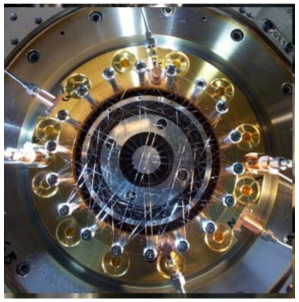
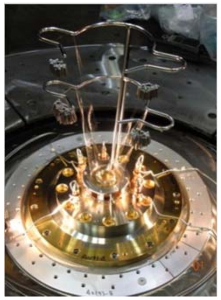
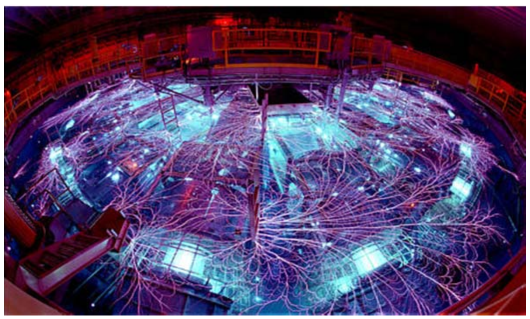
SAND2013-4858C







Sandia National Laboratories

Exceptional service in the national interest

A Renewed Argon Gas Puff Capability on Sandia's Z Machine

B. Jones, C.A. Jennings, A.J. Harvey-Thompson, D.J. Ampleford, S.B. Hansen, D.C. Lamppa, M.E. Cuneo, T. Strizic, D. Johnson, M.C. Jones, N.W. Moore, T.M. Flanagan, J.L. McKenney, E.M. Waisman, C.A. Coverdale

Sandia National Laboratories

M. Krishnan, P.L. Coleman, K. Wilson Elliott, R. Madden, J. Thompson, A. Bixler

Alameda Applied Sciences Corp.

J.W. Thornhill, J.L. Giuliani, Y.K. Chong, A.L. Velikovich, A. Dasgupta, J.P. Apruzese

Naval Research Laboratory

PPPS 2013, Monday, June 17, 1A-1

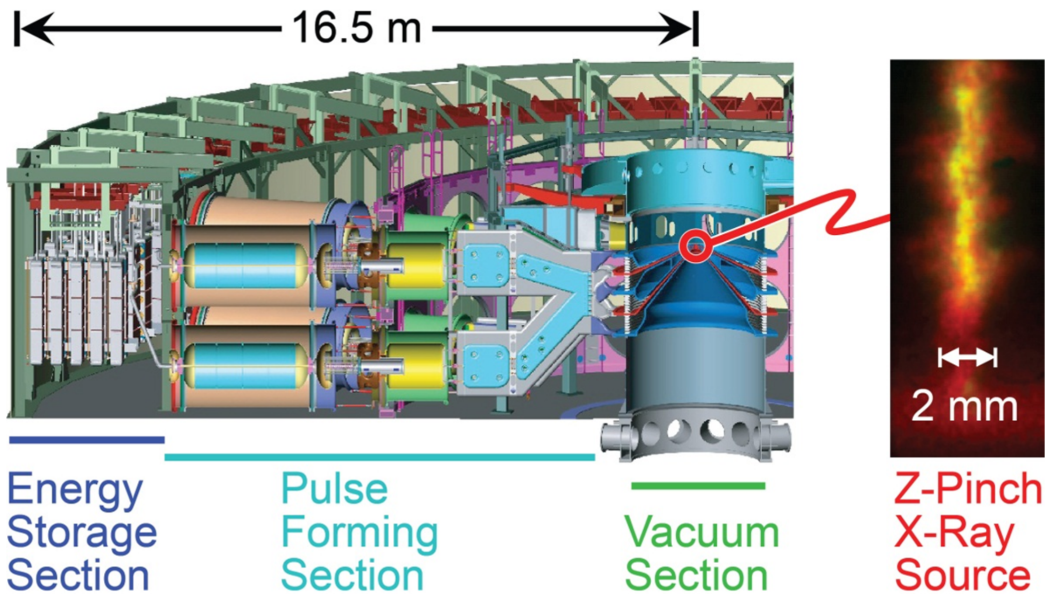
Work supported by NNSA and by DTRA

Progress report on Z gas puff source development

- We have commissioned a Sandia-operated gas puff capability on Z
- Numerical simulations are being used to design Z experiments
- Initial gas puff shots produced 250-400 kJ of Ar K-shell emission
- The plasma conditions produced on Z are studied using time-gated spectroscopy and self-emission imaging
- We are starting to use the experimental data to test and improve the numerical simulations

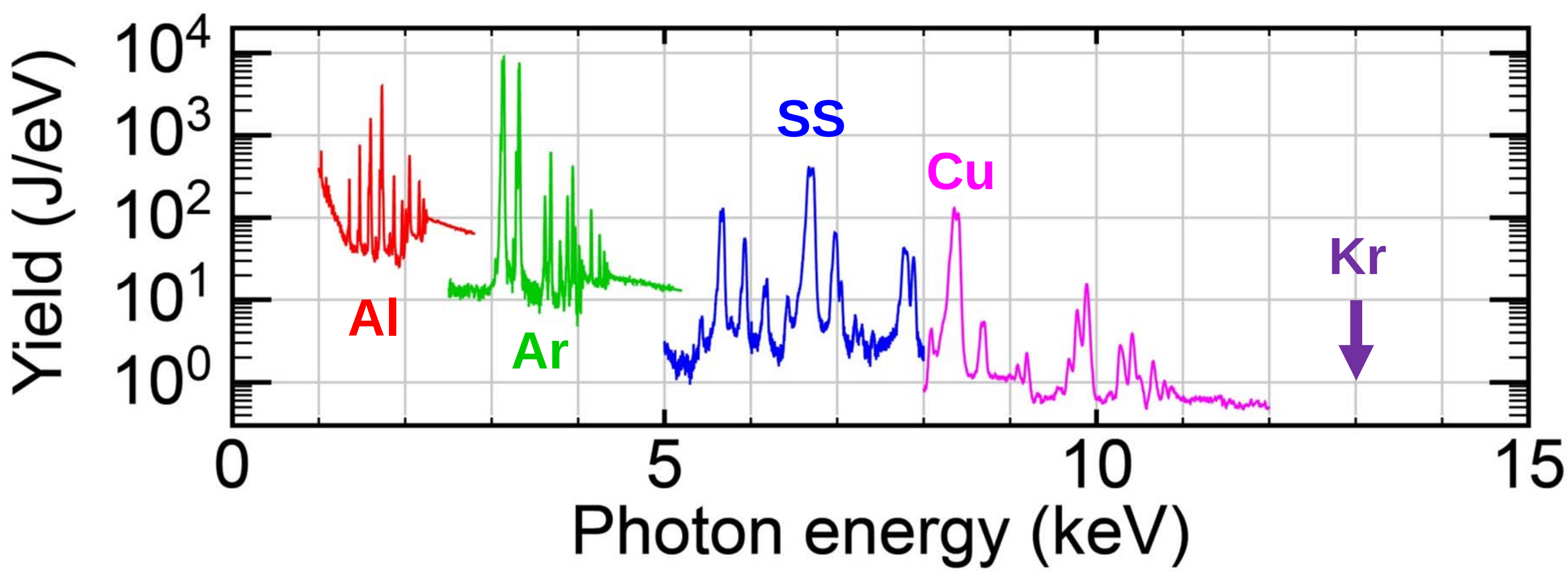
Z produces the brightest laboratory soft x-ray sources

20 MJ stored electrical energy

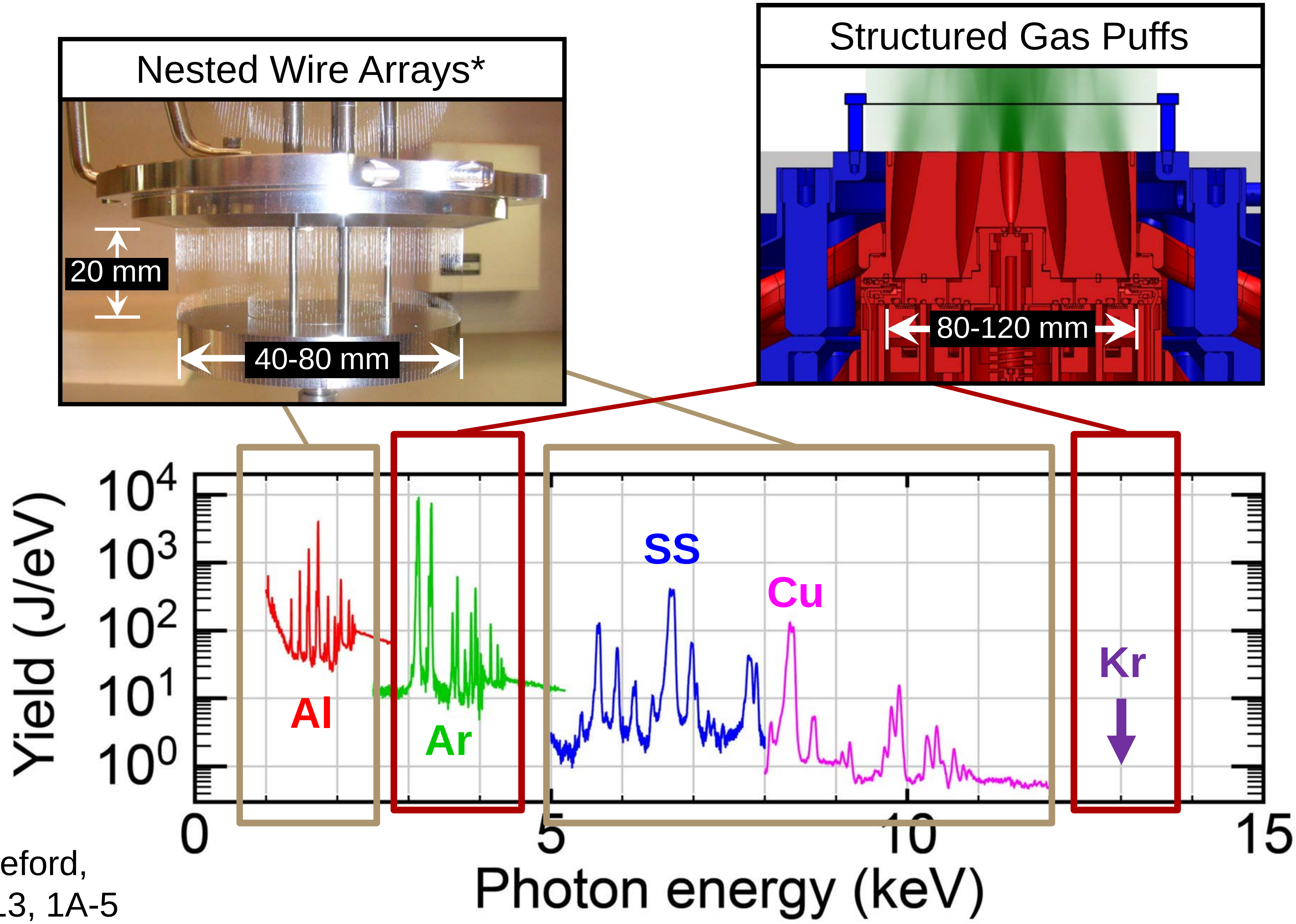


1-2 MJ total radiated x-rays

10s-100s kJ K-shell x-rays

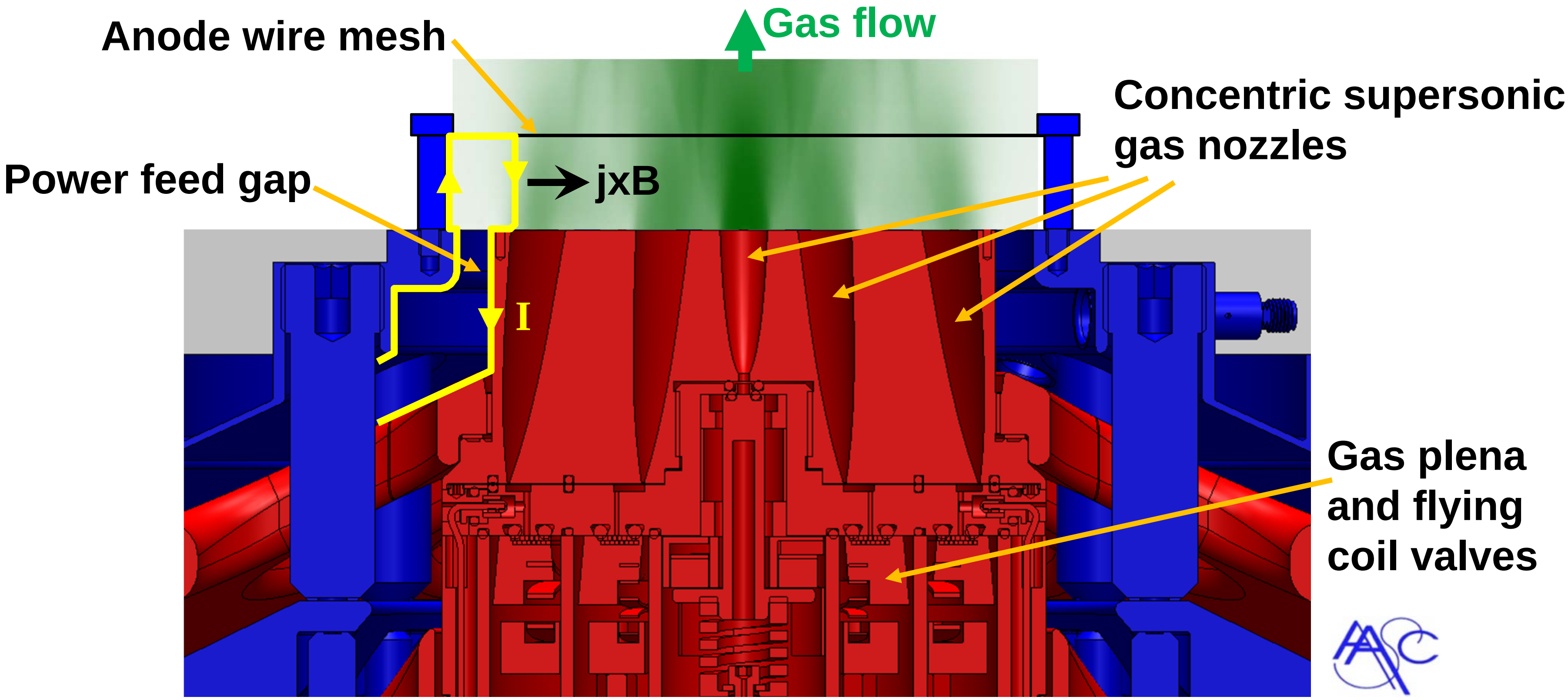


Wire arrays and gas puffs are used to access different regions of the spectrum



* D.J. Ampleford, PPPS 2013, 1A-5

Supersonic nozzle provides a column of gas which is magnetically imploded by the Z pulsed power generator

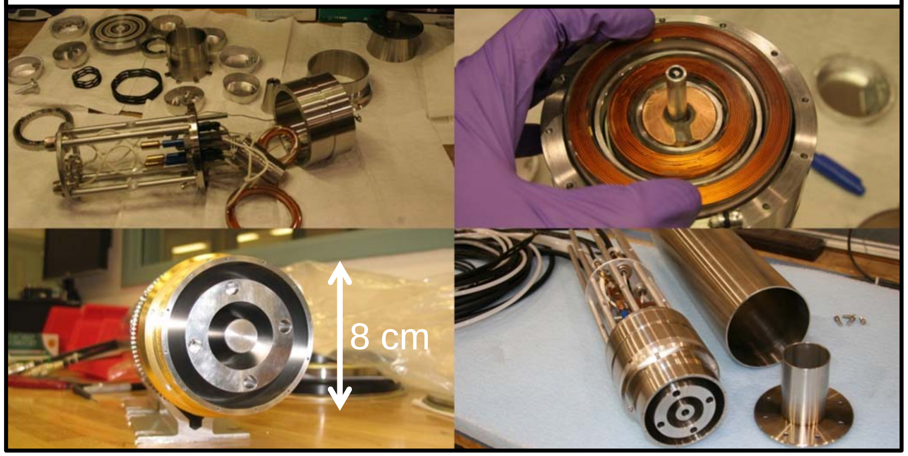


- Azimuthal symmetry is desired for best comparison of experiment and numerical modeling: no cathode grid is fielded, nozzle is not recessed
- Center jet capability is demonstrated, will be studied on Z in future work
- M. Krishnan *et al.*, RSI **84**, 063504 (2013) discusses the Z system development

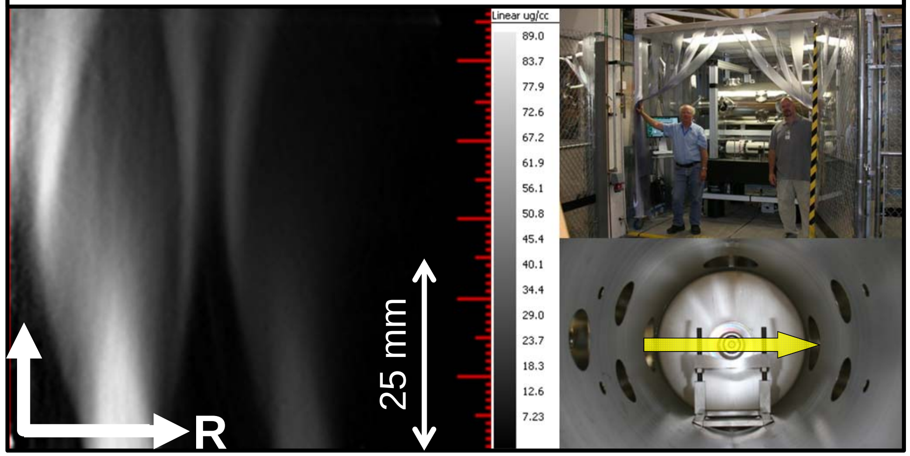
We have established gas puff capability on refurbished Z

- 2012-2013: 5 Ar and 1 Kr shots, first gas puffs on Z since 2006

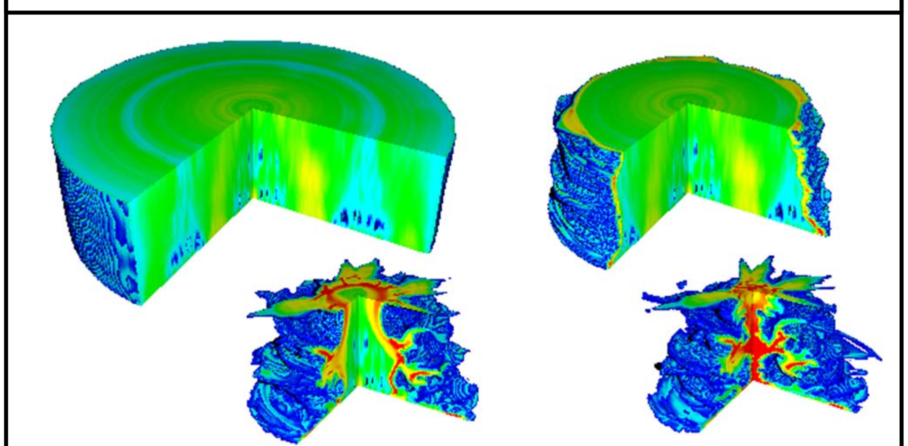
Nozzle fabrication and assembly



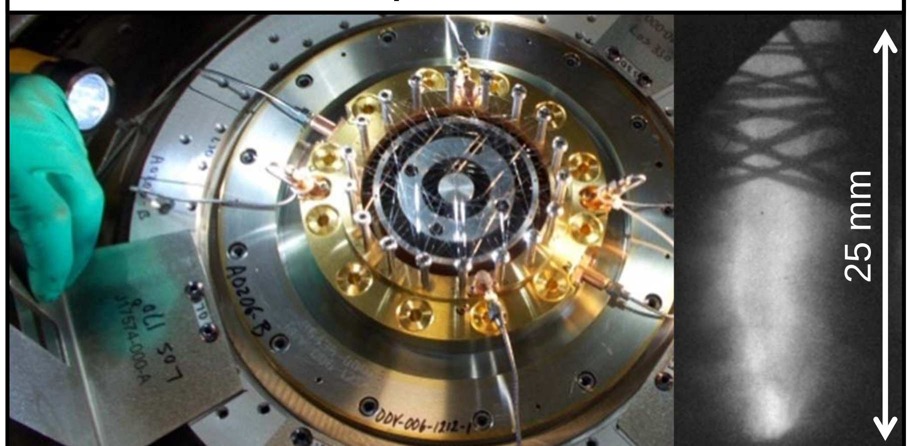
Mass profile characterization



Radiation-MHD simulations



Z experiments

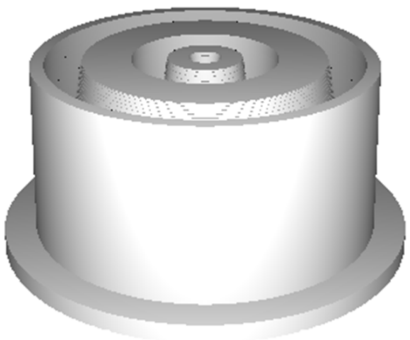


Numerical models are being used to design experiments and benchmarked post-shot to gain physics insight

- Cold gas flow models may be validated using experimental interferometer data

- Benchmarked simulated profiles can be used to initiate MHD simulations

- Tabulated atomic data are used to estimate K-shell x-ray outputs

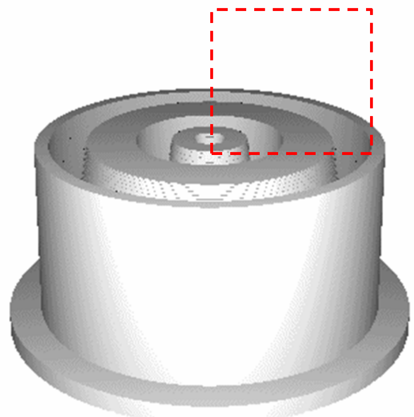


C.A. Jennings, SNL, GORGON

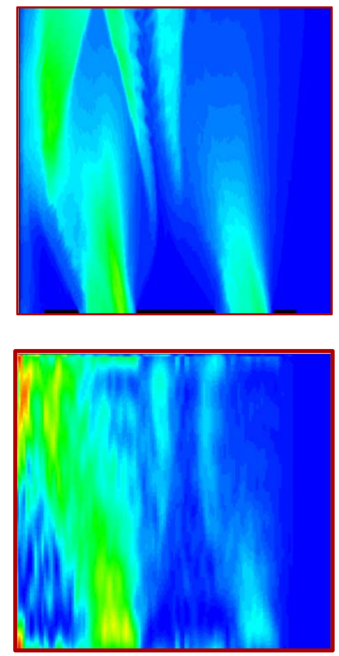
- Pre-shot NRL modeling [Thornhill *et al*., HEDP **8**, 197 (2012)] was consistent with SNL Gorgon simulations (Jennings)

Numerical models are being used to design experiments and benchmarked post-shot to gain physics insight

- Cold gas flow models may be validated using experimental interferometer data
- Benchmarked simulated profiles can be used to initiate MHD simulations
- Tabulated atomic data are used to estimate K-shell x-ray outputs



Simulation

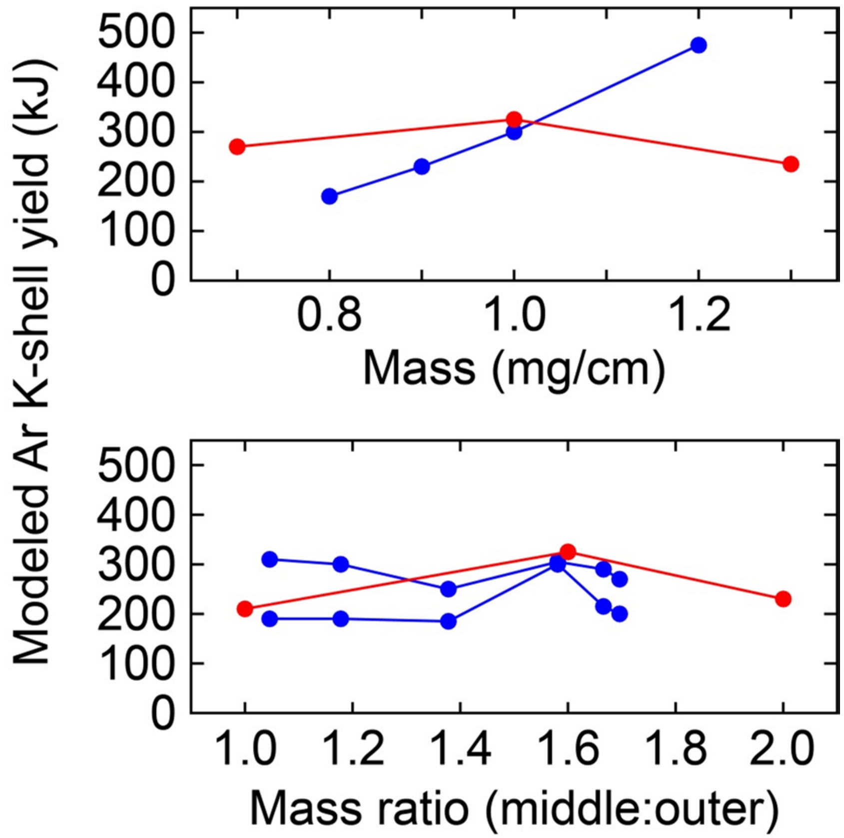


Interferometer

C.A. Jennings, SNL, GORGON

- Pre-shot NRL modeling [Thornhill *et al*., HEDP **8**, 197 (2012)] was consistent with SNL Gorgon simulations (Jennings)

3D Gorgon (SNL) and 2D Mach2 RMHD (NRL) models predicted similar yields, but with different trends

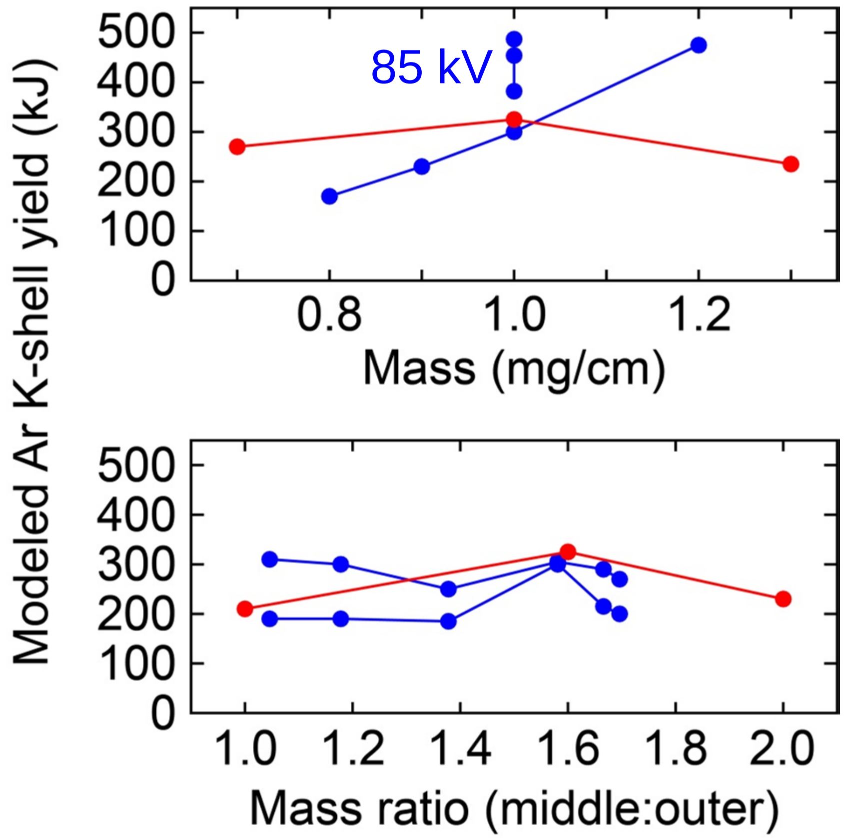


Gorgon, C.A. Jennings
- 3D resistive MHD
- Eulerian grid
- Tabulated emissivity/ opacity (S.B. Hansen)
- Single-group radiation diffusion

Mach2
[J.W. Thornhill *et al.*, HEDP **8**, 197 (2012)]
- 2D r-z resistive MHD
- Quasi-Lagrangian
- Tabulated CRE
- Probability of escape/ on-the-spot

- Unknown current loss behavior is a concern
- Trend to increasing yield with mass seen in 1D and 2D models could result from neglecting 3D plasma motion at stagnation

Modeling separate measurements of the same nominal gas profile indicated ~10% variability in K-shell yield

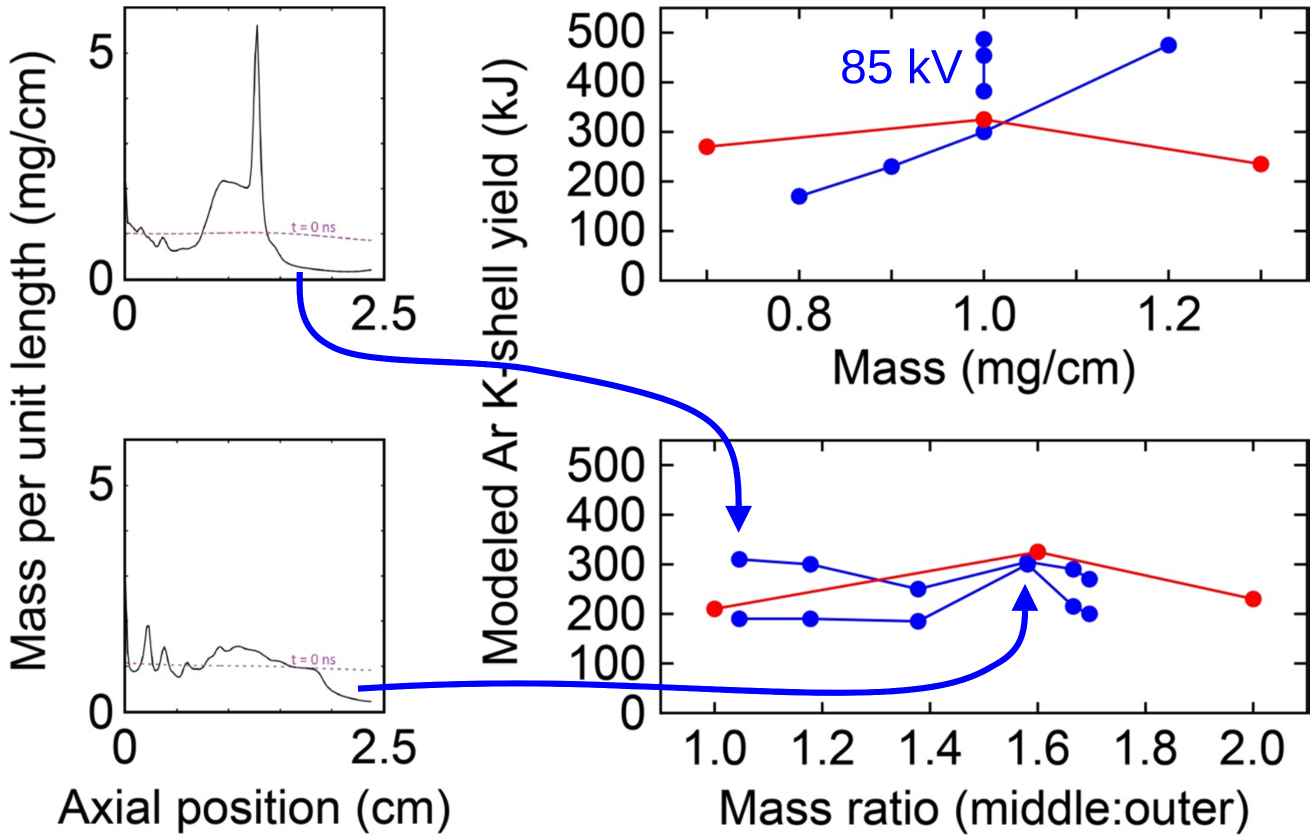


Gorgon, C.A. Jennings
- 3D resistive MHD
- Eulerian grid
- Tabulated emissivity/ opacity (S.B. Hansen)
- Single-group radiation diffusion

Mach2
[J.W. Thornhill *et al.*, HEDP **8**, 197 (2012)]
- 2D r-z resistive MHD
- Quasi-Lagrangian
- Tabulated CRE
- Probability of escape/ on-the-spot

- Detailed instability growth varies for each run
- Including a current/feed loss model based on initial gas puff shots, obtaining 300-500 kJ Ar K-shell yields is plausible

Modeling suggests that higher relative middle shell mass will help to stabilize magnetic Rayleigh-Taylor



Gorgon, C.A. Jennings

- 3D resistive MHD
- Eulerian grid
- Tabulated emissivity/ opacity (S.B. Hansen)
- Single-group radiation diffusion

Mach2

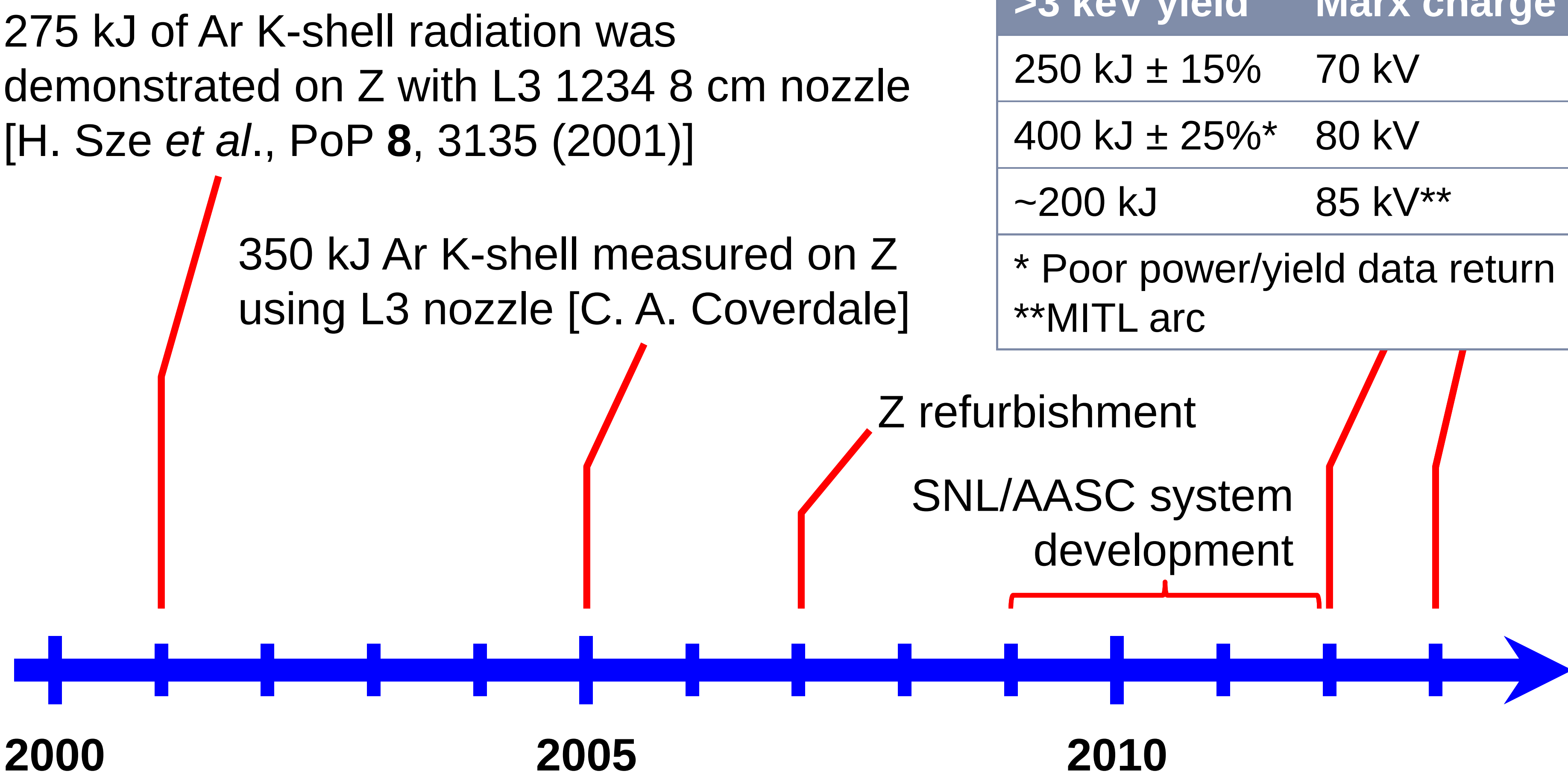
[J.W. Thornhill *et al.*, HEDP **8**, 197 (2012)]

- 2D r-z resistive MHD
- Quasi-Lagrangian
- Tabulated CRE
- Probability of escape/ on-the-spot

- Density map resolution affects modeled yield
- 1 mg/cm total mass, 1:1.6 outer:inner shell mass ratio chosen for initial Z experiments at 80-85 kV Marx charge

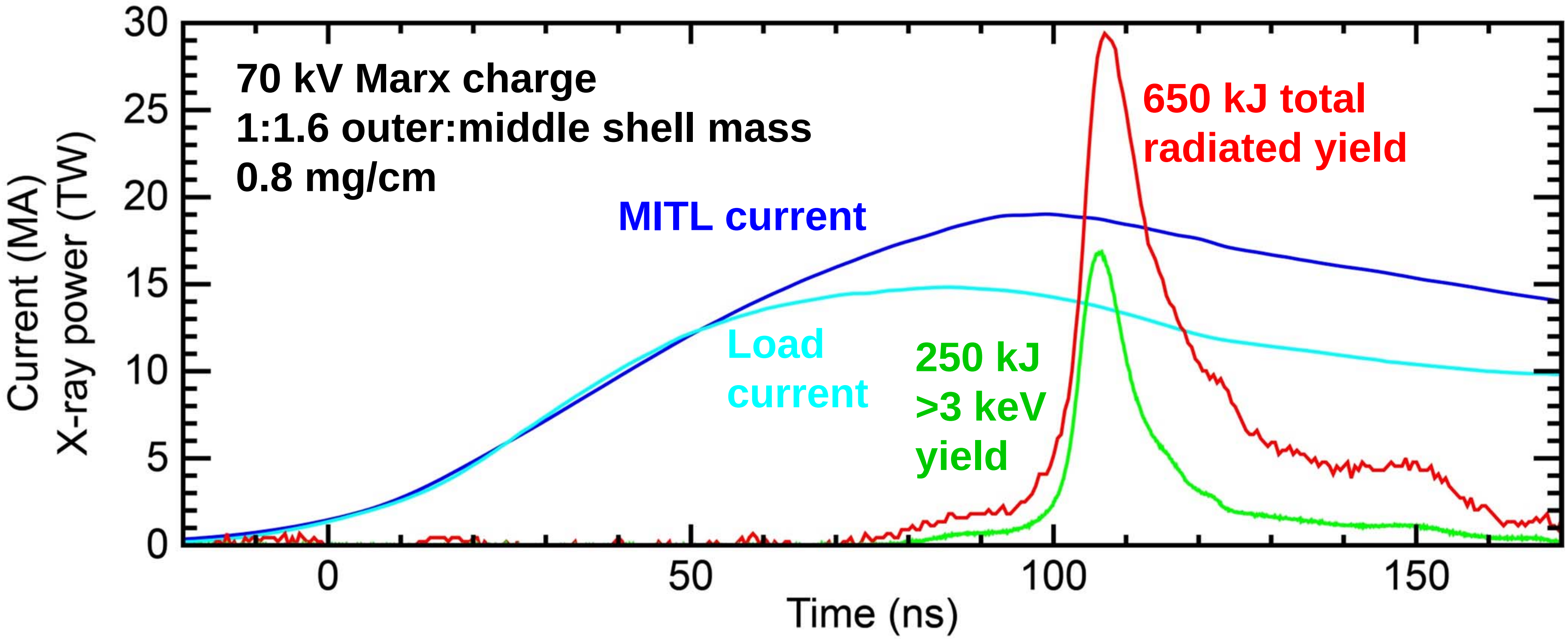
We have reestablished Ar K-shell sources on Z

>3 keV yield	Marx charge
250 kJ ± 15%	70 kV
400 kJ ± 25%*	80 kV
~200 kJ	85 kV**
* Poor power/yield data return **MITL arc	



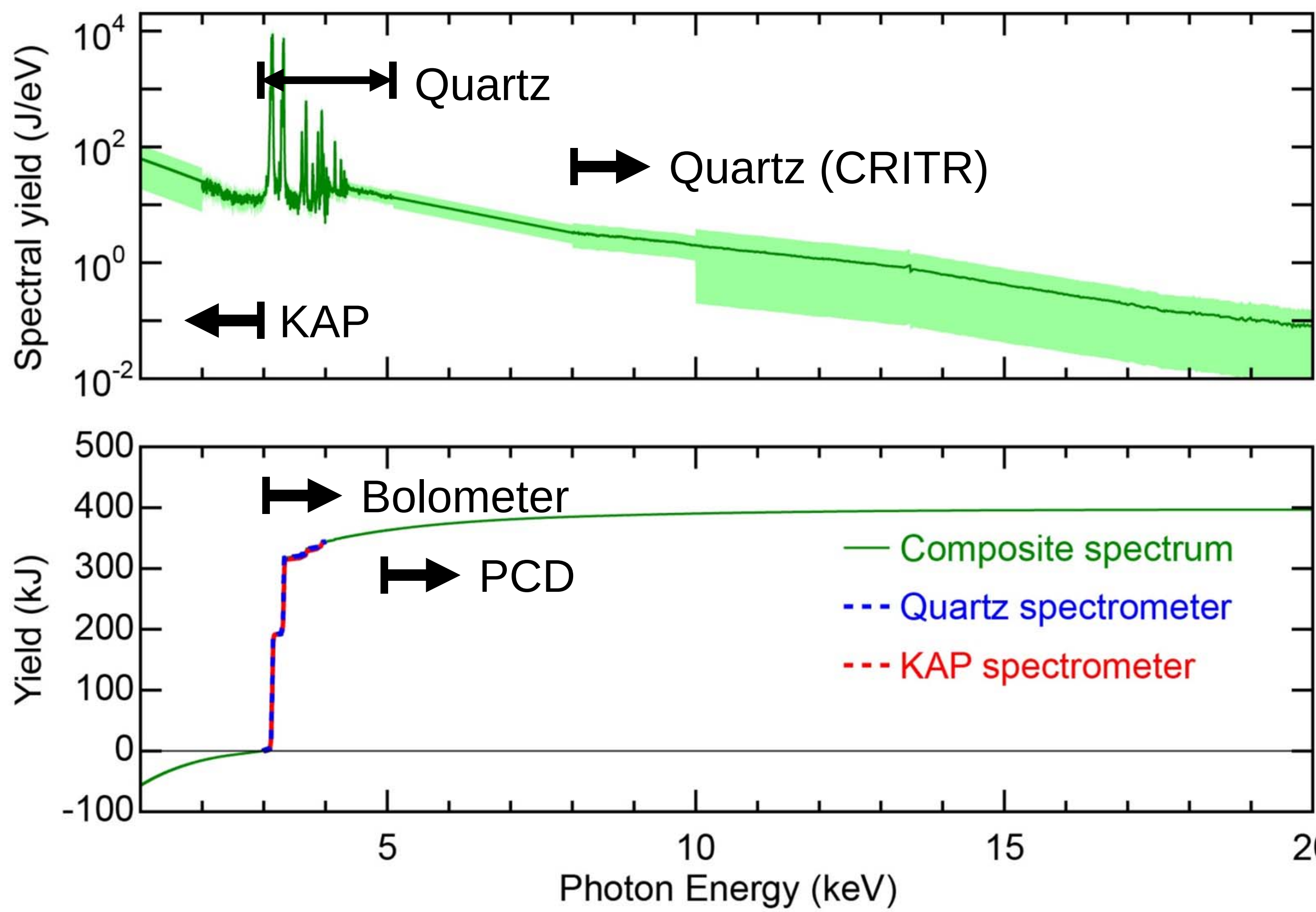
- Additional source optimization and reproducibility studies are needed on Z

Ar on Z is a very efficient K-shell radiation source



- >30% of the total radiation is emitted in the K shell
- Current losses are significant in the convolute and perhaps feed

Broadband time-integrated x-ray spectrum is measured



Photon energy range (keV)	Spectral uncertainty (%)
1-2	70
2-3	35
3-5	25
5-8	35
8-10	45
10-20	90

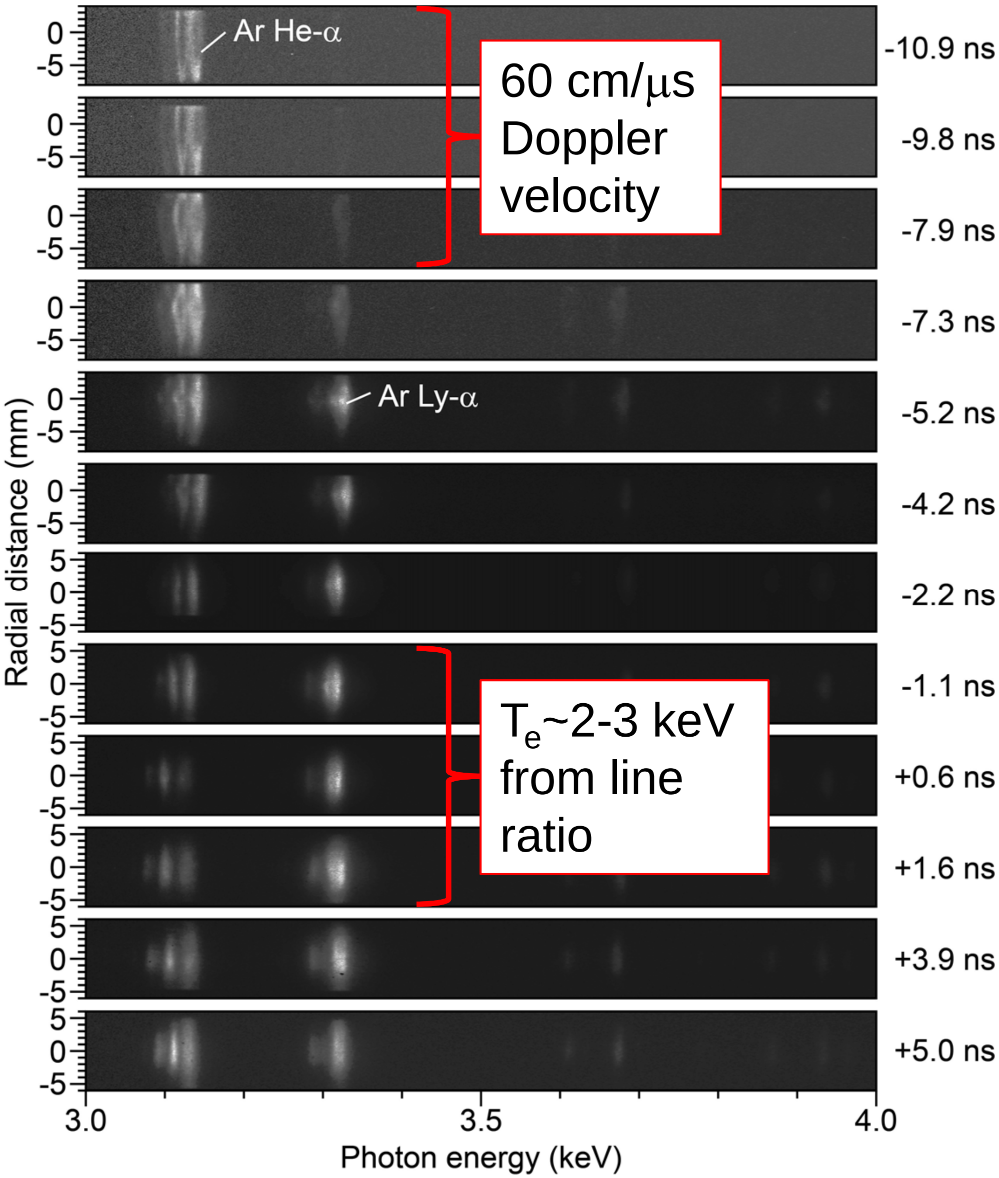
80 kV Marx charge

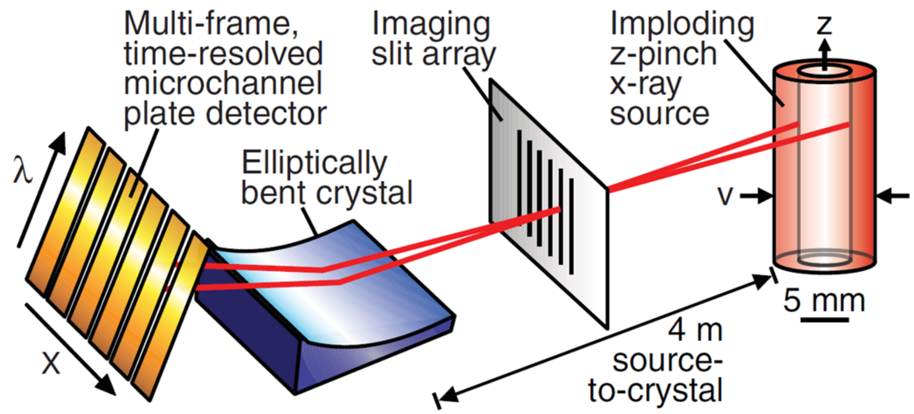
1:1.6 outer:middle mass ratio

1 mg/cm total mass

- Same Ar K-line spectrum measured with KAP and Quartz crystals
- 400 kJ ± 25% at >3 keV is constrained by only one bolo this shot

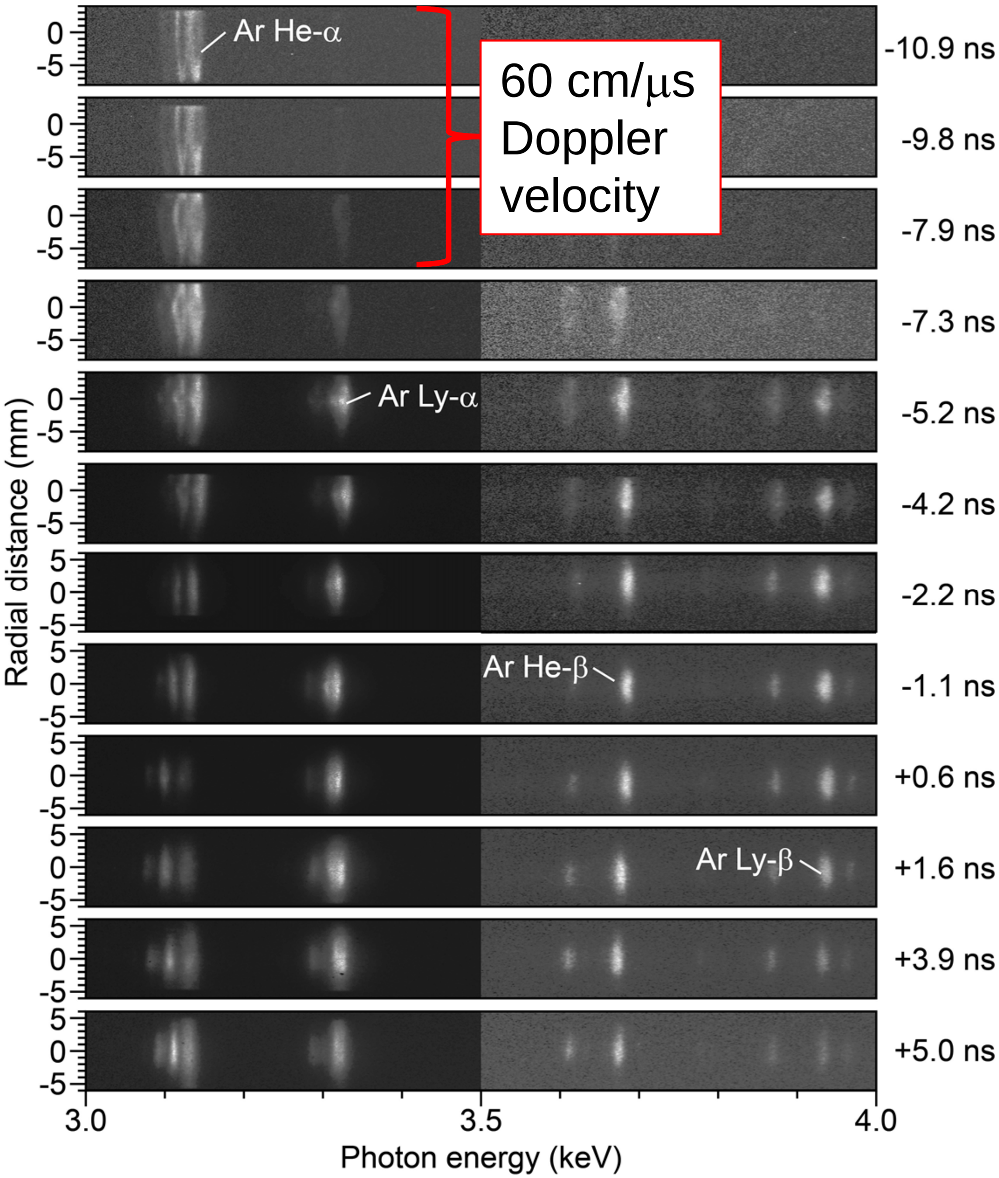
High achieved T_e allows efficient Ar K-shell emission on Z

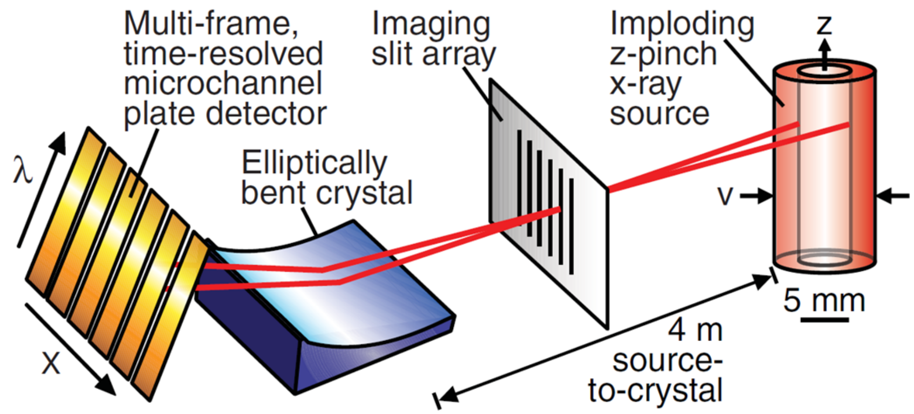




- Time-gated, radially-resolved spectra are measured on Z
- 60 cm/μs (η=2) inferred from Ar He-α Doppler splitting
- T_e~2-3 keV from Ar Ly-α/ He-α+IC ratio near peak power
  - Similar T_e from time-integrated free-bound continuum slope

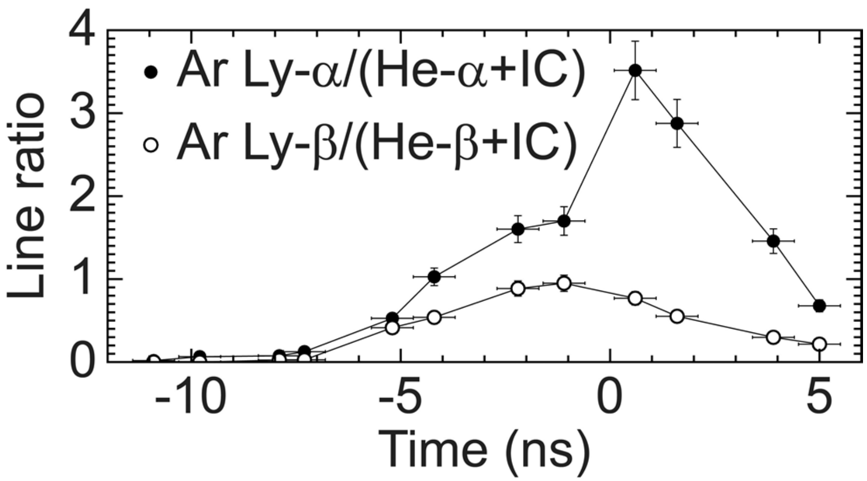
High achieved T_e allows efficient Ar K-shell emission on Z



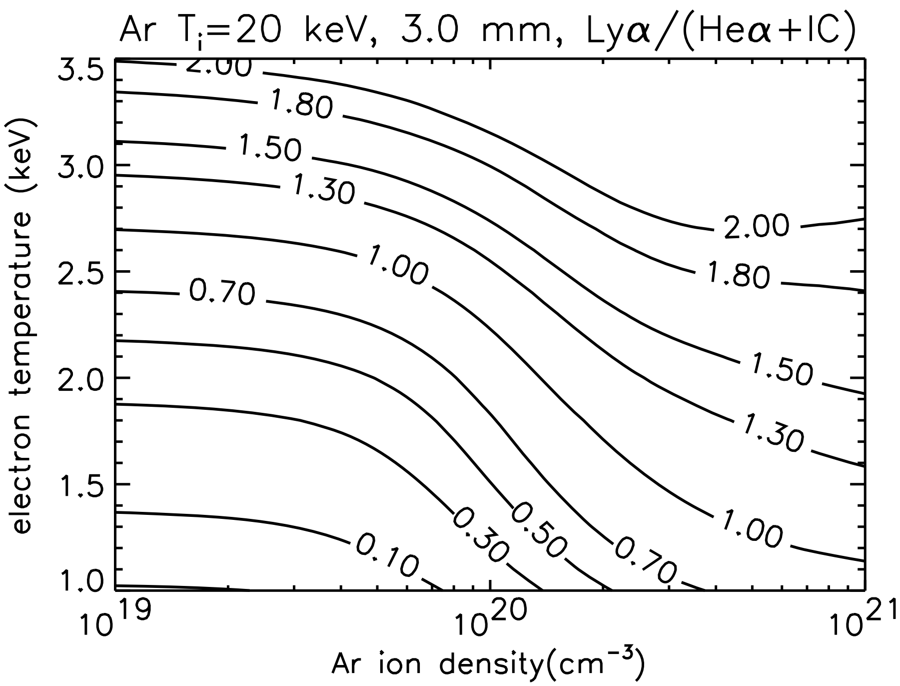


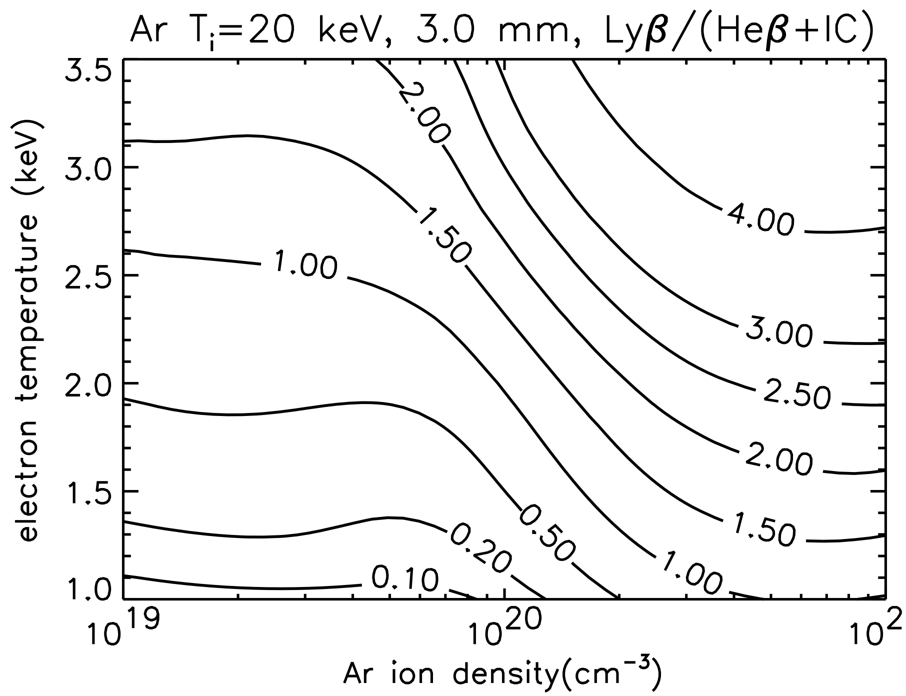
- Time-gated, radially-resolved spectra are measured on Z
- 60 cm/μs (η=2) inferred from Ar He-α Doppler splitting
- T_e~2-3 keV from Ar Ly-α/He-α+IC ratio near peak power
  - Similar T_e from time-integrated free-bound continuum slope

Uniform plasma model cannot explain observed line ratios

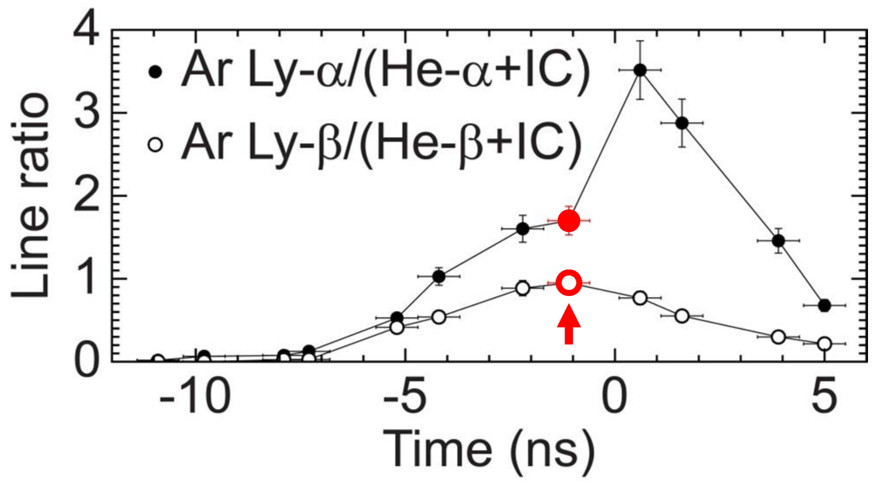


- Line ratios are measured as a function of time
- Ratios are calculated assuming a uniform plasma column
  - Apruzese *et al.*, JQSRT **57**, 41 (1997)
  - Added finite T_i affecting opacity

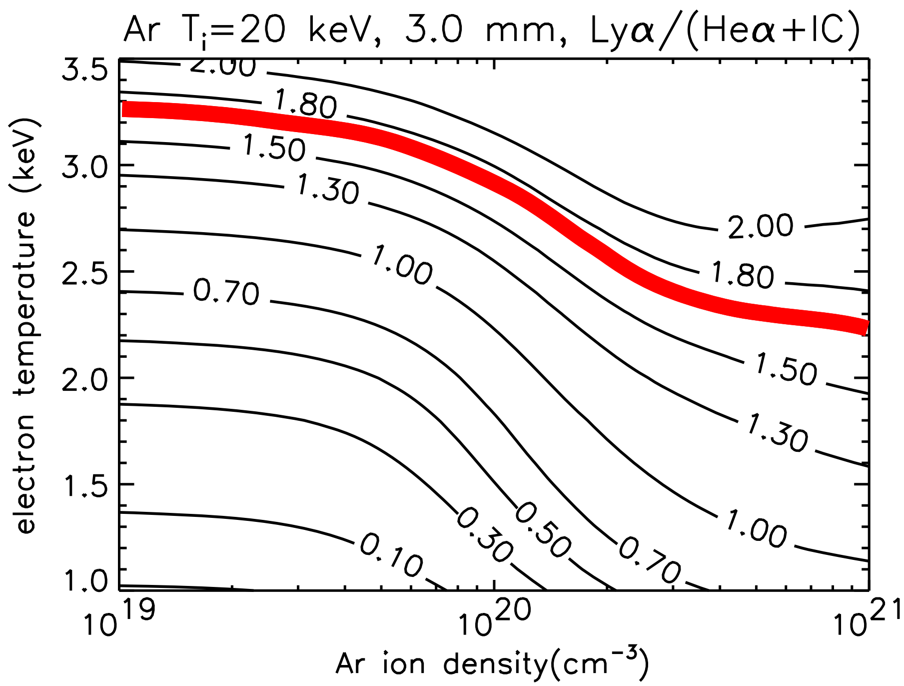


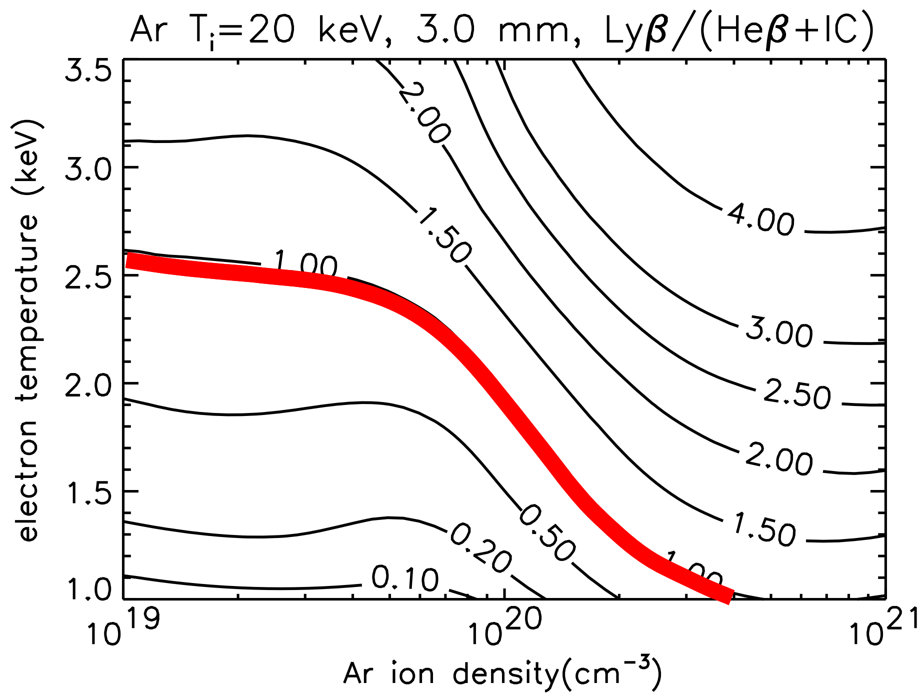


Uniform plasma model cannot explain observed line ratios

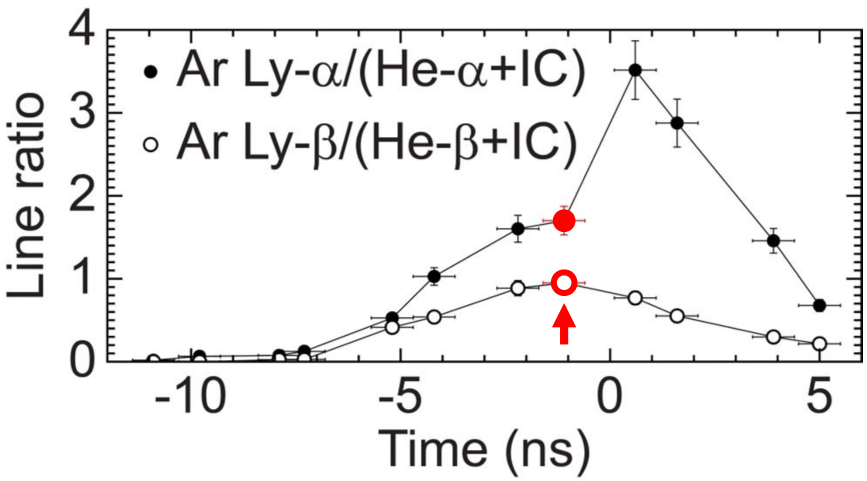


- Compare the measured ratios with calculations just before peak x-ray power

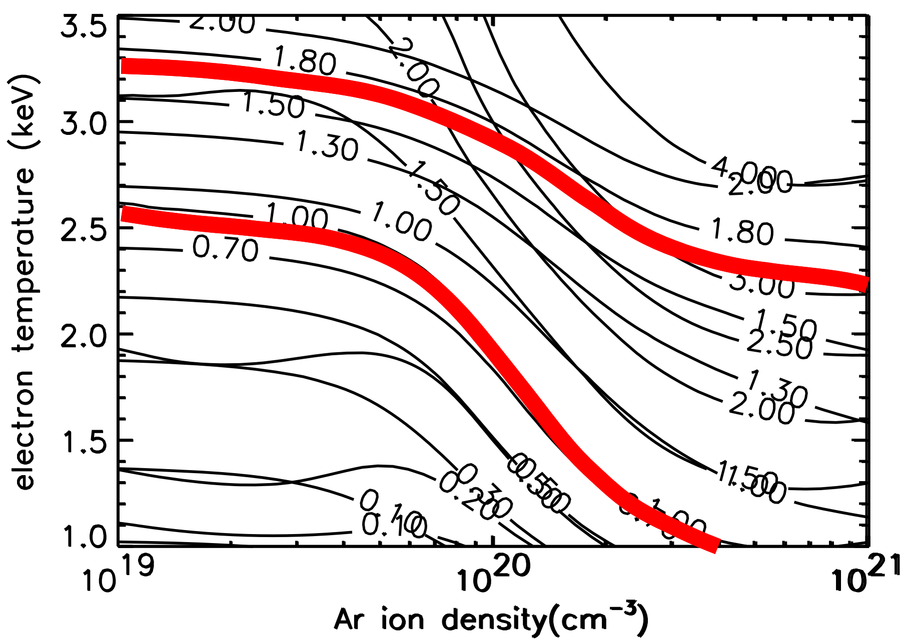




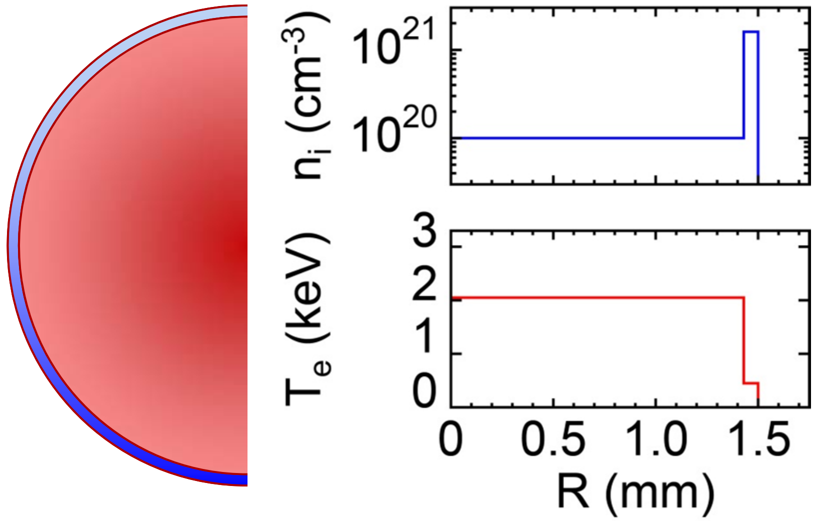
Uniform plasma model cannot explain observed line ratios



- Compare the measured ratios with calculations just before peak x-ray power
- There is no solution for plasma conditions that match both α and β line ratios



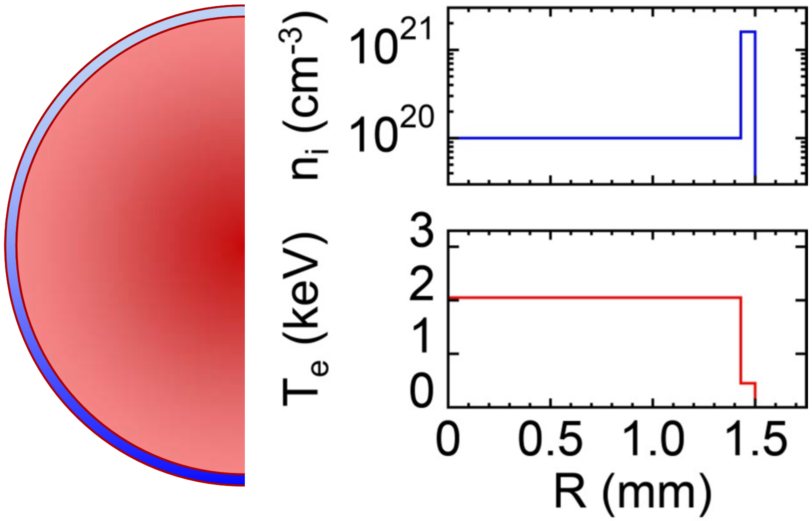
Cold, dense outer layer can attenuate He-α, affecting ratios

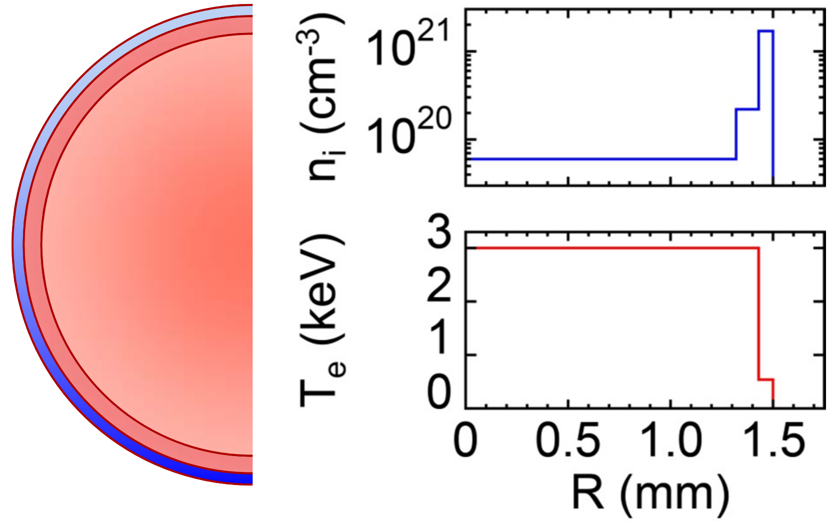


	Data	Model
Lyα/Heα+IC	1.70 ± 10%	1.57
Lyβ/Heβ+IC	0.95 ± 10%	1.03
P_K (TW/cm)	18 ± 50%	22
Mass (mg/cm)	1.0 ± 0.1	1.09

- This model [J. P. Apruzese] includes collisional-radiative equilibrium in each zone
- Radiation transport calculation determines the emerging spectrum
- Higher He-α opacity modifies the α line ratio, allowing for a consistent fit
- Measured line ratios constrain the plasma properties in the core and blanket

Solution is not unique, can admit a 'hollow' emission profile



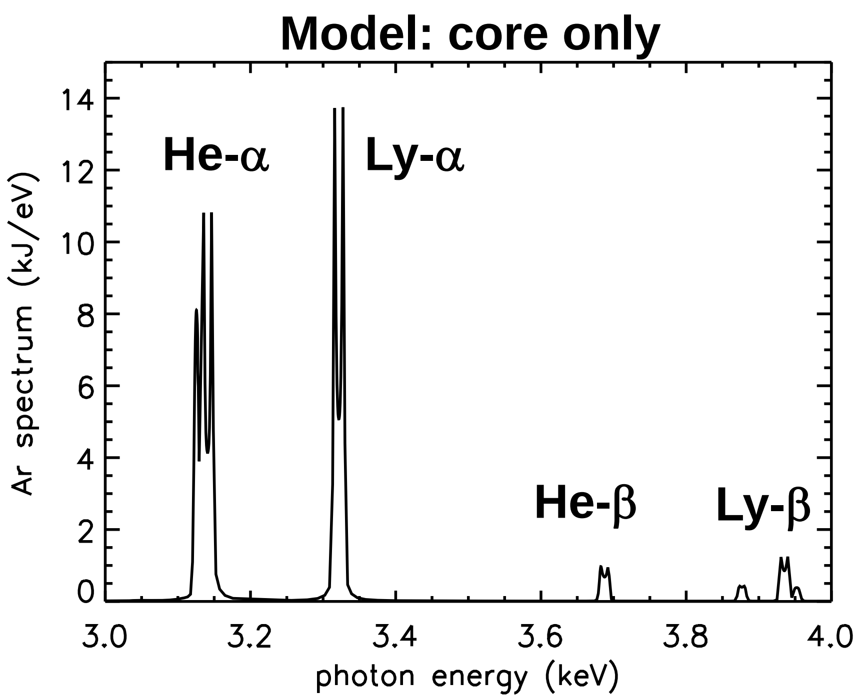


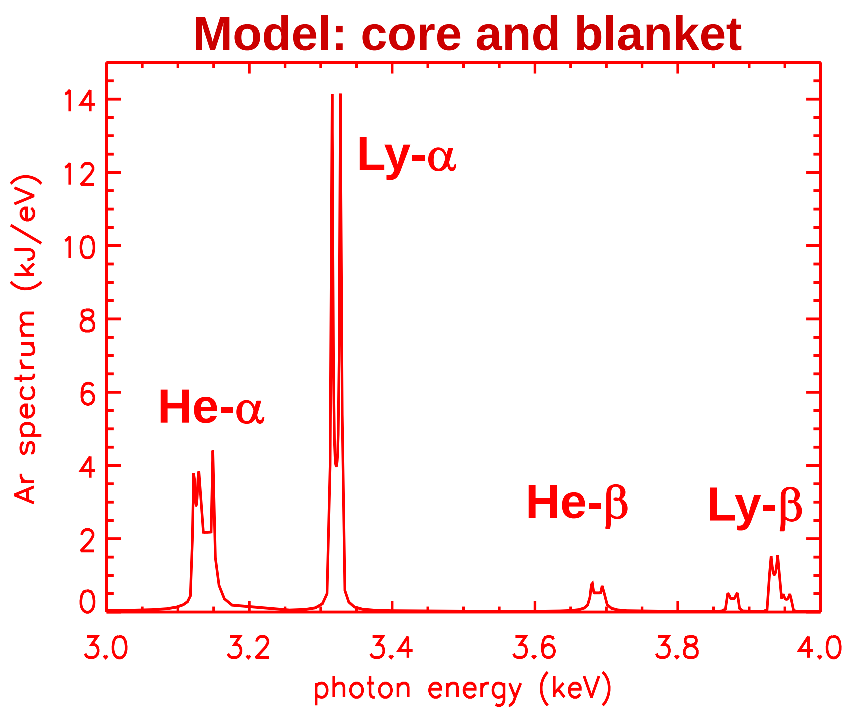
	Data	Model
Lyα/Heα+IC	1.70 ± 10%	1.57
Lyβ/Heβ+IC	0.95 ± 10%	1.03
P_K (TW/cm)	18 ± 50%	22
Mass (mg/cm)	1.0 ± 0.1	1.09

	Data	Model
Lyα/Heα+IC	1.70 ± 10%	1.59
Lyβ/Heβ+IC	0.95 ± 10%	1.01
P_K (TW/cm)	18 ± 50%	33
Mass (mg/cm)	1.0 ± 0.1	1.09

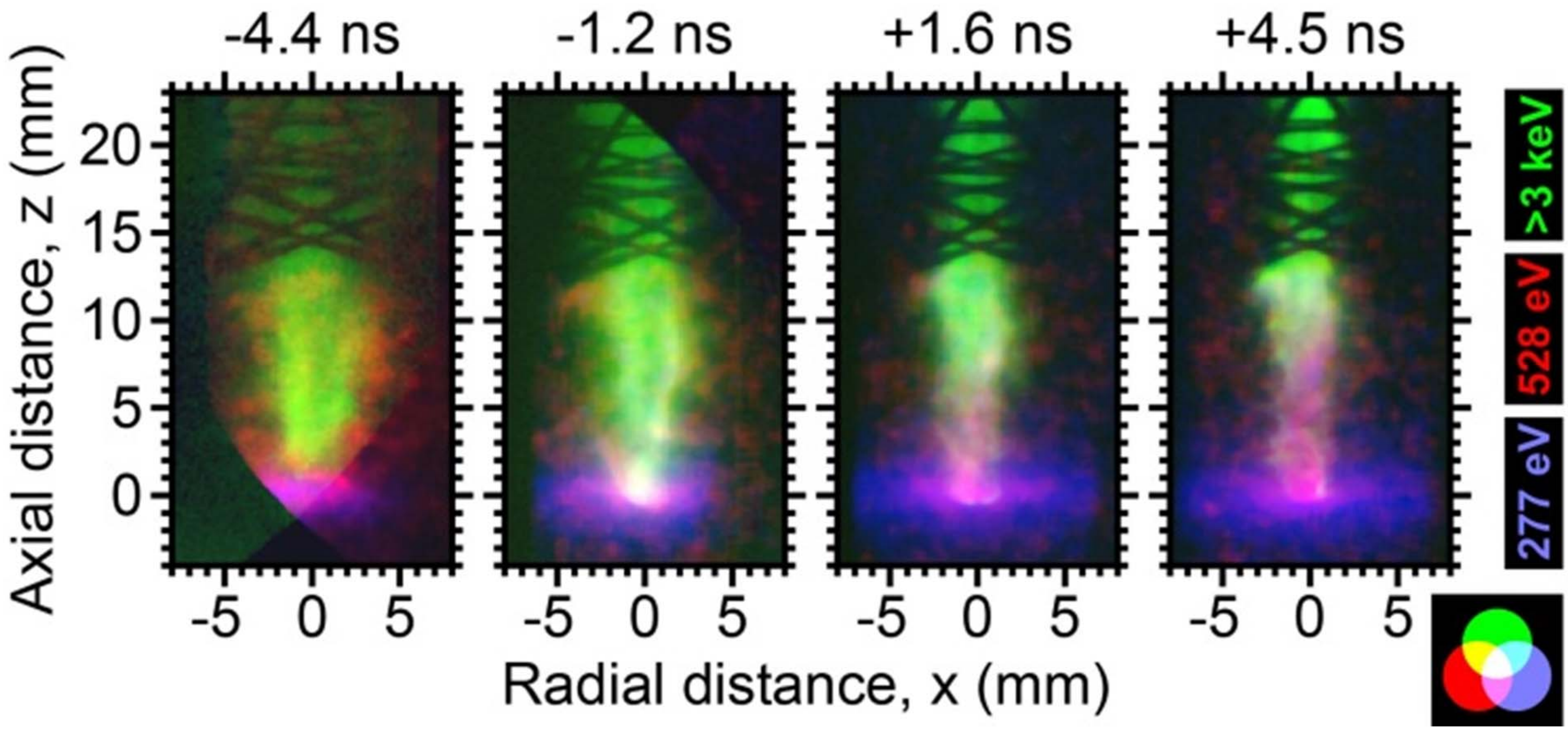
Opacity in the blanket has a strong effect on He-α emission

- Only ~10% effect on net K yield for Ar, which has strong Ly-α
- Opacity may be more harmful to yield for predominantly He-α radiators (e.g. Kr gas puffs)
- In both models, 60-70% of the mass is in the outer blanket
- More mass in the hot core could improve Ar K-shell yield



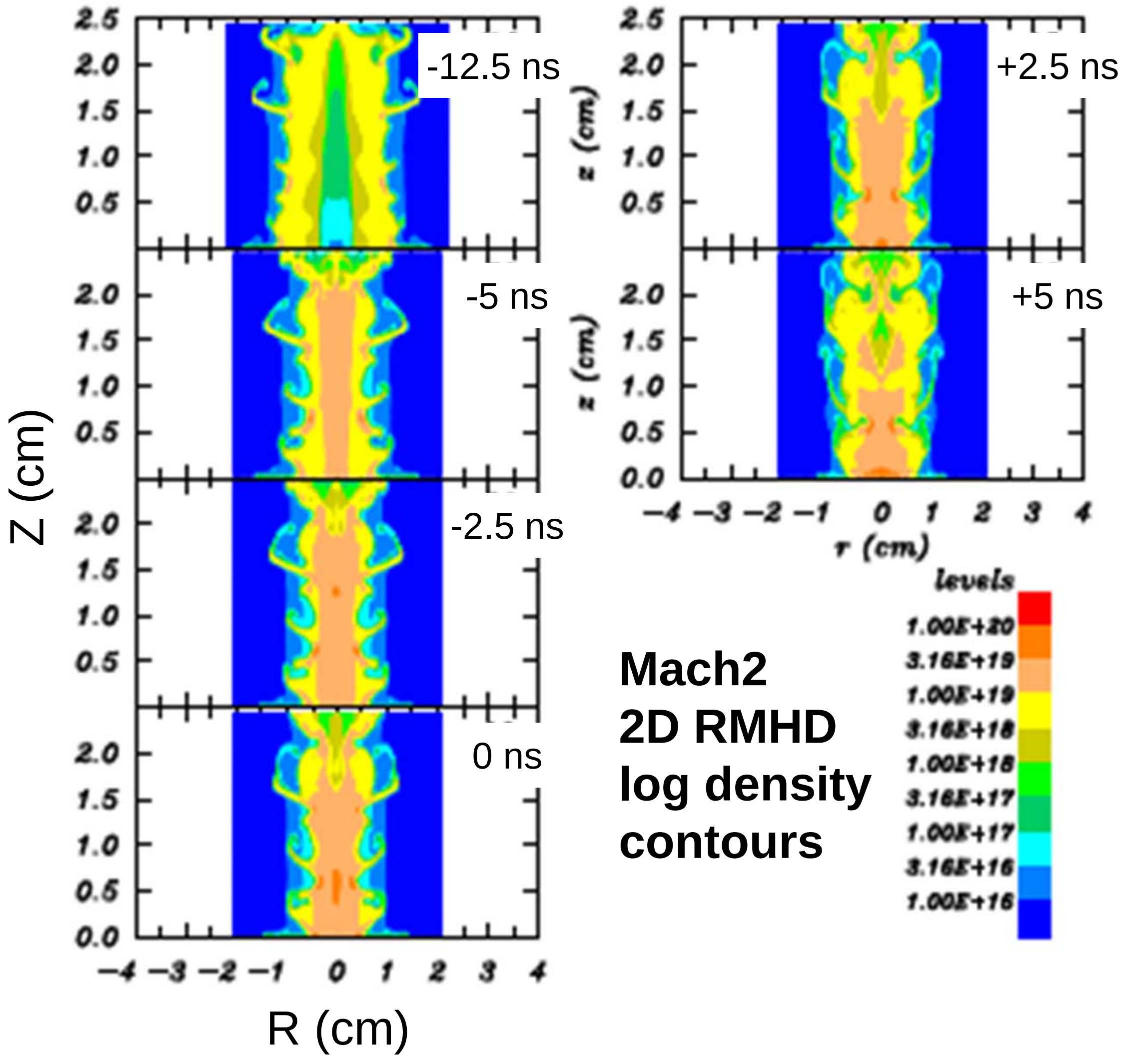


Stagnating plasma exhibits hollow structure and zippering



- Limb brightening observed in pinhole imaging at 277 eV, 528 eV, and >3 keV suggesting a hot, dense annulus in the plasma column
- Pinch zippers from cathode to anode

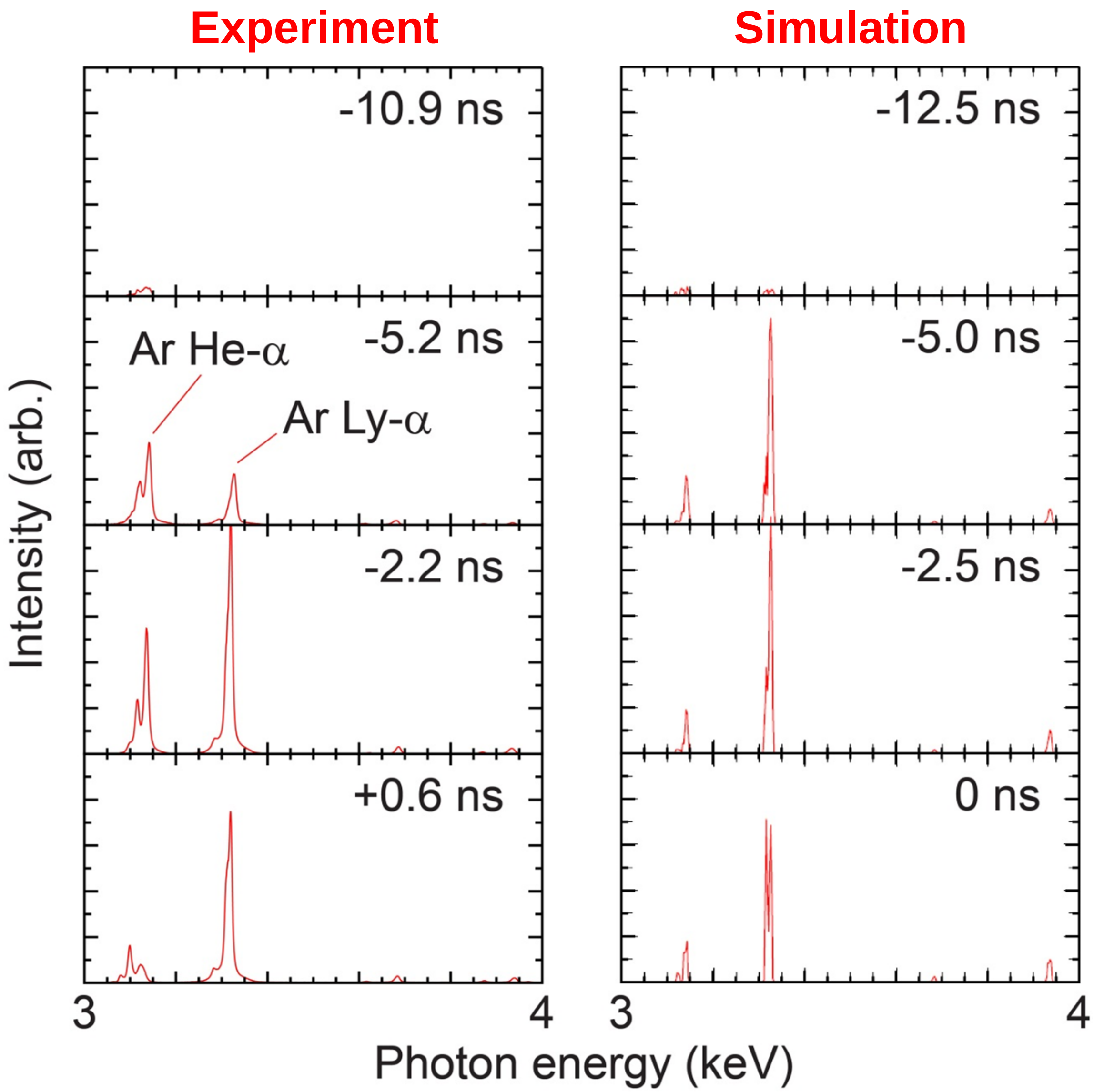
Z experimental data may now be used to validate the numerical models and improve simulation capability



Mach2
2D RMHD
log density
contours

- Simulated zippering in the wrong direction, from anode to cathode: initial (unknown) current path may be incorrect
- Simulation does not show hollow plasma structure at stagnation: plasma parameters in imploding shell may be inaccurate

Electron temperature is too high in Mach2 2D RMHD model



- Ar Ly-α turns on early in model, and exceeds Ar He-α well before stagnation (e.g. -5 ns)
- Could be the result of the on-the-spot radiation opacity model, which may tend to trap radiation locally and retain too much internal energy

Summary

- Z gas puffs have been designed with the aid of RMHD modeling
- Bright Ar K-shell emission is produced on Z with 250-400 kJ yields
- An initial study of the stagnating plasma structure suggests that a cold, dense blanket surrounds the hot core
- Future work will seek to understand and to optimize gas puffs
  - Continue to study the structure in the stagnating plasma and the role of opacity in affecting line ratios and yield
  - Vary the radial mass distribution, including assessment of a center jet, to stabilize magnetic Rayleigh-Taylor and control final plasma conditions
  - Understand the energy coupling to the plasma and current losses
  - Measure the initial current path and early time implosion dynamics in order to validate simulations early in the pinch evolution
  - Compare numerical models to understand differences in trends
  - Kr 12 cm diameter implosions (D. J. Ampleford/C. A. Jennings)
    Ar 12 cm diameter long pulse and central jet (A. J. Harvey-Thompson)
    Deuterium gas puffs (P. F. Knapp)