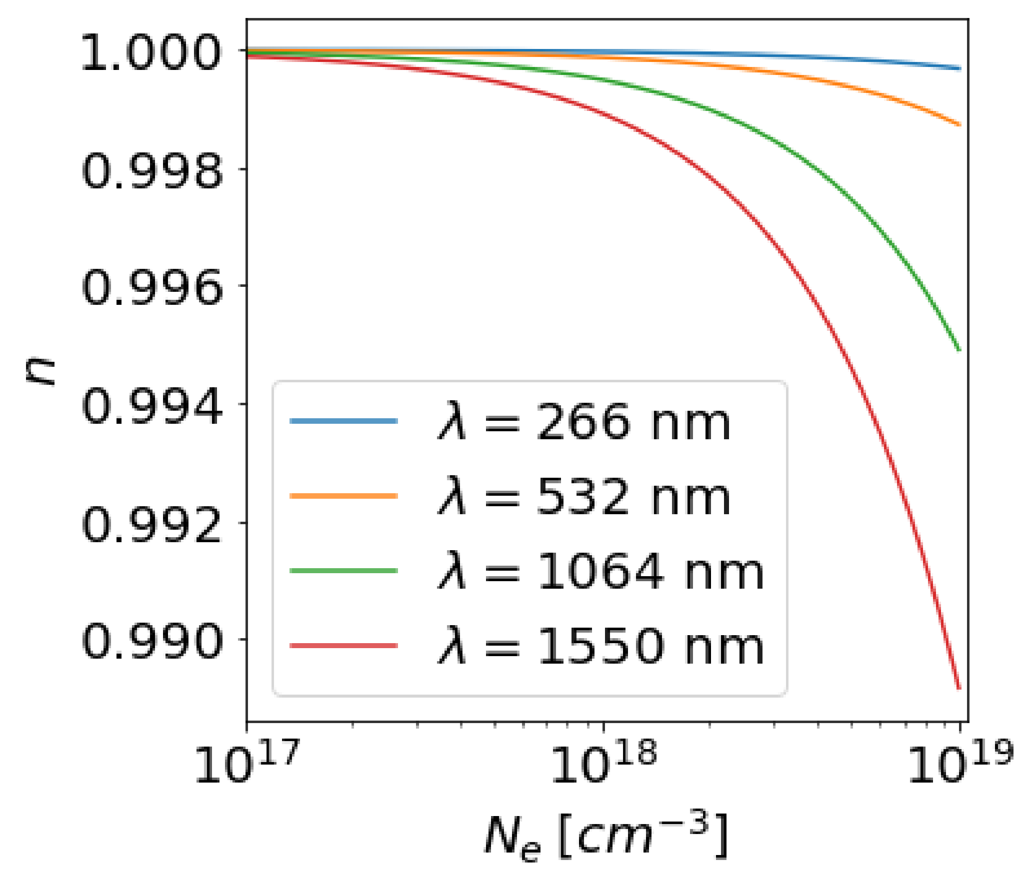
Photon Doppler velocimetry enables measurement of electron density inside the gas cell

- From the time rate of change in optical path length, the time rate of change in the refractive index of a plasma can be inferred.[1]

$$\frac{d}{dt}\Delta_{OPL}(t) = -\frac{d}{dt}\int_{x_0}^{x_f} n(x,t)dx$$

- The index of refraction of the plasma is dependent on the electron density.

$$n(N_e) = \sqrt{1 - \frac{N_e}{N_c}} = \sqrt{1 - \frac{(e\lambda)^2 N_e}{m_e \varepsilon_0 (2\pi c)^2}}$$

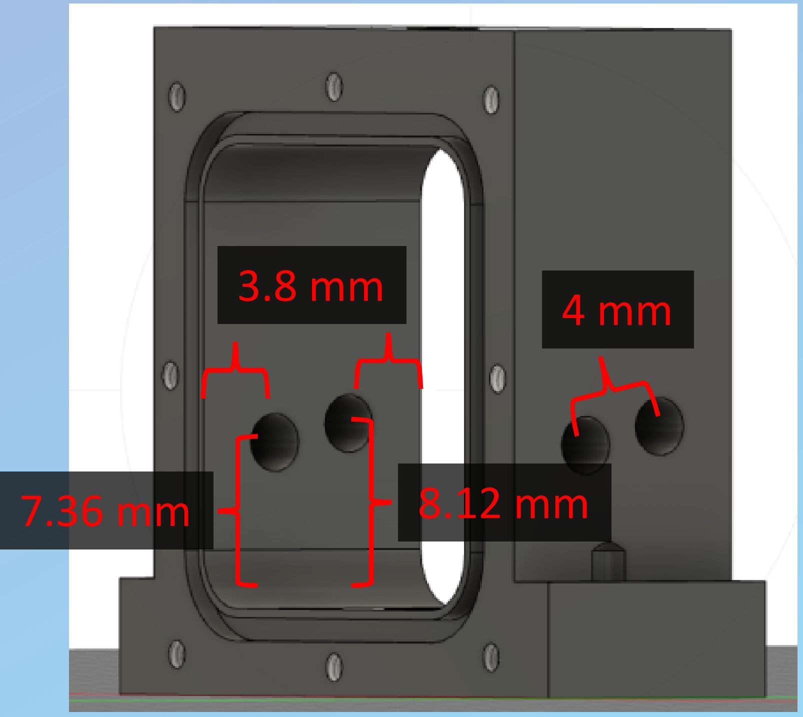


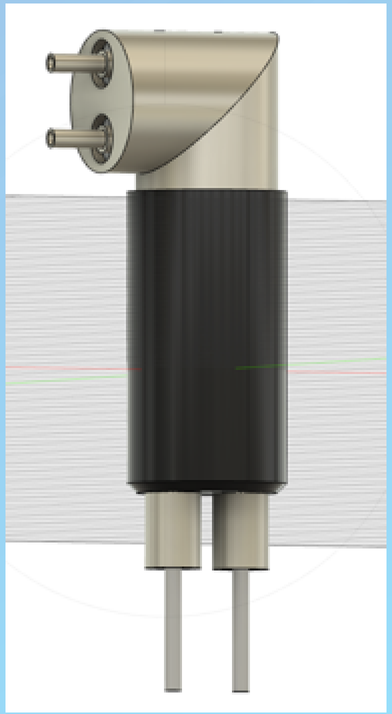
1) D. Dolan et al. JAP 2018

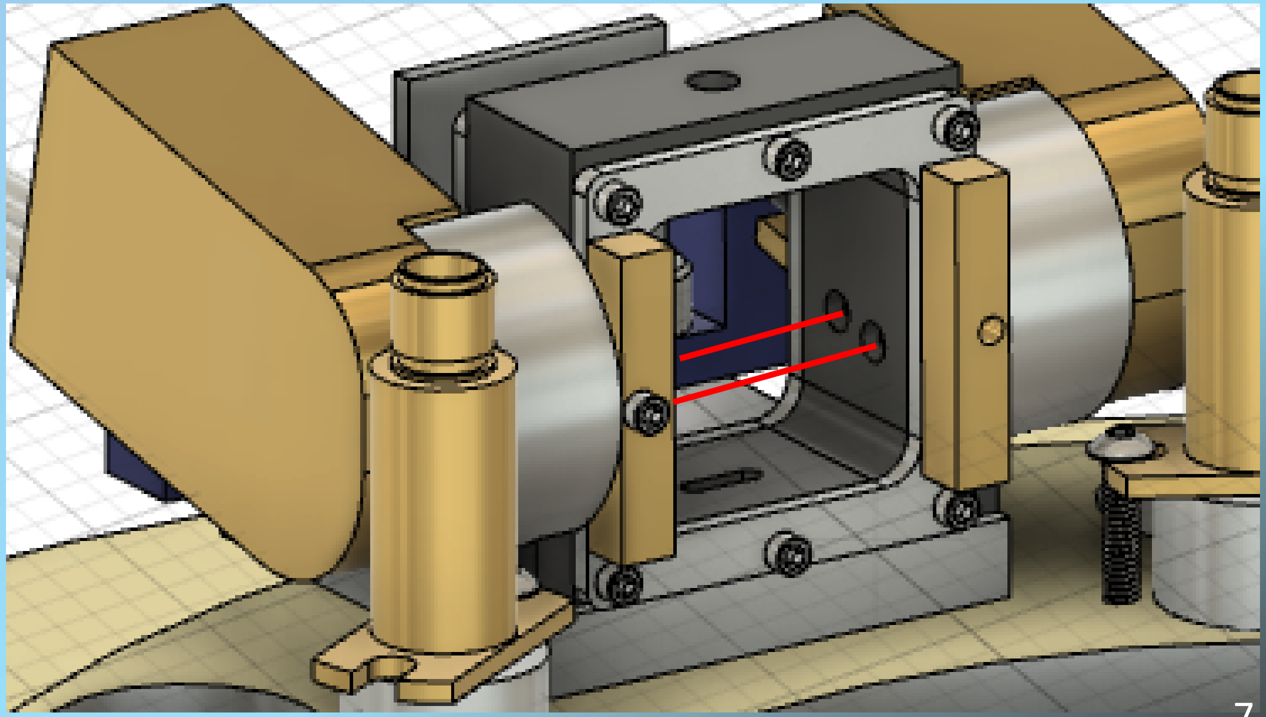
Plasma uniformity can be assessed with two PDV probes

Initial goals for PDV were testing the feasibility of measurements within the gas cell platform

1. Assess the uniformity of the photoionized plasma in the gas cell via two PDV probes
2. Measure the electron density of the photoionized plasma within the gas cell

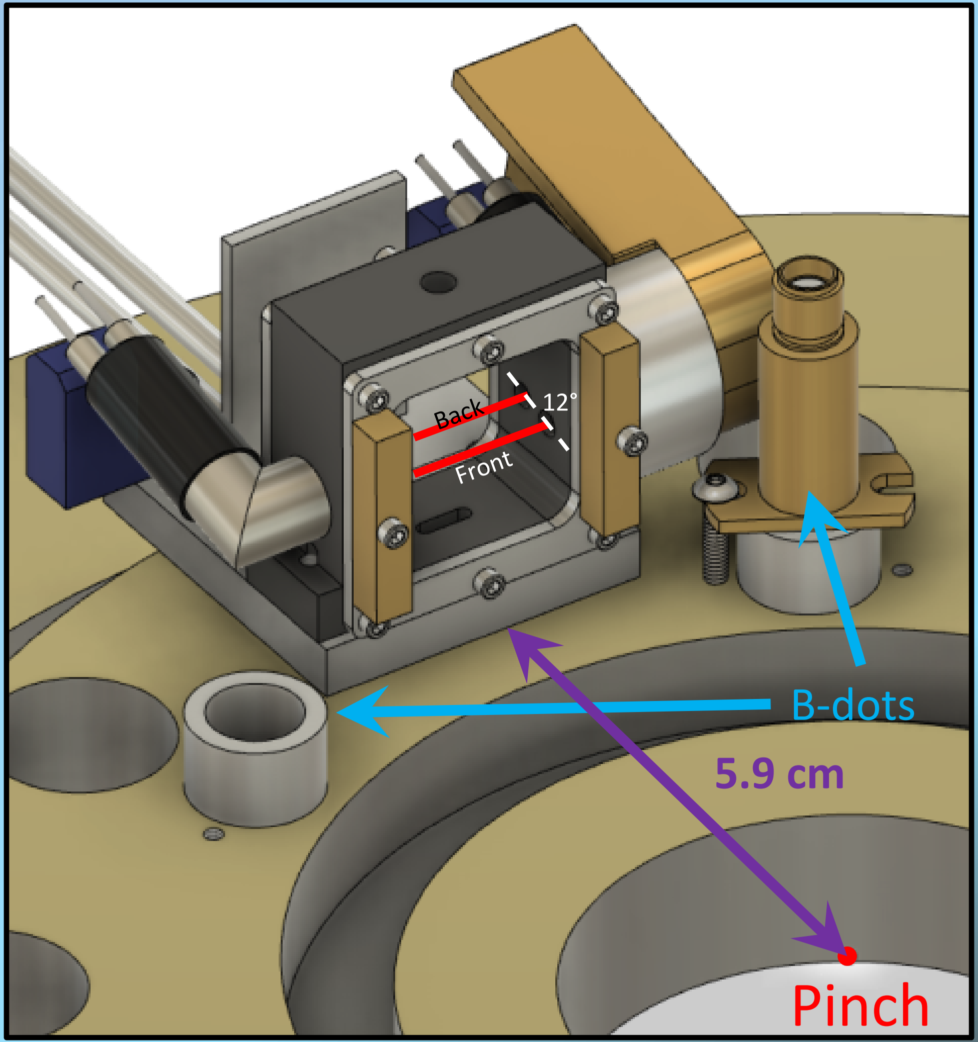






Gas cell PDV implementation design considerations

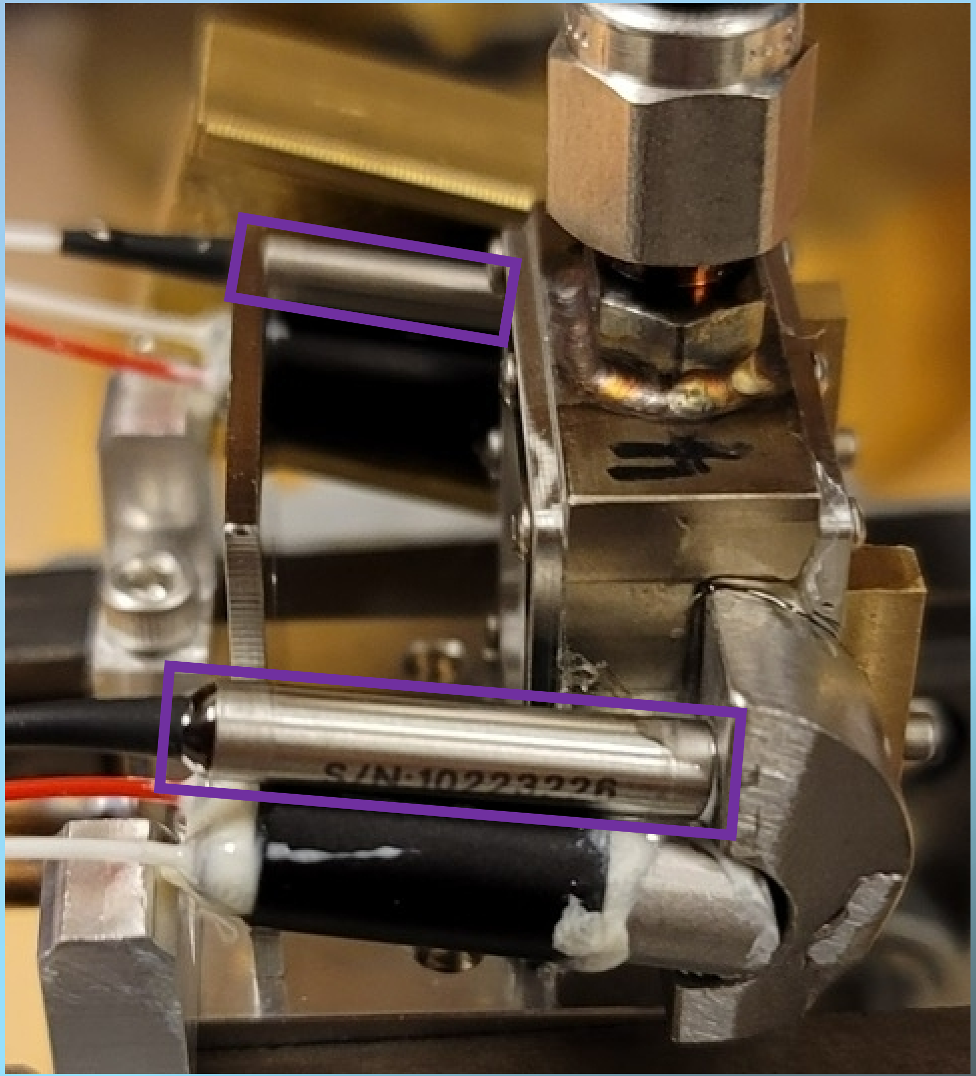
1. Gas cell placement ~ 6 cm from the z-pinch
   - Fiber optics are susceptible to extreme radiation environments
     - Opposite effect of plasma detection with PDV
     - Three radiation shields were developed to mitigate radiation exposure of the fiber optics
2. Gas cell footprint constrained by anode B-dots
   1. 90° dual fiber optic mirror assemblies were developed and used
      1. Reduce exposed surface area of fibers
      2. Avoid interference with anode hardware



PDV Radiation Induced Attenuation Characterization

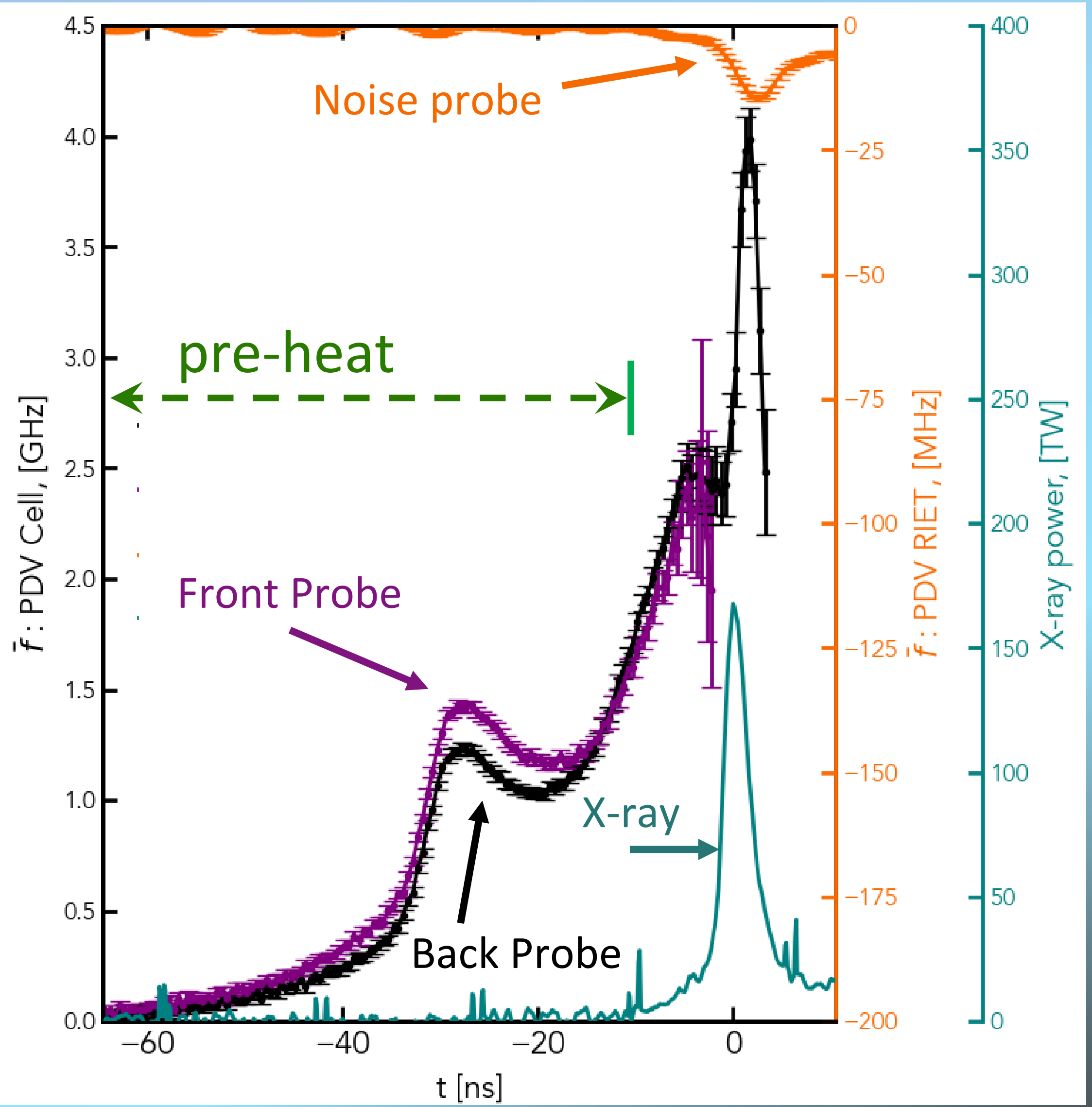
- Bi-directional PDV probes with mirrors on the end were included on the right and left side of the gas cell

- To ensure the best comparison between data and noise probes the fibers used in noise probes were of the same make and model as the gas cell PDV probes



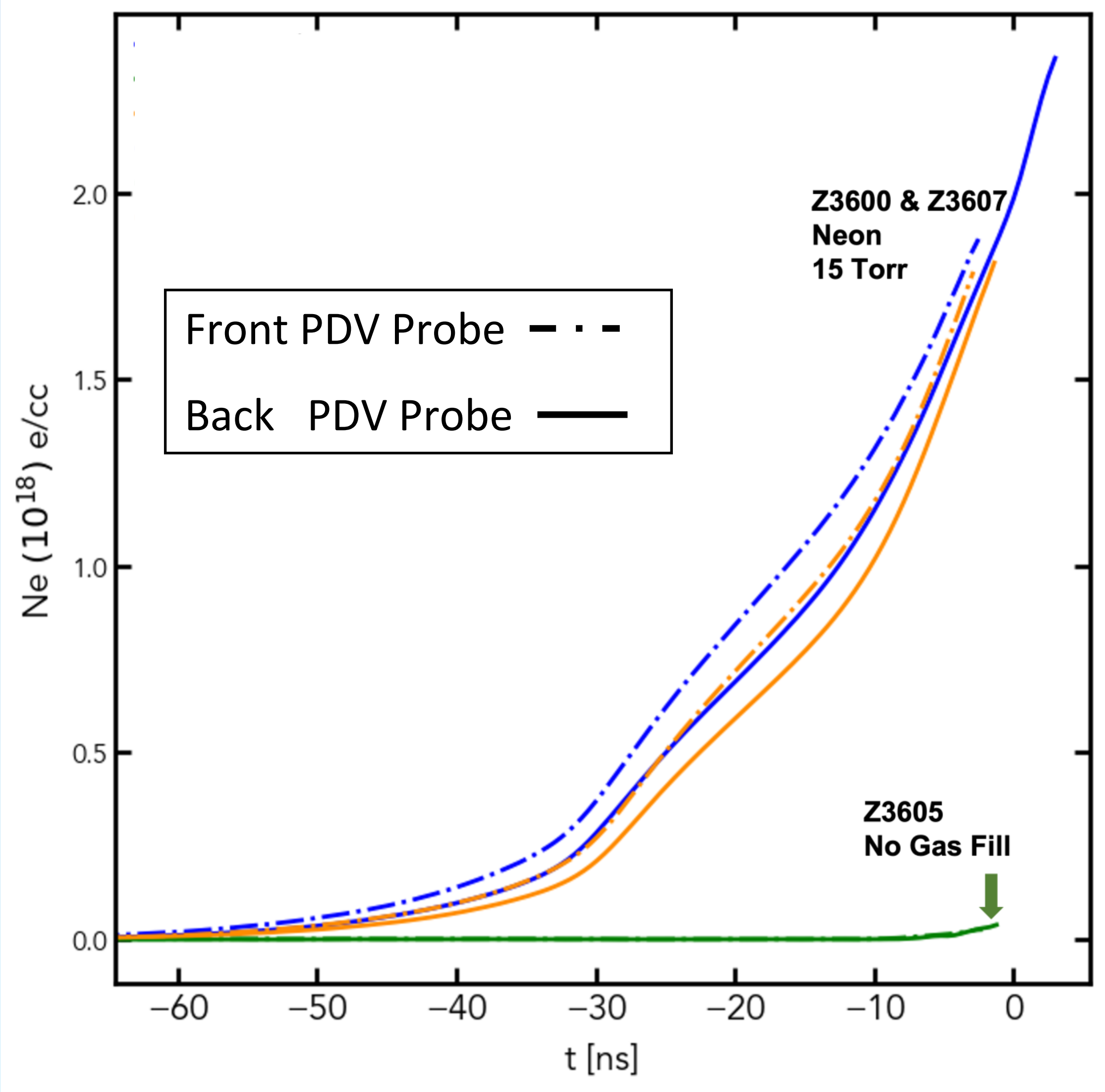
First direct observation of the “pre-heat” radiation phase

- Pre-heat
  - Lasts ~50 ns prior to the main x-ray pulse
  - Driven by radiation from z-pinch produced by the run-in phase
- Radiation induced noise within the fiber optics is negligible
  - ~ 2 orders of magnitude lower



Time resolved electron density measurements are made possible with chordal interferometry

- Front probe observes rise in electron density before back probe
- Nominally identical experiments show reasonable agreement
  - Neon @ 15 Torr: Z3600 & Z3607
- Null shot indicates photoionization of gas is the dominant source of electron density



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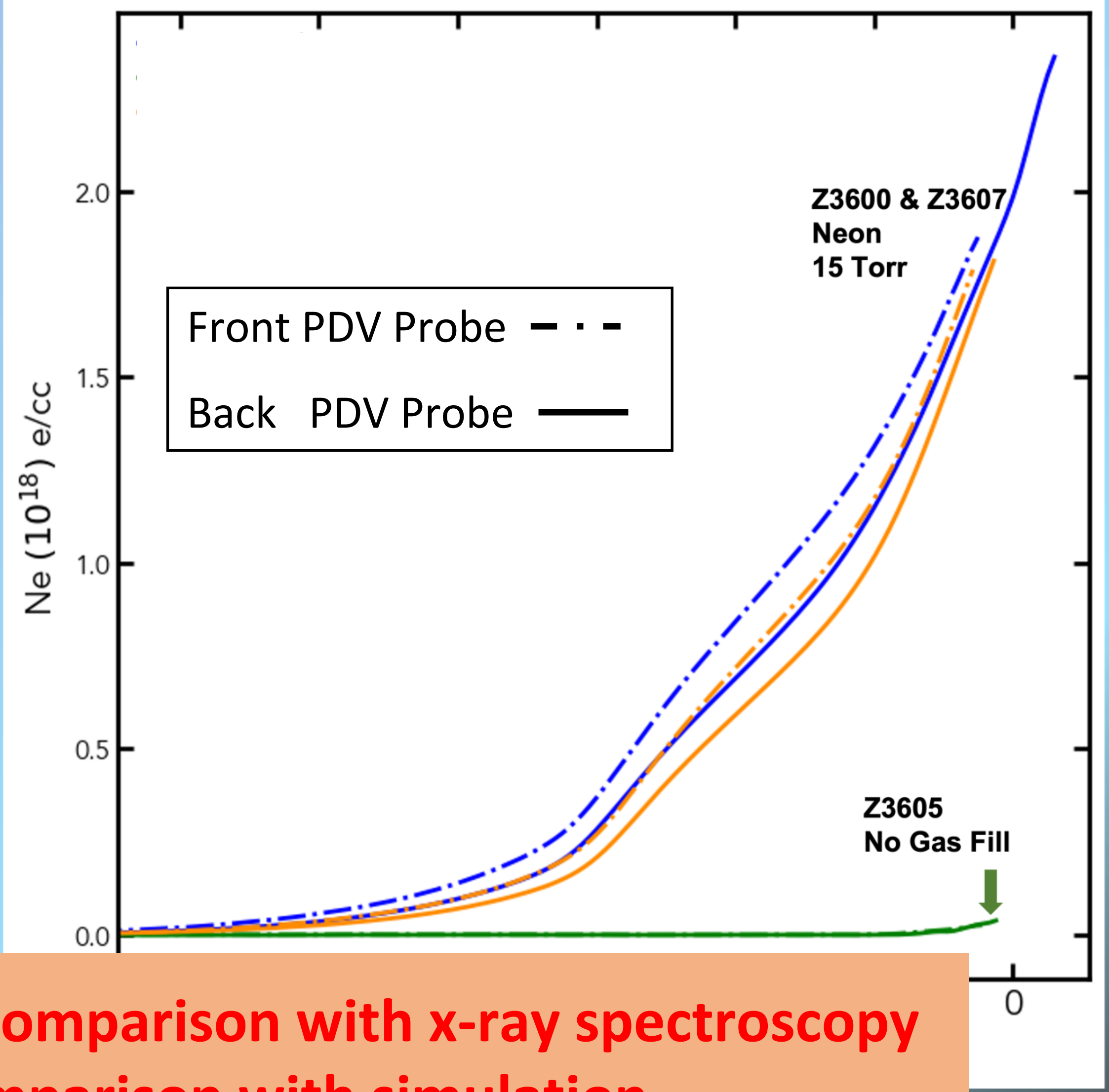
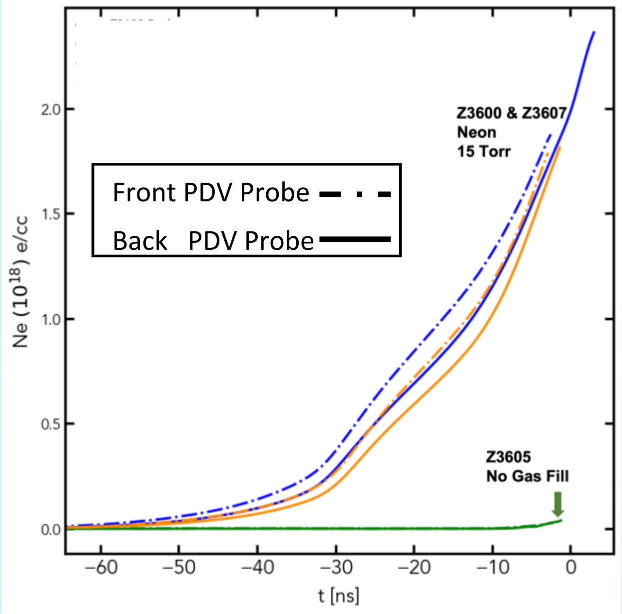


Electron density measurements allow comparison with x-ray spectroscopy measurements as well as comparison with simulation

The inclusion of a complementary electron density diagnostic has proven to be a valuable addition to the gas cell platform

- Implementation of PDV as a diagnostic to assess plasma conditions inside the gas cell has been accomplished
- First fielding of PDV diagnostic at Z in an experiment driven by a strong x-ray flux close to the pinch source
- Dual PDV probes were used to assess plasma uniformity and density inside the gas cell, for the <u>first time</u>
- Future use PDV will include more probes to:
  - Further constrain plasma dynamics
  - Observe evolution of shocks generated from the front and rear windows



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