SAND2022-6160C

U.S. NAVAL RESEARCH LABORATORY

Bright-Spot Contributions to Hard-Photon Continuum K-Shell Yield from Argon and Stainless-Steel Implosions on Z

Presented at the 49th IEEE International Conference on Plasma Science Seattle, Washington, USA, May 22-26, 2022

A. L. Velikovich,[1] N. D. Ouart[1] J. L. Giuliani (Emeritus),[1] A. Dasgupta,[1] V. Tangri,[1] A. J. Harvey-Thompson,[2] M.-A. Schaeuble,[2] J. Schwarz,[2] C. E. Myers,[2] D. J. Ampleford,[2] R. A. Vesey,[2] B. Jones,[2] Y. Maron,[3] V. Bernshtam,[3] Yu. Zarnitsky,[3] and V. Fisher[3]

[1]Plasma Physics Division, Naval Research Laboratory, Washington DC 20375 USA
[2]Sandia National Laboratories, Albuquerque, NM 87185 USA
[3]Weizmann Institute of Science, Rehovot 7610001, Israel

Work at NRL is supported by the US DOE/NNSA. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

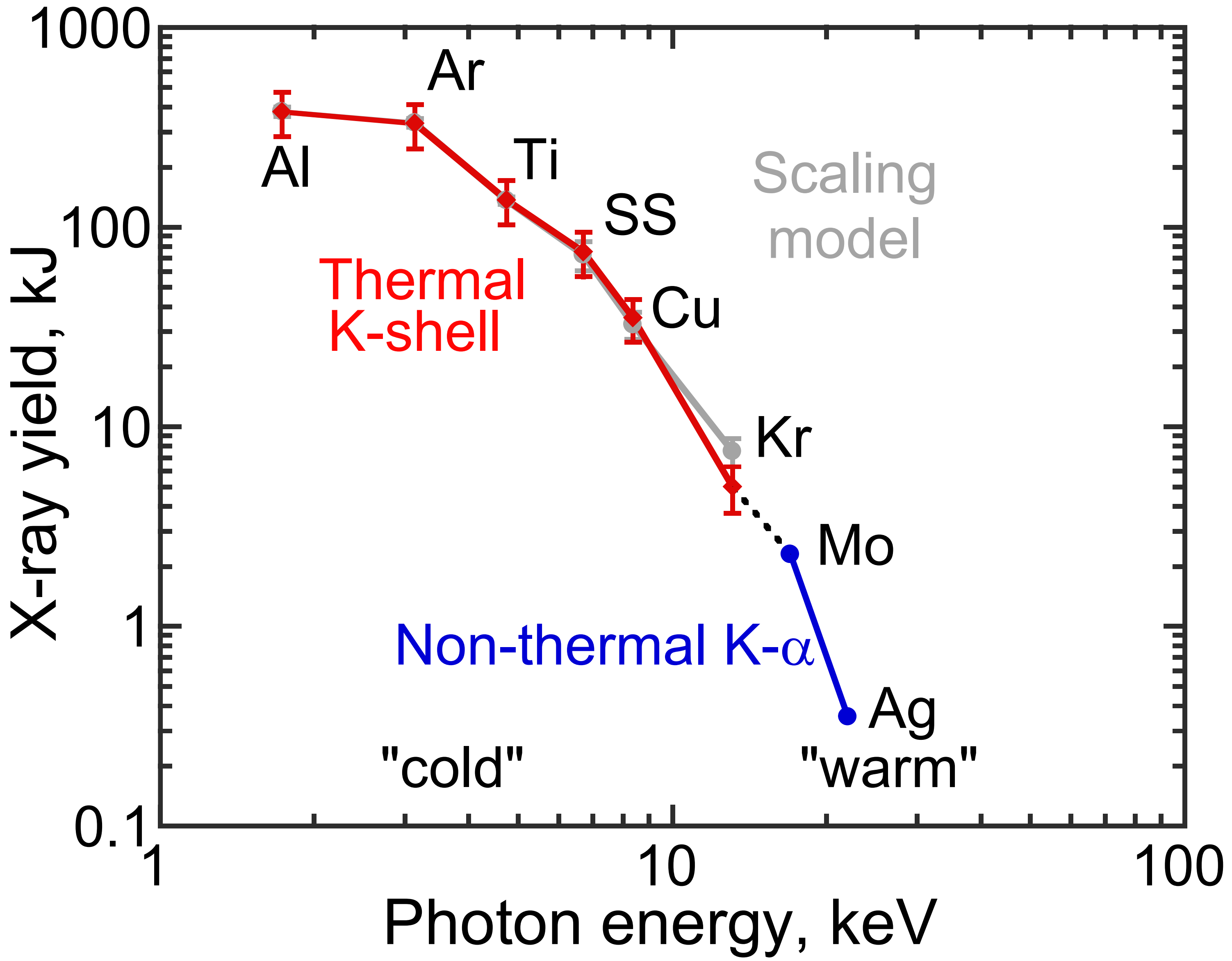
Summary/Conclusions

- Hard-photon direct recombination continuum alternative paths to “warm” x-ray production above 15 keV with pulsed power for next-gen pulsed power facility, NGPP
- A scaling model is needed to confidently predict the radiation yields from NGPP
  - Densities and temperatures of radiating plasmas at stagnation need to be confidently scaled up
- Scaling models are based on the conventional assumption of a uniform radiating plasma column, which is plausible for Ar but not for stainless steel
- Most likely, stainless steel emits K-shell from bright spots
- Continuum yield data from Z is consistent with the spectroscopic analysis indicating that the dense, hot bright spots containing a small fraction of the load mass radiate most of the K-shell x rays
  - Dimensions, densities, and temperatures of the bright spots can be inferred
  - The mechanism of their creation and energy replenishment is still obscure

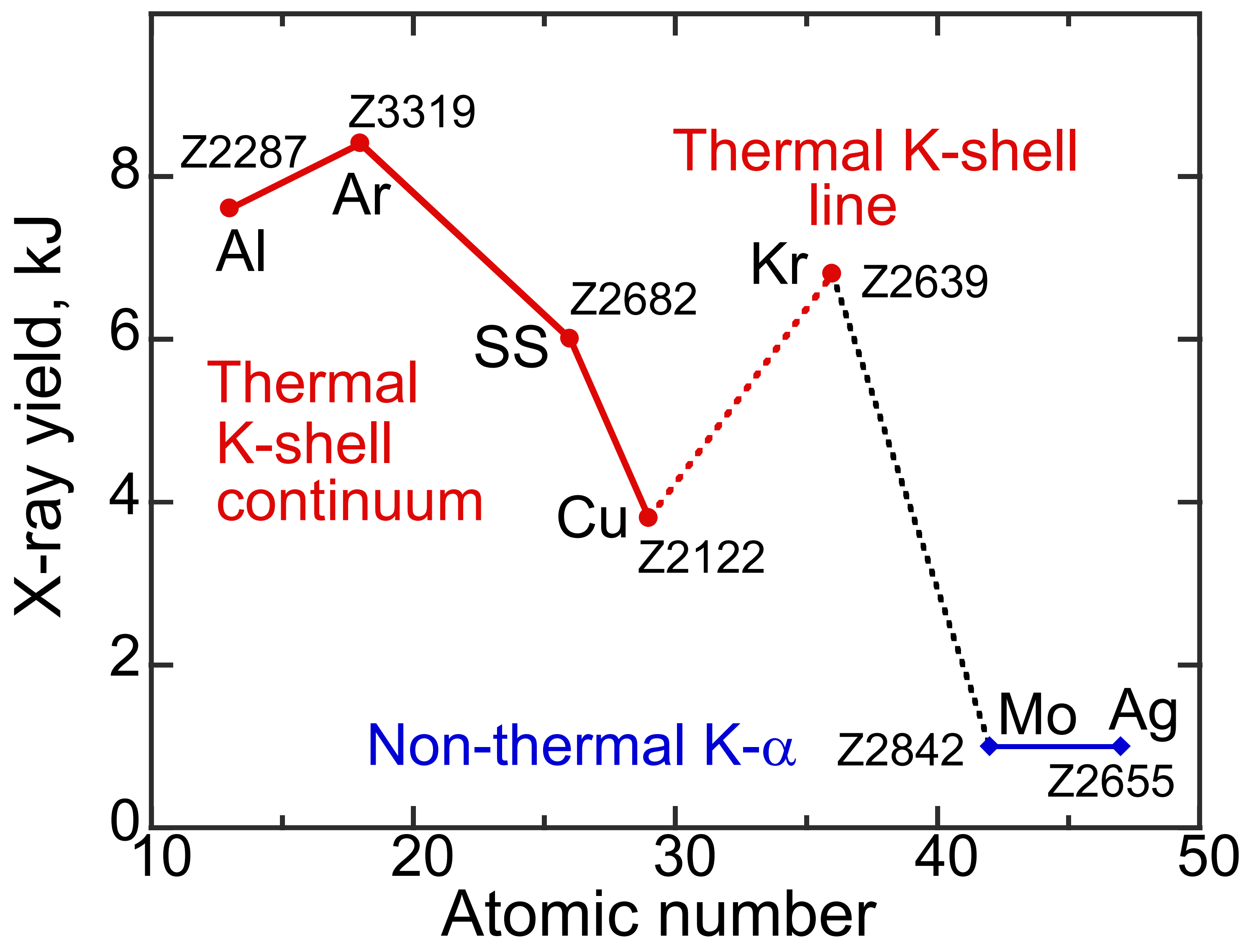
Motivation

NRL PPD

K-line yields on Z are low for high atomic numbers



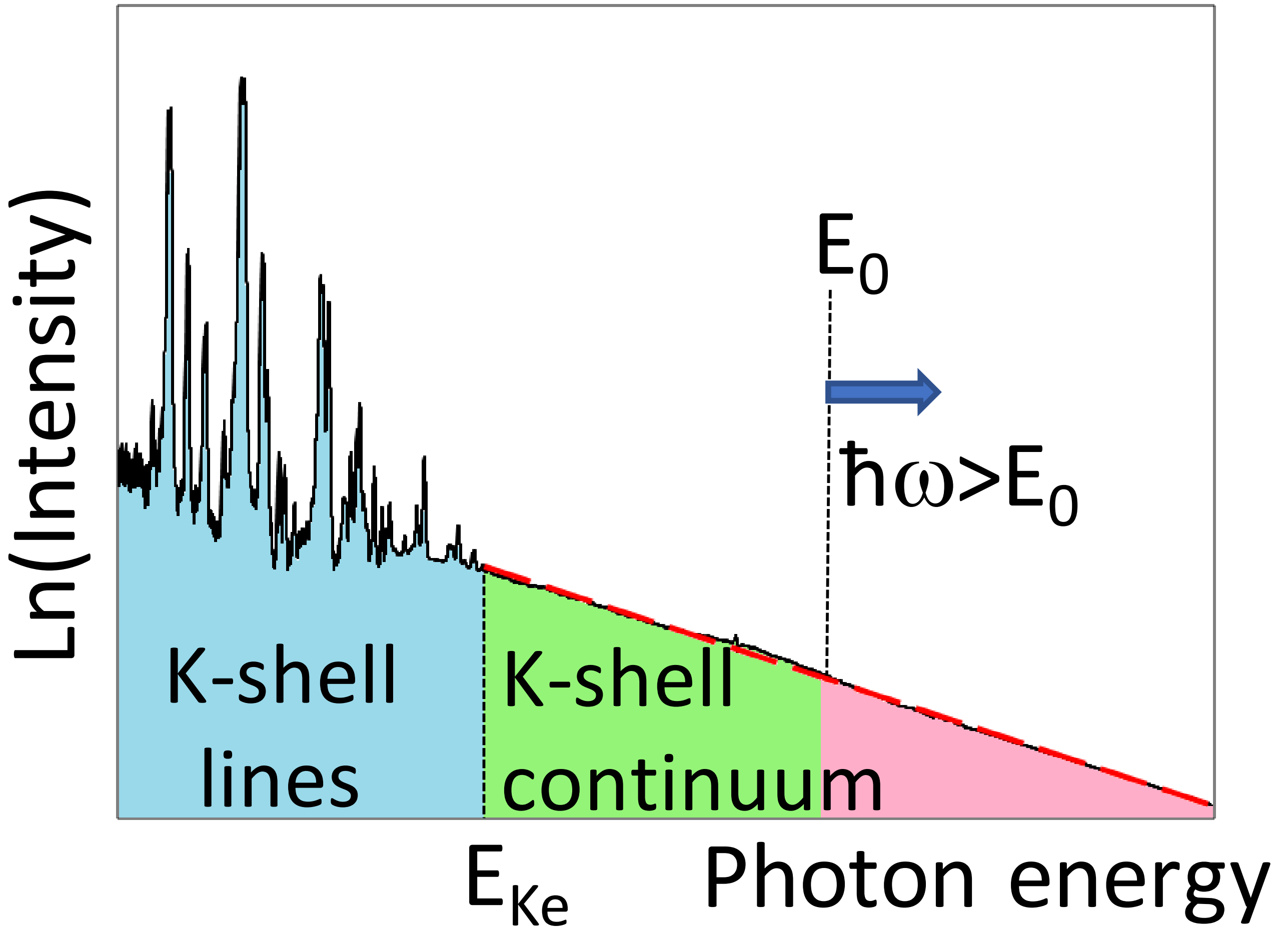
Continuum & line yields on Z in photon energies between 10 and 15 keV



Scaling: J. Schwarz et al., “A model for K-shell x-ray yield from magnetic implosions at Sandia’s Z machine,” submitted to Phys. Plasmas 2022.

Background

Example: Z3151 stainless wire array

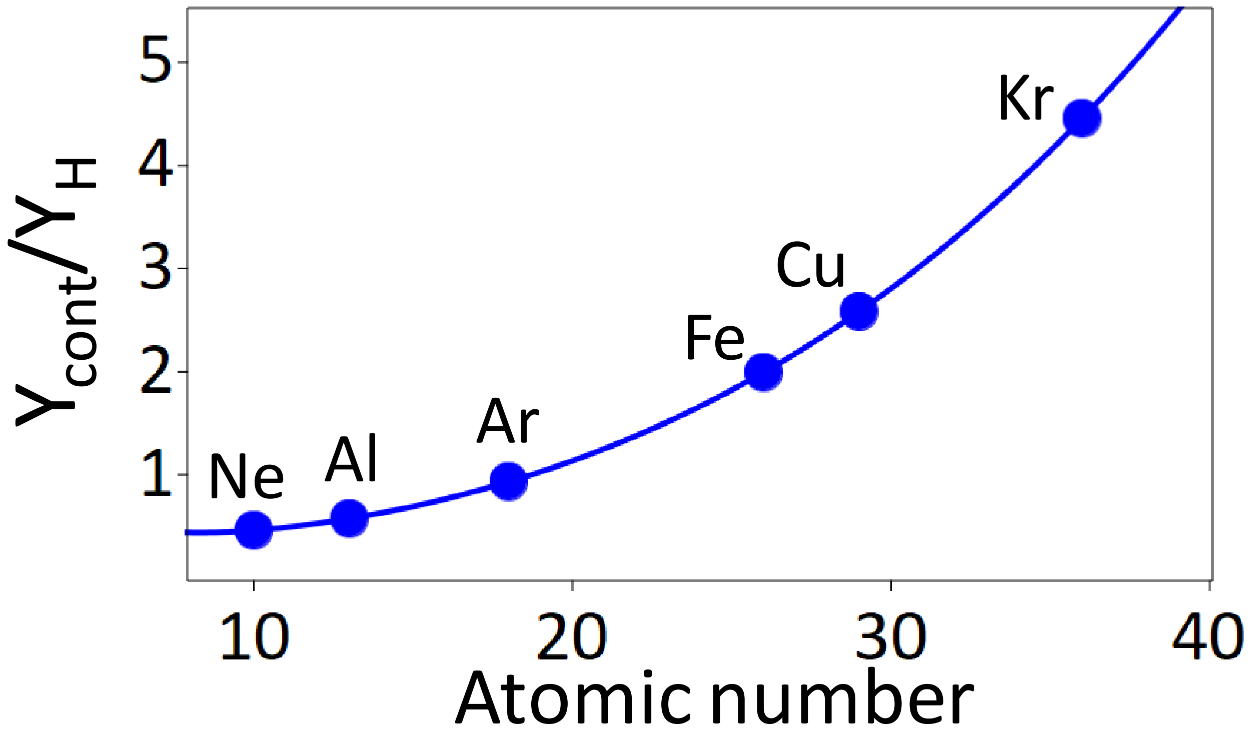


T_e = 3.56 keV
E_{Ke} = 9.2 keV
Y_{cont} = 6.3 kJ

T_e, keV

$$Y(\hbar\omega > E_0) = Y_{cont}\exp\left(-\frac{E_0 - \mathrm{Ryd}\cdot Z^2}{T_e}\right)$$

$$\frac{Y_{cont}}{Y_H} = \frac{2\alpha^3}{3\pi\phi_H}\left(Z_A - \frac{1}{2}\right)^4 \exp\left[\frac{\mathrm{Ryd}}{4T_e}(3Z_A - 1)(Z_A - 1)\right]$$



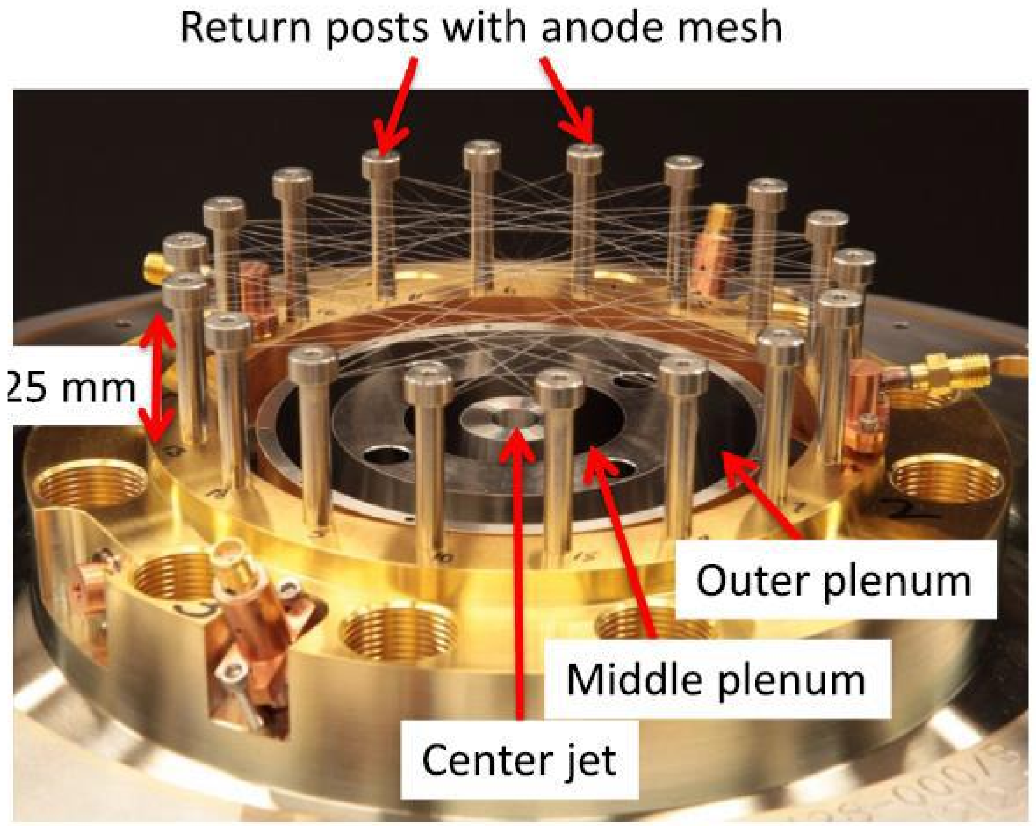
@ K-shell production optimal temperature

$$T_e = 0.3\times Z_A^{2.9}\ \mathrm{eV}$$

Argon and stainless steel PRS load designs optimized for K-shell emission

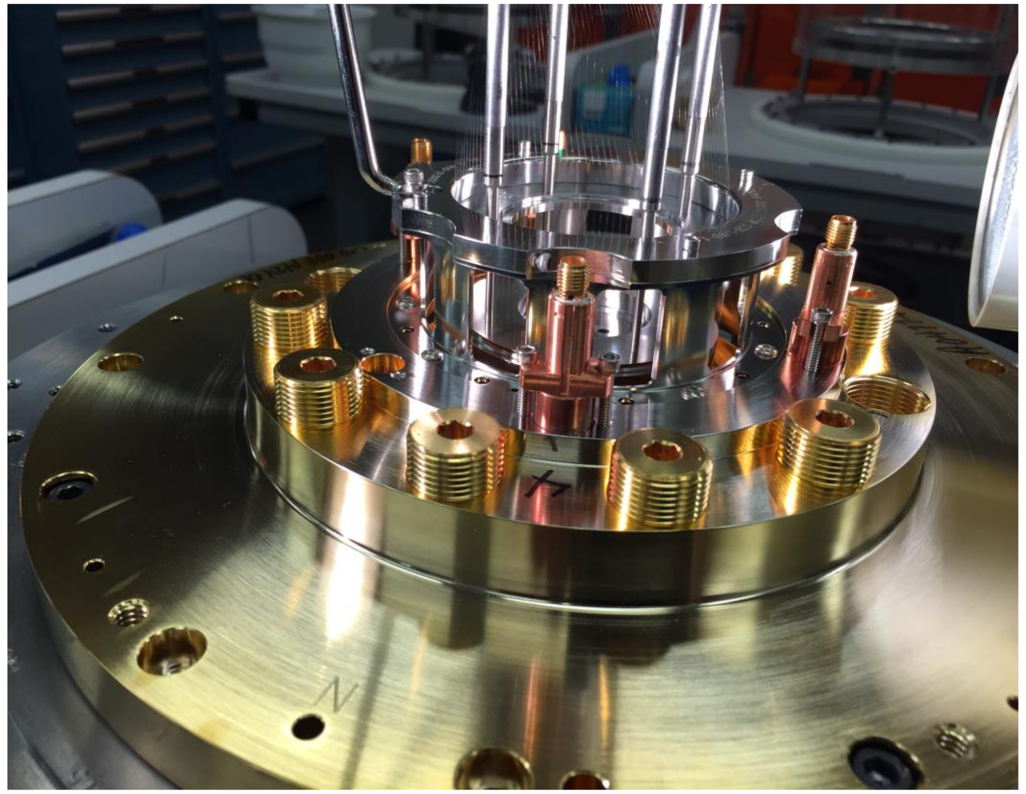
NRL PPD

Argon, 25 shots



- Double-shell ∅80 mm gas puff
- Most shots w/o central jets
- Line masses ~385/616 μg/cm
- Height 3 cm

Stainless steel, 8 shots



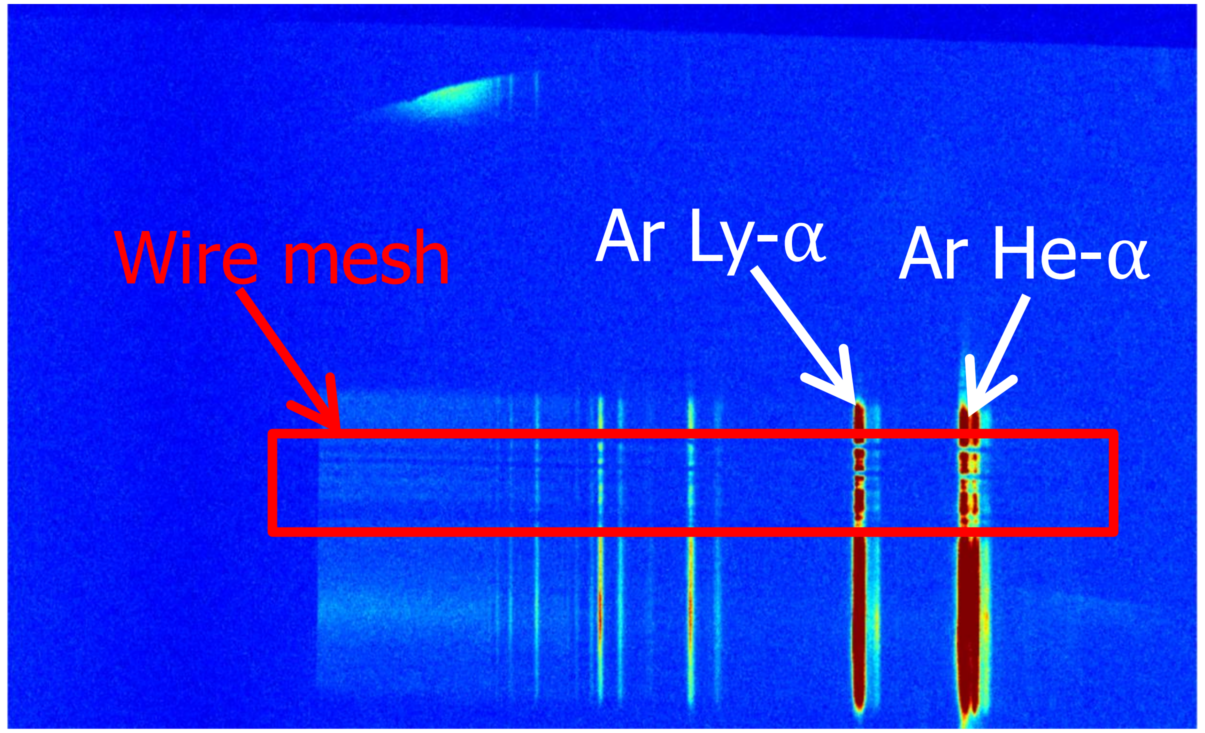
- Nested wire array, ∅70/35 mm, 112/56 wires
- Wire diameter 8.56 μm
- Total mass ~1.533 mg
- Height 2 cm

B. Jones *et al.*, Phys. Plasmas **22**, 020706 (2015); A. J. Harvey-Thompson *et al.*. Phys. Plasmas **23**, 101203 (2016); D. J. Ampleford, *et al.*, Phys. Plasmas **21**, 056708 (2014).

Dimensions and of the K-shell emitting plasma are confidently measured

NRL PPD

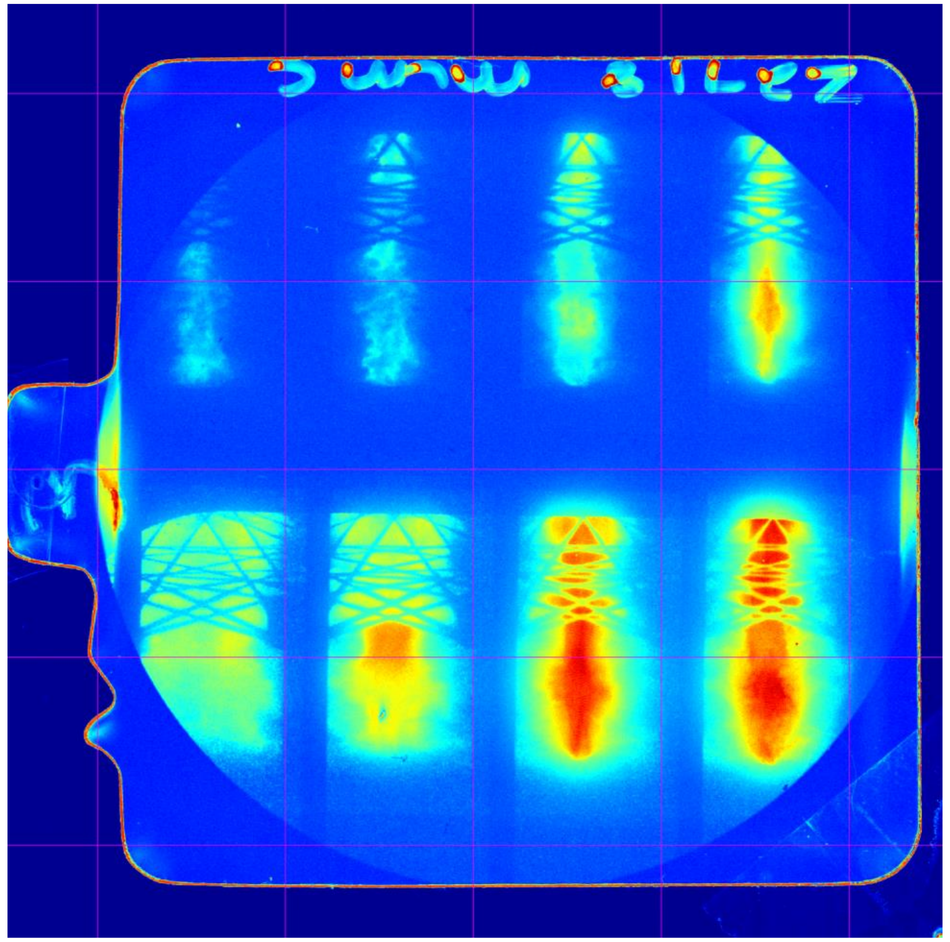
Time-integrated, axially resolved spectroscopy



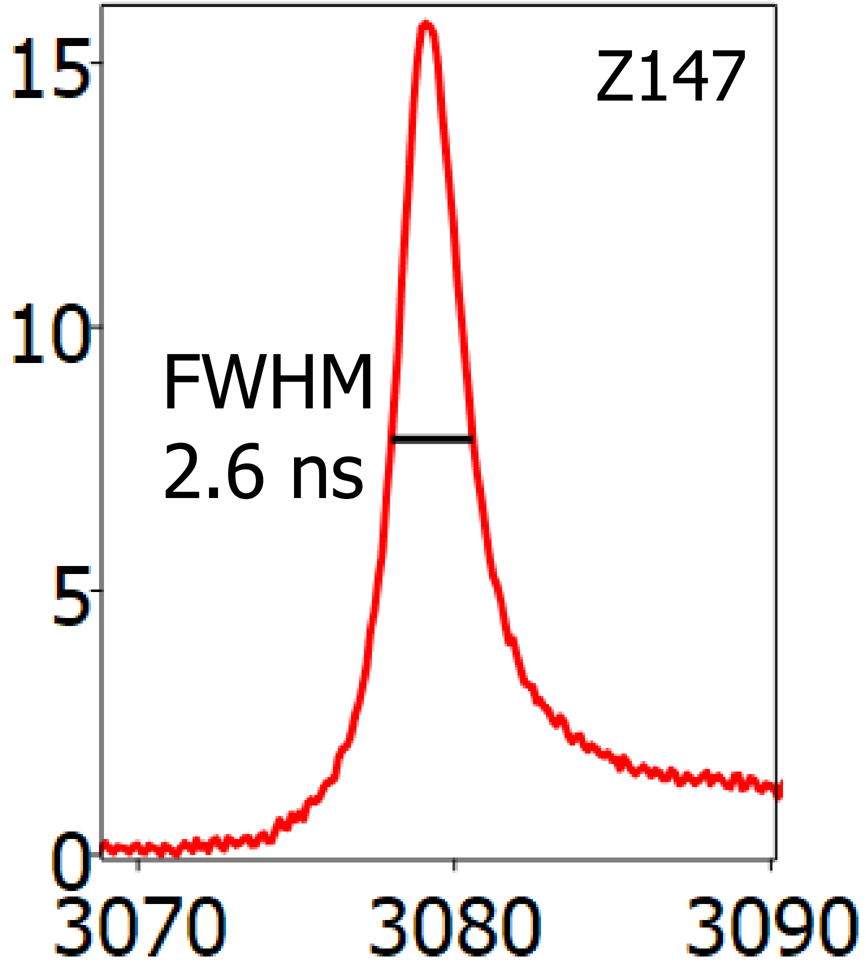
K-shell height Ar

K-shell diameter Ar

Time-gated multi-layer-mirror (MLM) x-ray camera



X-ray power signal, arb. units



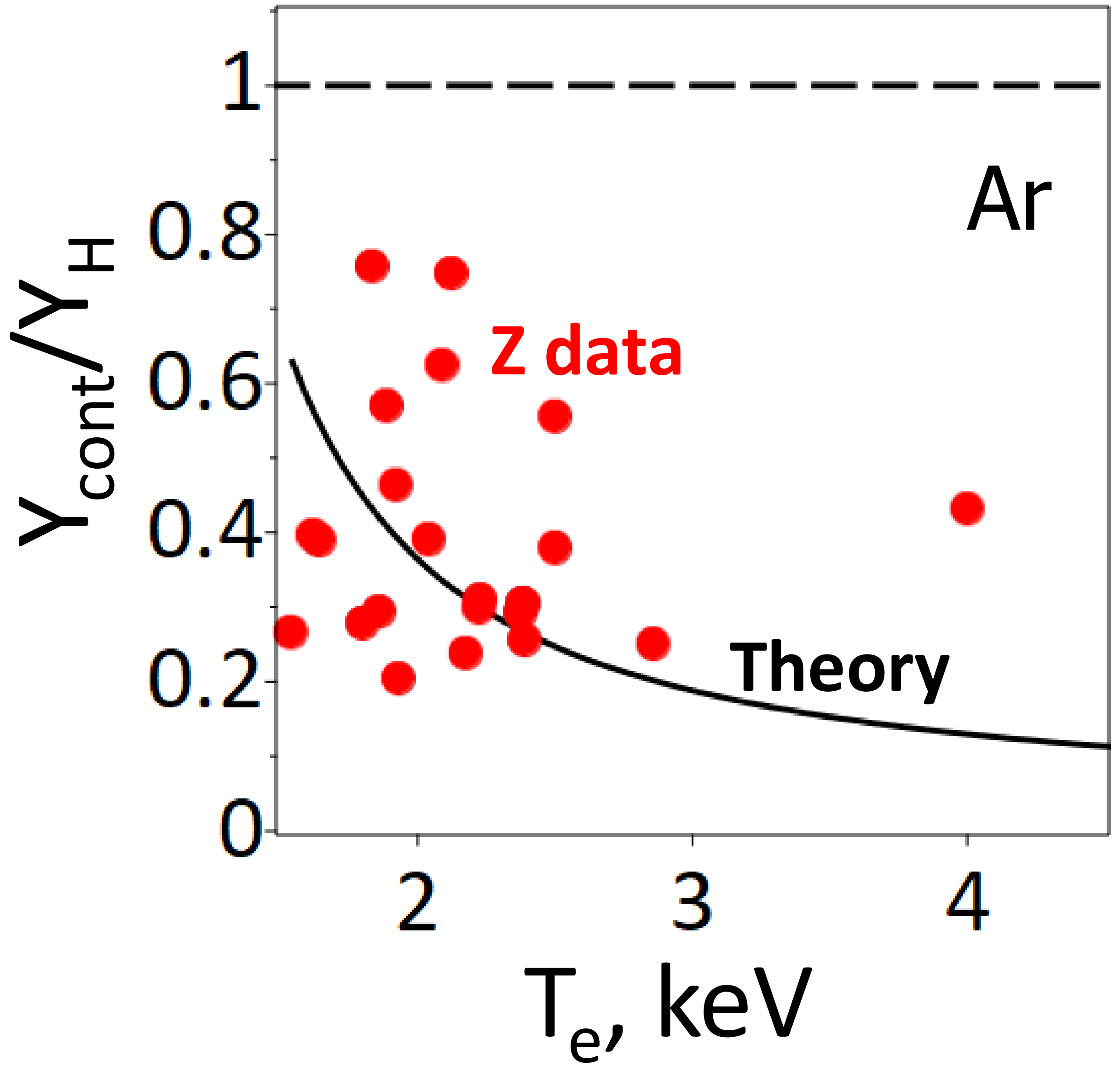
t, ns

K-shell FWHM SS

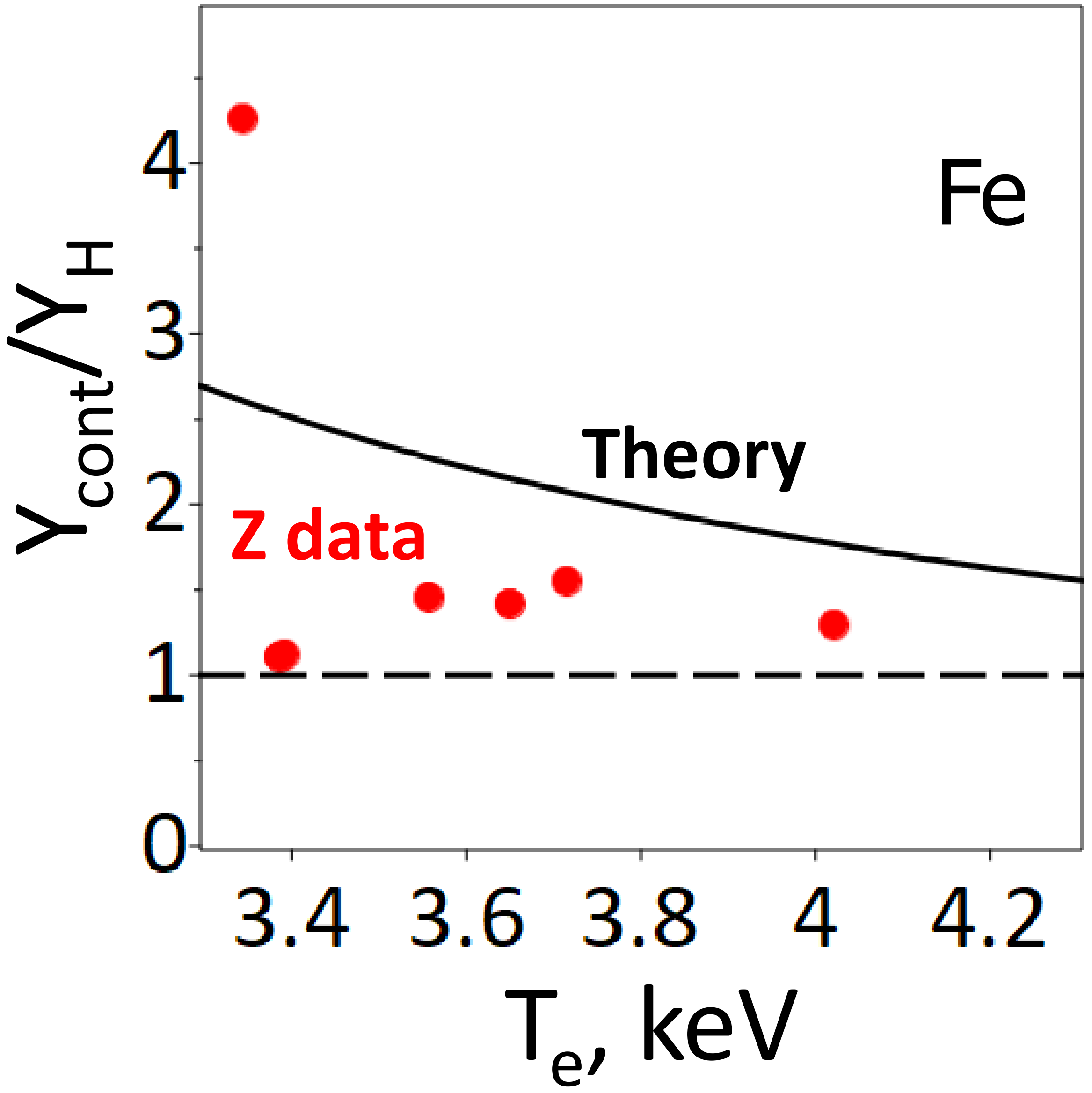
	Height, mm	Diameter, mm	Volume, cm^3	FWHM, ns
Argon	2.5 to 3.5	1 to 3	0.05 to 0.36	4 to 12
Stainless	2	0.8	0.01	2.5 to 3.5

Higher-atomic-number materials radiate relatively more in the continuum

Argon: the yield in continuum is less than in Ly lines, even though bare ions contribute



Iron: the yield in continuum is greater than in Ly lines; no contribution from bare ions



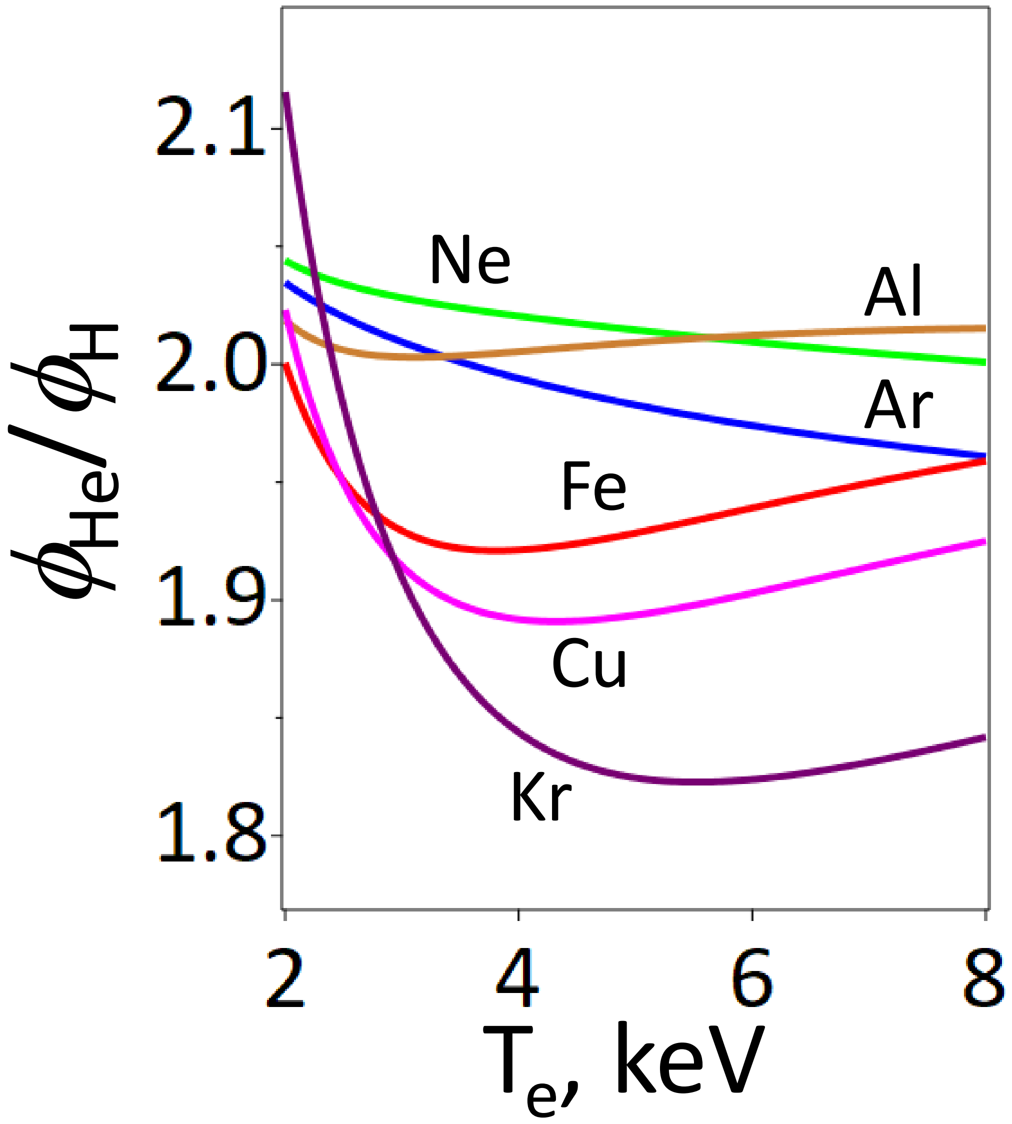
He-like ions are more efficient K-line radiators than H-like by a factor of ~2

NRL PPD

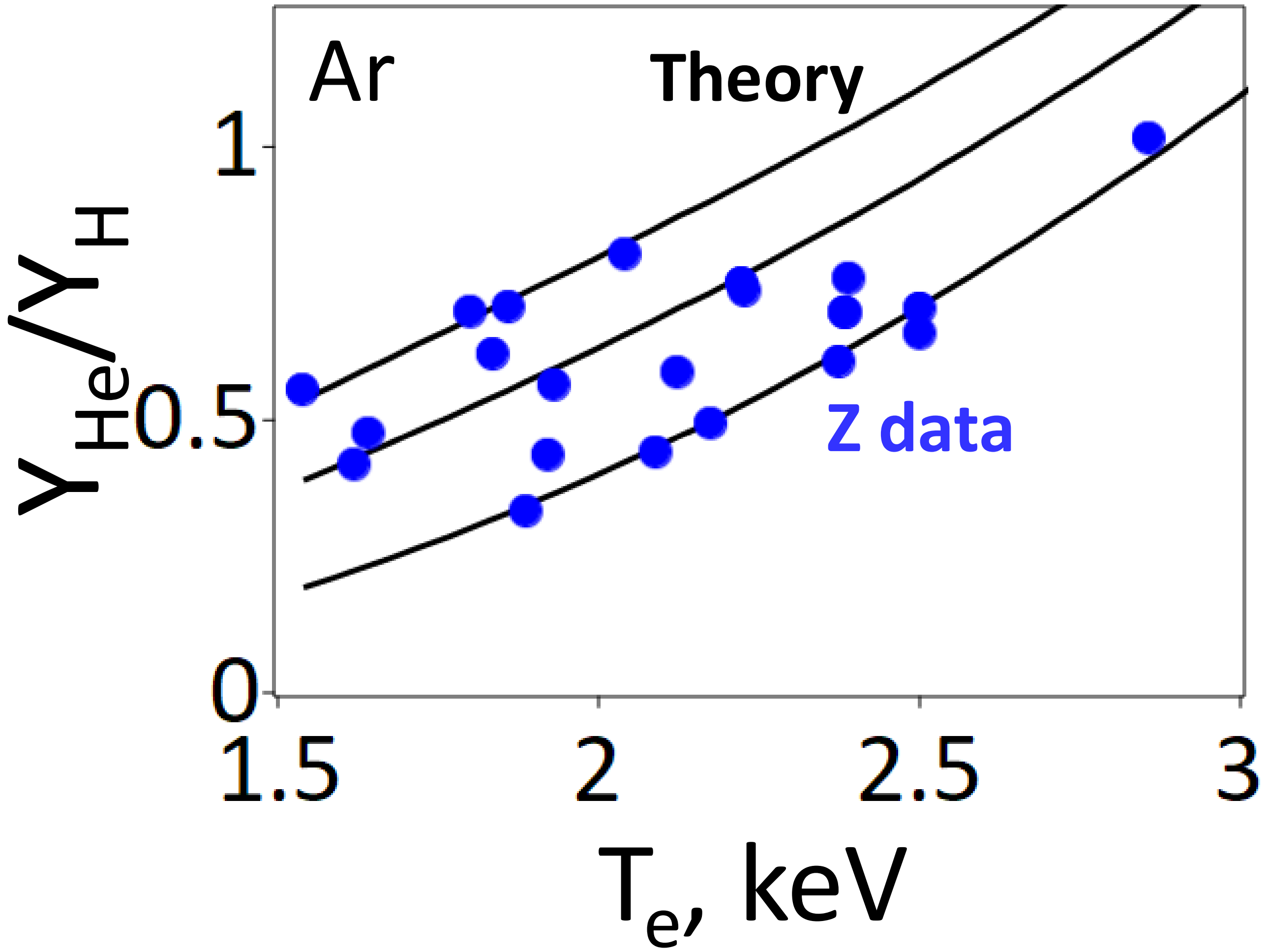
Ratio of H-like to He-like yields

$$\frac{Y_H}{Y_{He}} = \frac{n_{i,H}}{n_{i,He}} \cdot \frac{\phi_H}{\phi_{He}}$$

Seaton's formula fit with FAC atomic data



Argon on Z: more H-like than He-like ions, Yield in He lines slightly higher than in Ly lines



The highest hard-photon continuum fractions we can reasonably expect

NRL PPD

Moderate-Z_A argon, accessible now

Z

$Y_H/Y_{He} = 0.6$

$Y_{cont}/Y_H = 0.4$

=>

$Y_{cont}/Y_K \sim 0.13$

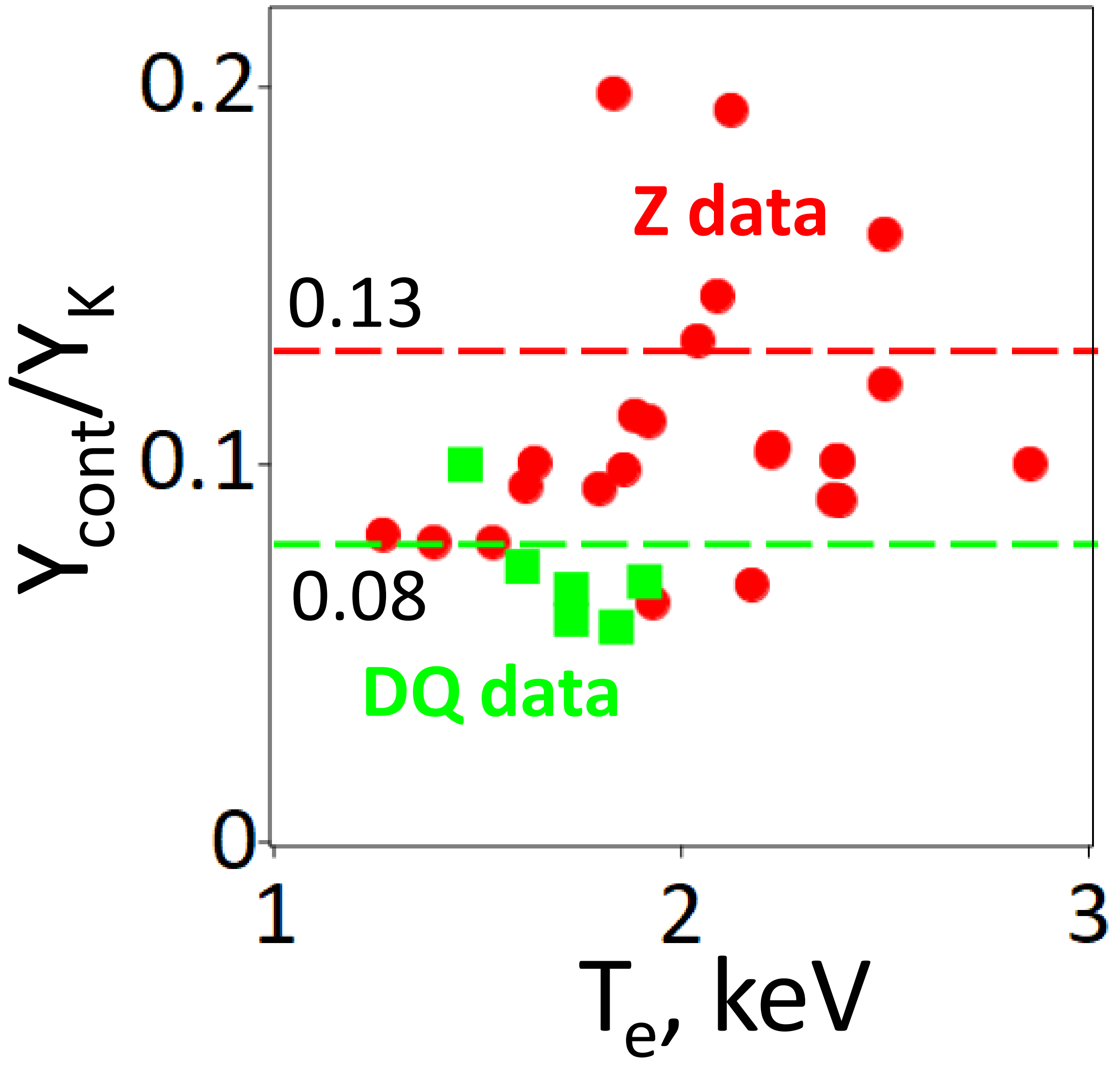
DQ

$Y_H/Y_{He} = 0.4$

$Y_{cont}/Y_H = 0.3$

=>

$Y_{cont}/Y_K \sim 0.08$



DQ data from F. C. Young *et al.*, IEEE Trans. Plasma Sci. **34**, 2312 (2006).

High-Z_A iron or copper on NGPP

If $Y_H/Y_{He} = 0.5$

Then $Y_{cont}/Y_H > 1$

=>

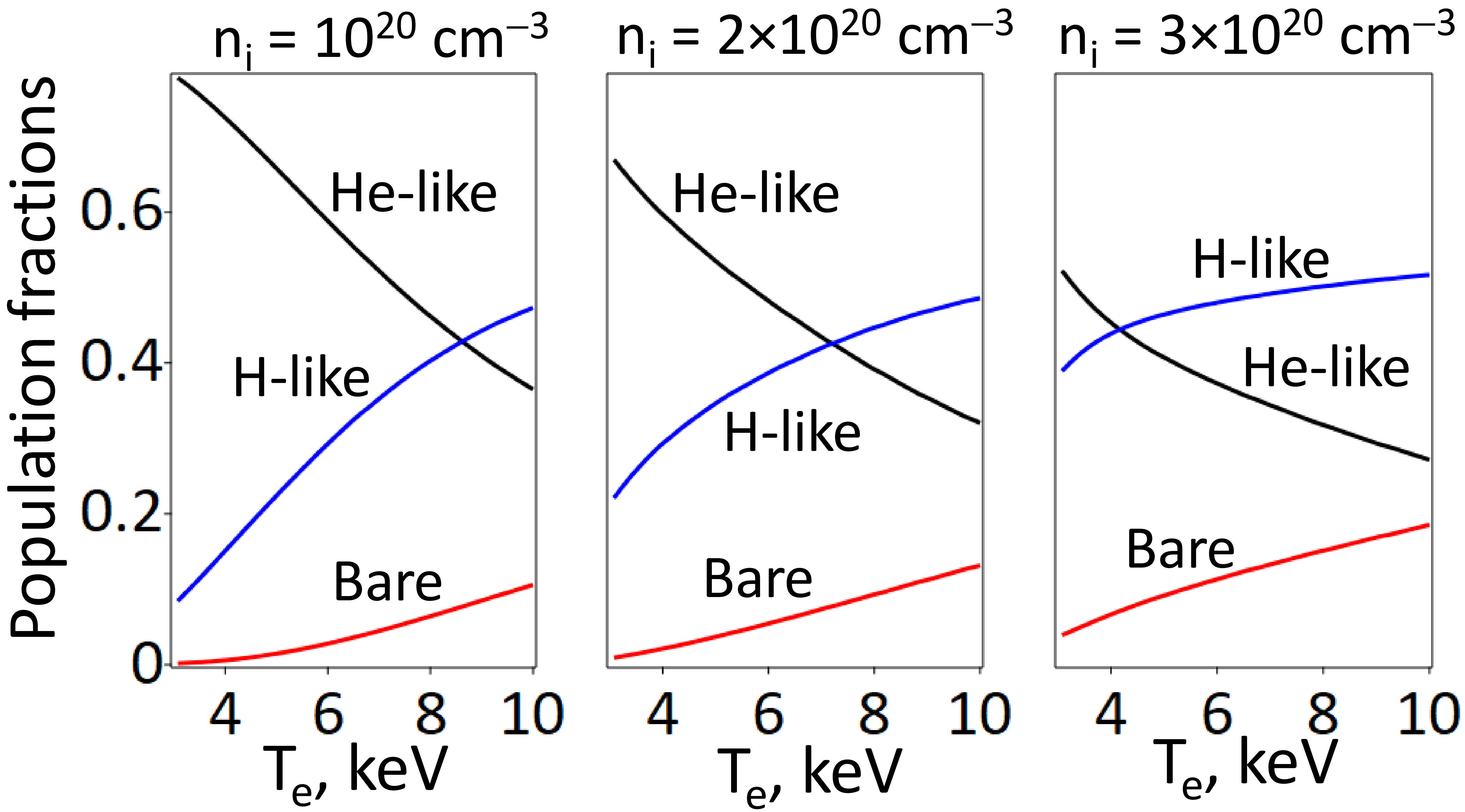
$Y_{cont}/Y_K > 0.25$

A 25% continuum efficiency at high Z_A is possible if we can produce an H-like population no less than He-like

Distribution Statement A. Approved for public release, distribution is unlimited

We need high temperatures and densities to ionize Fe to H-like

CRE equilibrium populations calculated for a ∅3 mm plasma cylinder with DRACHMA-II



Ion populations are very sensitive to the ion densities above $n_i \sim 2\times10^{20}$ cm^{-3}

Ion number density can be inferred from the hard-photon continuum power

NRL PPD

$$W_{cont} = F\left(T\right) m_K n_i \left(2 f_b + f_H\right)$$

Radiation power is proportional to the product of the radiating mass and ion density

$$n_i = \frac{W_{cont}}{F\left(T\right) m_K \left(2 f_b + f_H\right)}$$

where the ion populations for our parameter range are estimated as

$$2 f_b + f_H \approx \begin{cases} 1 \text{ for Ar} \\ f_{He} \cdot 2Y_H / Y_{He}, \quad f_{He} \approx 0.7 \quad \text{for SS} \end{cases}$$

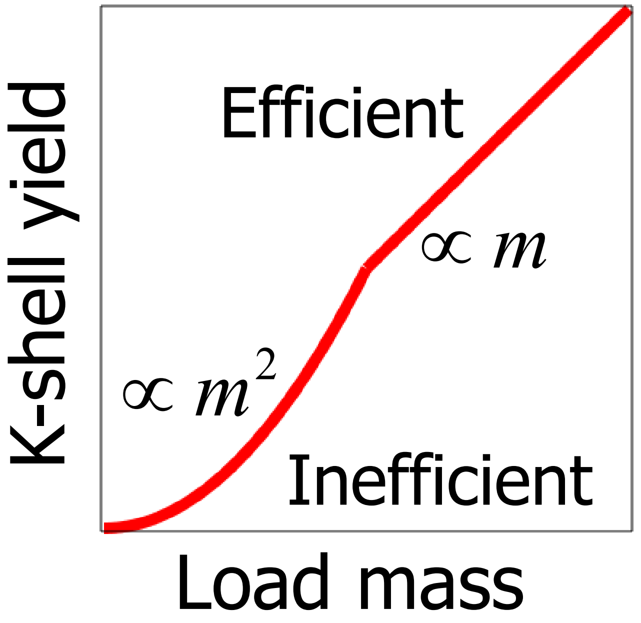
$$m_K = R_K \sqrt{\frac{W_{cont} \pi m_i}{F\left(2 f_b + f_H\right)}}$$

Self-consistent value of the continuum K-shell emitting mass, obtained by assuming the radiating plasma to be uniform

Assumptions for scaling line and continuum K-shell yields to higher currents

$$Y_K \propto m \cdot (\text{K-shell mass participation}) \cdot n_i$$

- Matched load mass increases as I^2. Some options for self-similar scaling:[1]
  - Mass participation and ion density stay constant[2]
    - Efficient K-shell emission, $Y_K \propto I^2$, radiating volume increases $\propto m$
    - Works well for argon above 5 MA
  - Mass participation and radiating volume stay constant[2]
    - Inefficient K-shell emission, $Y_K \propto I^4$
    - Works well for argon[3] below 5 MA and for stainless[4] up to 20 MA
    - Uncertain about stainless above 20 MA – what stays constant, what changes?

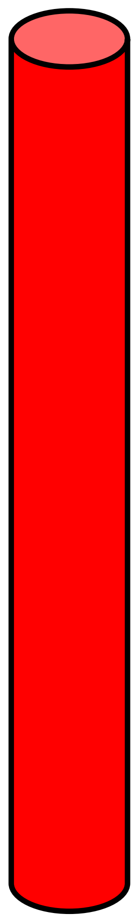


[1]P. F. Schmit and D. E. Ruiz, Phys. Plasmas **27**, 062707 (2020).
[2]J. W. Thornhill *et al.*, IEEE Trans. Plasma Sci. **34**, 2377 (2006).
[3]This conference: V. Tangri *et al.*, PO 4.33 "Scaling of efficient Ar K-shell emission from fast gas-puff Z-pinches in 10 to 100 MA current range"; A. Esaulov *et al.*, PO 4.37 "Progress in the refining of the K-shell yield scaling model for Z-pinch plasma radiation sources."
[4]J. Schwarz *et al.*, "A model for K-shell x-ray yield from magnetic implosions at Sandia's Z machine," submitted to Phys. Plasmas 2022.

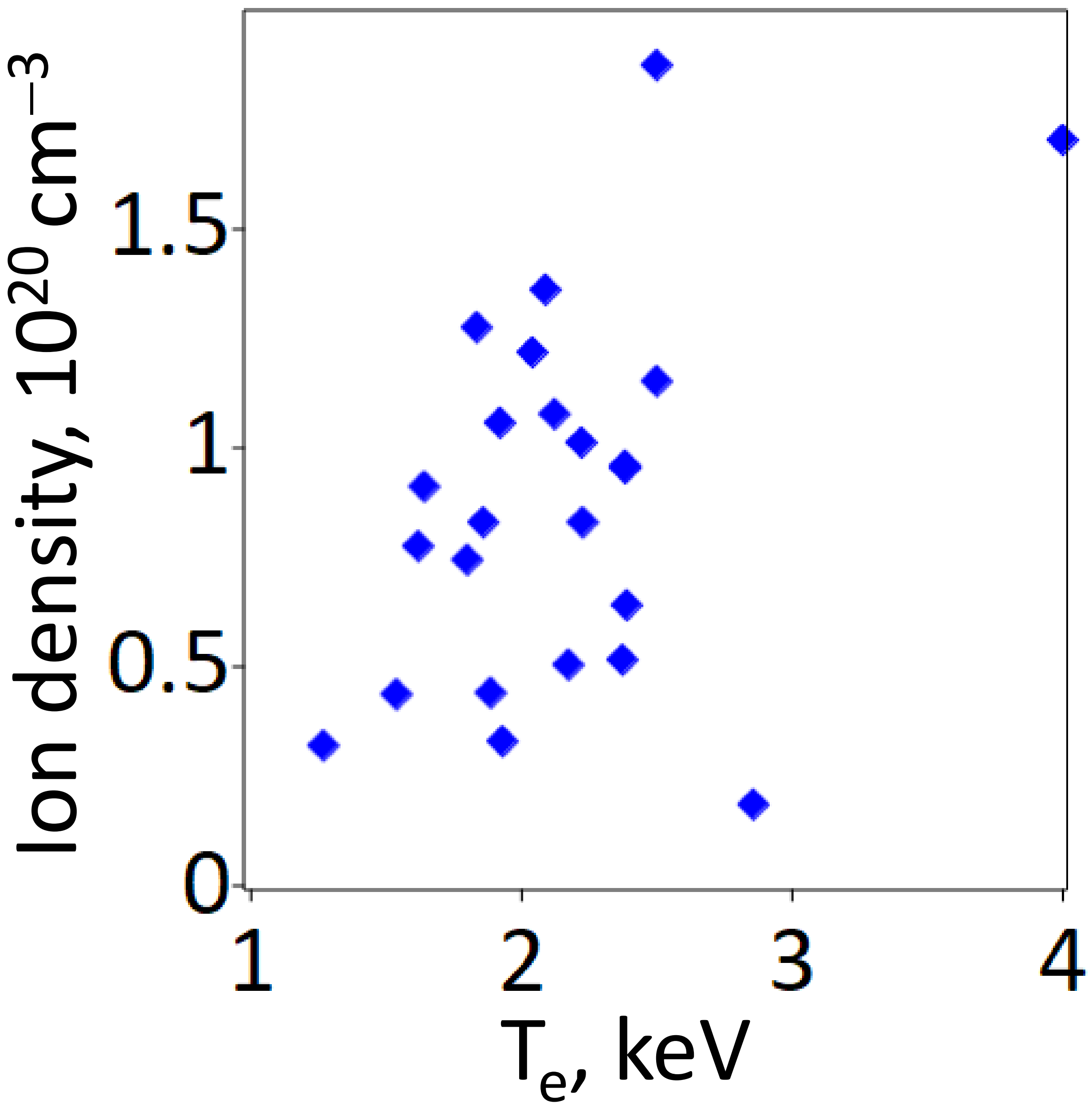
$Y_K \propto m \cdot (\text{K-shell mass participation}) \cdot n_i$

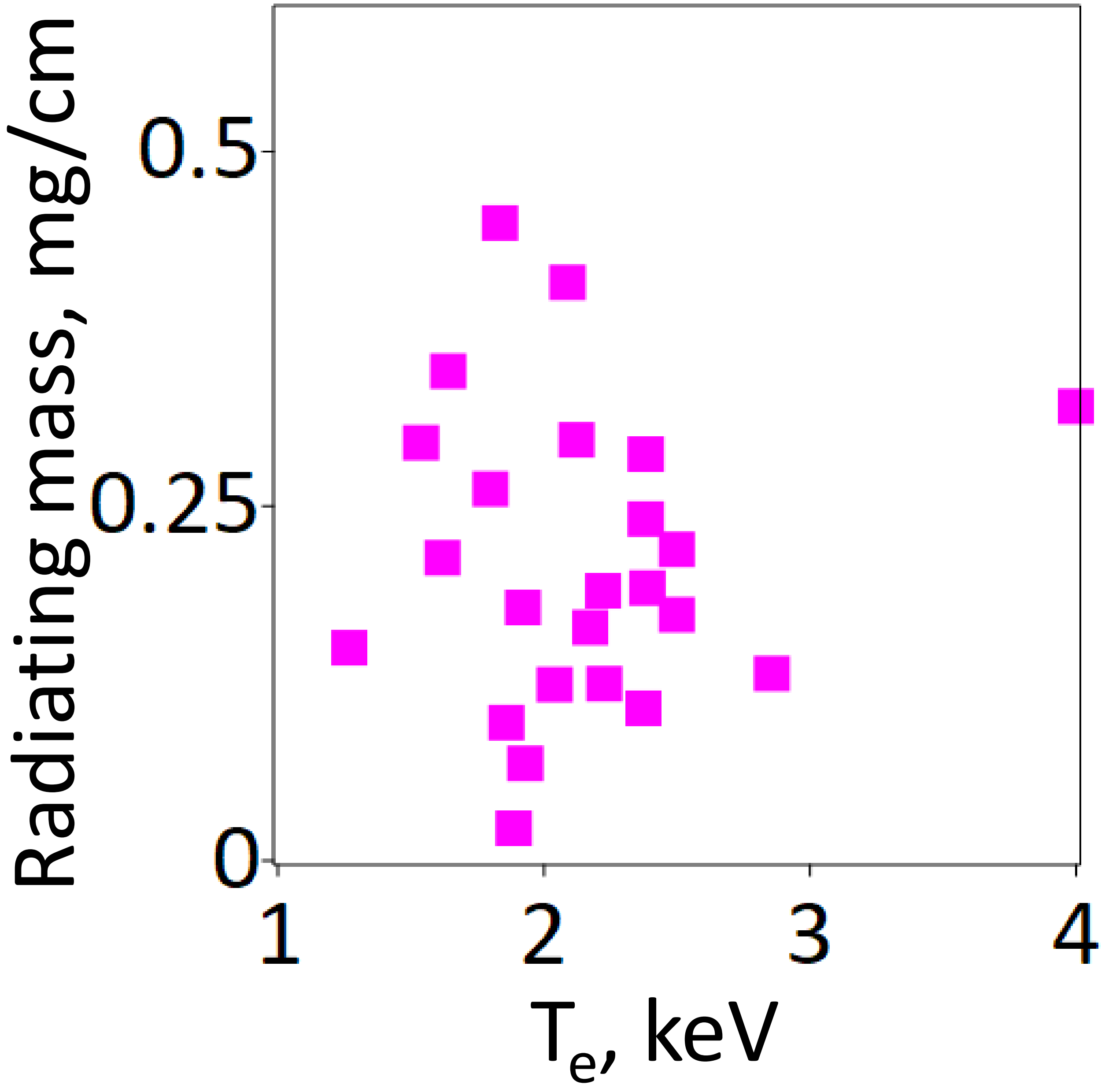
For argon, the assumption of uniformity makes sense

For 1 mg/cm, ∅3 mm Ar load, the assumption of a ~20% average mass participation in the K-shell, leads to reasonable estimates of the ion density, 10^{20} cm^{-3} and line mass, 0.2 mg/cm.



Uniform hot core plasma emits K-shell photons

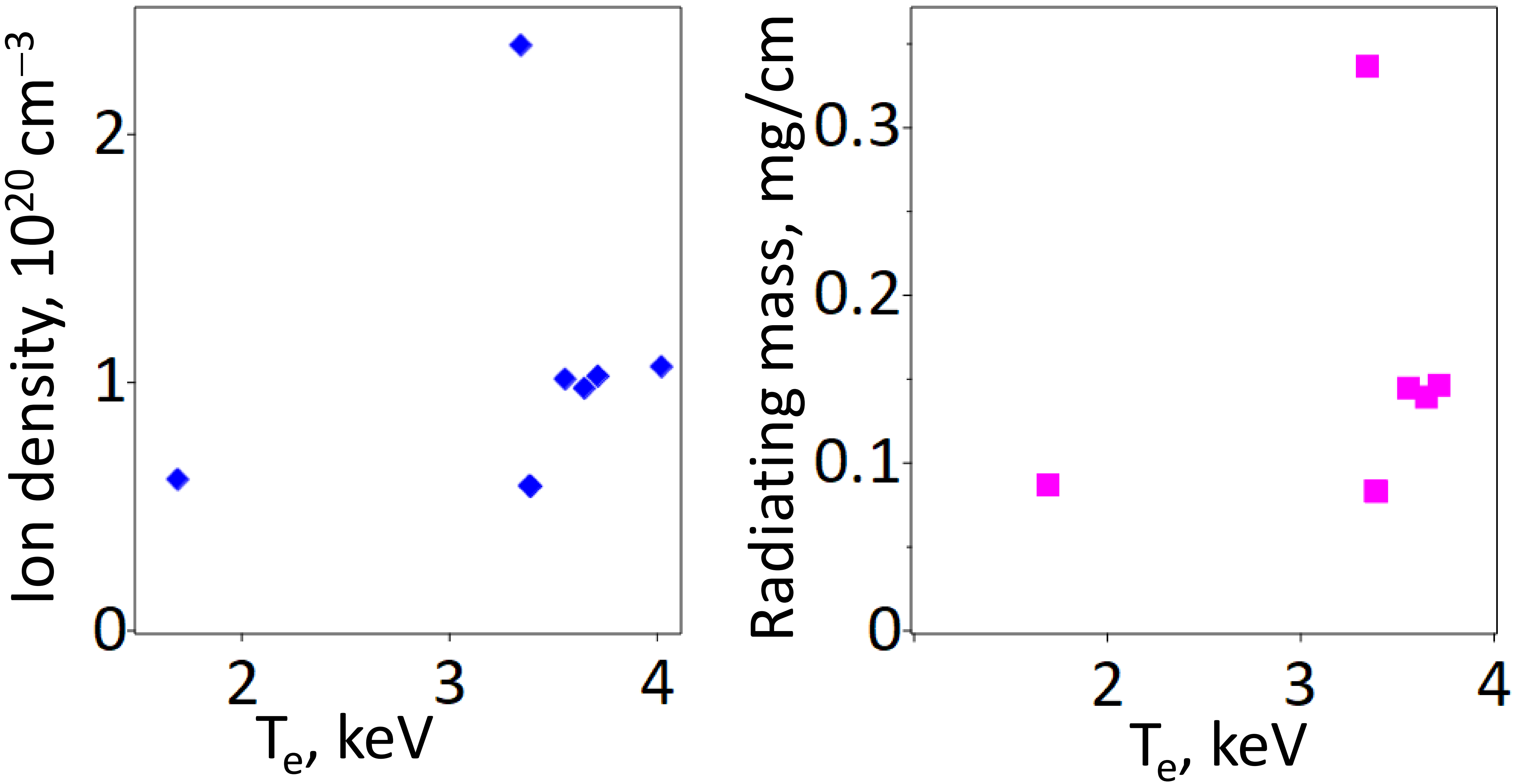




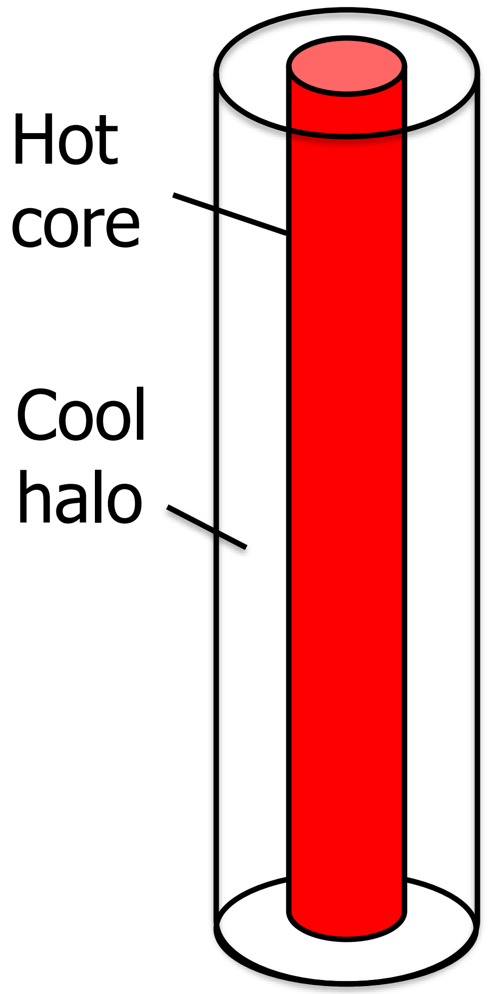
For stainless, the uniformity implies high mass participation, same as in Ar

For 0.75 mg/cm, ∅1.4 mm Ar load, the assumption of a ~18% average mass participation in the K-shell, leads to estimates of the ion density, ~10^{20} cm^{-3} and line mass, 0.14 mg/cm.

Estimated SS plasma parameters are close to argon's, but:
The radius is twice smaller and the temperature is ~40% higher



Time-resolved spectroscopy agrees with this early in the K-shell pulse



Cool halo absorbs some K-shell photons, affecting observed spectra

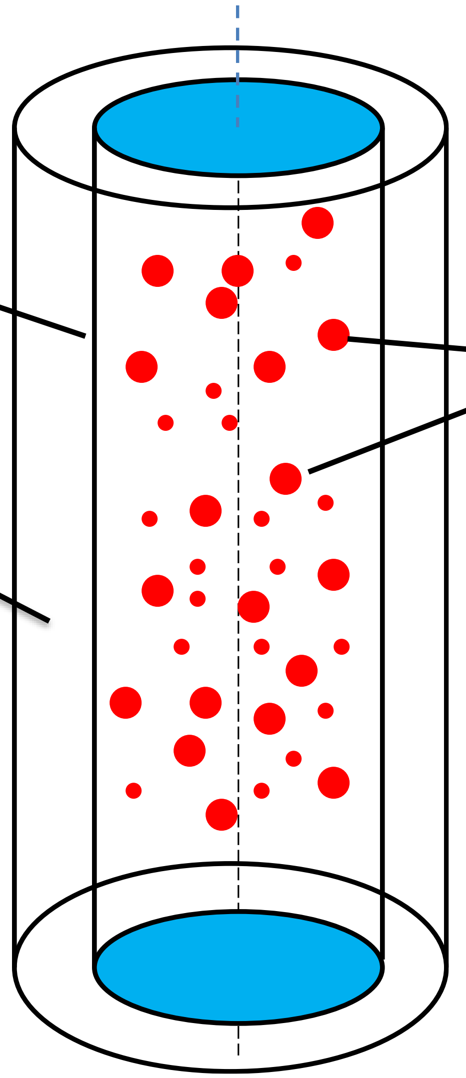
- Analysis of time-resolved spectroscopy from Z stainless nested wire-array shots done at Weizmann in 2014-2016
- The ratios of the FWHMs of resonant lines of Fe, Cr, Ni, and Mn, that are of different abundances , are analyzed. It also requires the determination of Doppler broadening for each element, and the correction for splitting effects.
- At early time, the spectra are consistent with a hot core surrounded with a cool halo

t, ns	Cylinder diameter, mm	n_i, cm^{-3}	T_e, keV	Mass participation, %
-2.7	1.8	3×10^{19}	2	12
-1.8	1.6	5×10^{19}	3	17

Near the K-shell peak, the K-line shapes are consistent with coming from a large number of small hot spots: higher density and higher temperature

NRL PPD

The spot parameters are constrained by the low opacity inferred and the requirement to generate the entire K power



Bright spots emit all K-shell photons, warm core background emits softer photons

t=–0.8 ns, T_e = 4 keV, T_i (hydro) = 40 keV

D, μm	No. of spots	n_i, cm^{-3}	Mass participation, %	Photon mfp, mm
50	8900	5×10^{20}	3.1	1.3
100	4200	2.5×10^{20}	5.9	0.68
150	2930	1.67×10^{20}	9.2	0.43

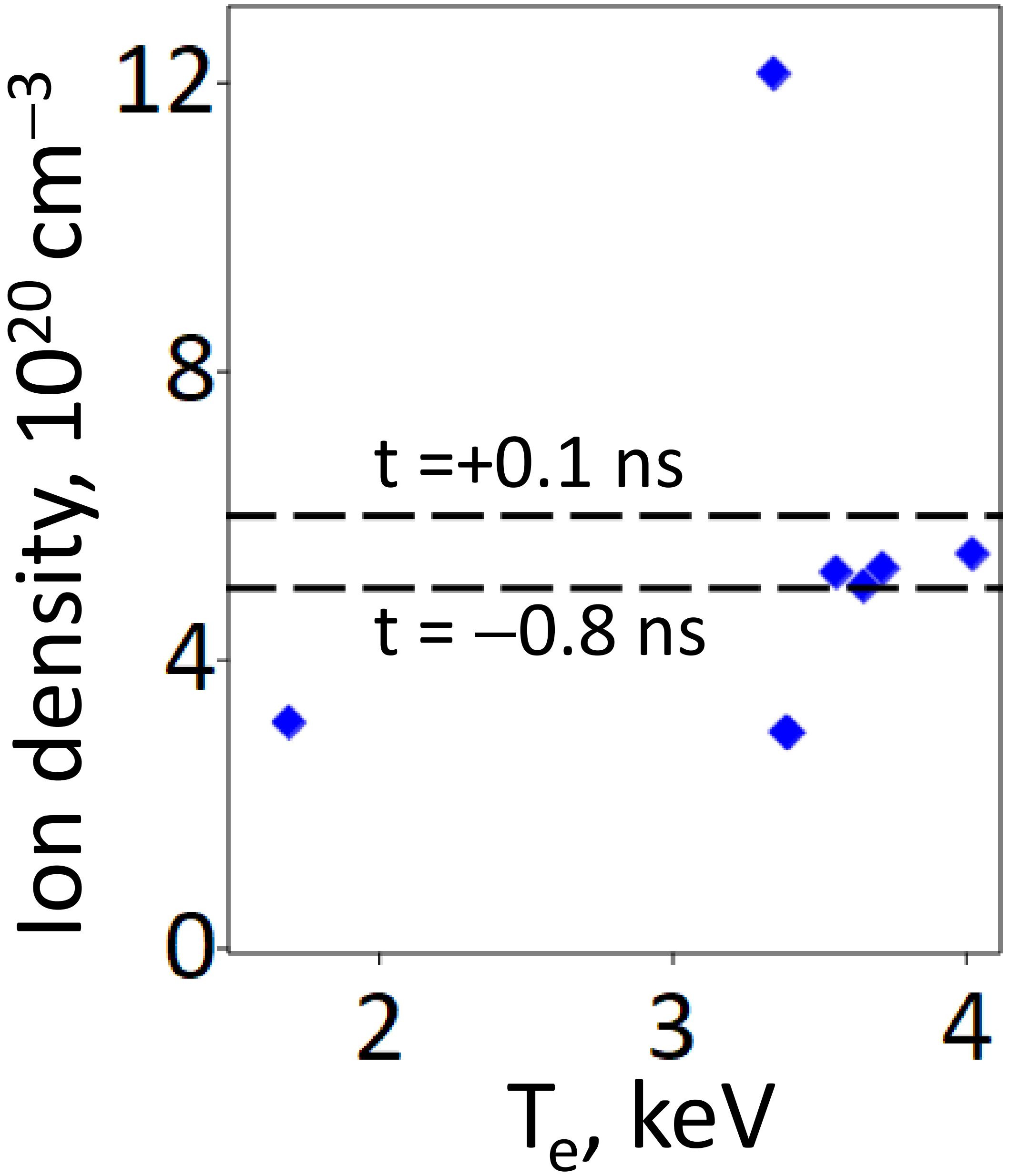
t=+0.1 ns, T_e = 6 keV, T_i (hydro) = 30 keV

D, μm	No. of spots	n_i, cm^{-3}	Mass participation, %	Photon mfp, mm
50	8200	6×10^{20}	3.4	1.4
100	3800	3×10^{20}	6.4	0.76
150	2350	2×10^{20}	9.2	0.54

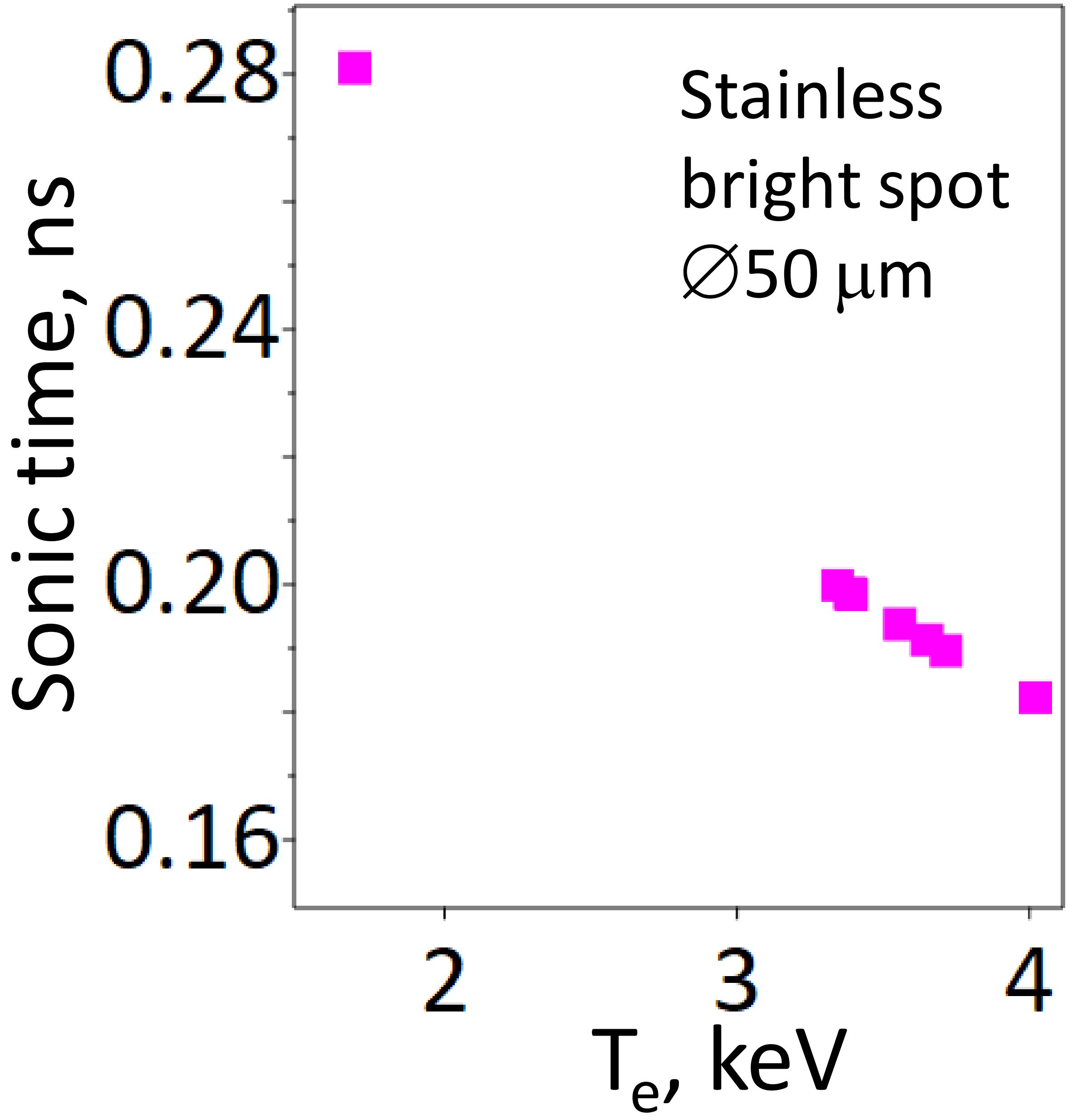
Continuum yield are also consistent with this assumption

NRL PPD

Stainless mass participation 3.5%



Life time of spots is less than 1 ns. They must be replaced or re-energized.



$$t_s = \frac{2R}{c_s}$$

Summary/Conclusions

NRL PPD

- Hard-photon direct recombination continuum alternative paths to "warm" x-ray production above 15 keV with pulsed power for next-gen pulsed power facility, NGPP
- A scaling model is needed to confidently predict the radiation yields from NGPP
  - Densities and temperatures of radiating plasmas at stagnation need to be confidently scaled up
- Scaling models are based on the conventional assumption of a uniform radiating plasma column, which is plausible for Ar but not for stainless steel
- Most likely, stainless steel emits K-shell from bright spots
- Continuum yield data from Z is consistent with the spectroscopic analysis indicating that the dense, hot bright spots containing a small fraction of the load mass radiate most of the K-shell x rays
  - Dimensions, densities, and temperatures of the bright spots can be inferred
  - The mechanism of their creation and energy replenishment is still obscure