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Two-Dimensional Radiation MHD Model Assessment of Designs for Initial Argon Gas Distributions to be Imploded on the Z machine*

NRL

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Outline

In the near future scientists at Sandia National Laboratories will be performing, for the first time, argon gas puff experiments on the refurbished Z machine. As part of the effort to determine the initial argon loads to be deployed, we theoretically assess the K-shell emission and stability properties of the gas distributions generated by the new Alameda Applied Sciences (*AASC*) 8 cm diameter double-annulus nozzle with a central jet that was recently constructed for these experiments .

- Review past performance of pre- refurbished Z argon experiments and their implications for future ZR argon experiments.

- Employ 2D rad-MHD model to analyze the stability and K-shell emission properties of several measured (interferometry) initial *AASC* nozzle gas distributions and compare results with that of the Titan1234 nozzle used in earlier Z experiments. Especially interested in how the central jet and the ratio of outer (annulus) mass : inner mass affect stability and K-shell properties.

- Use 2D rad-MHD model to determine optimal *AASC* nozzle gas distribution and make predictions for K-shell yield attainable from future Z argon experiments.

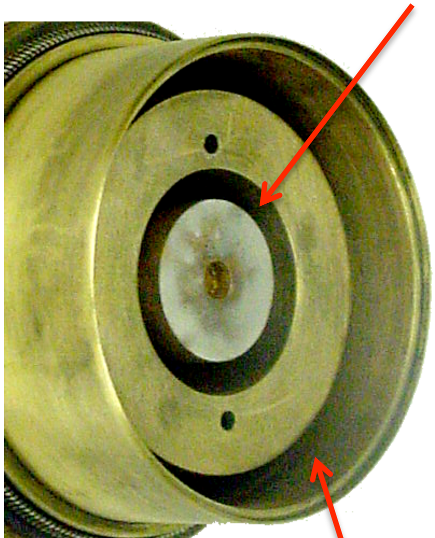
- Conclusions

- Describe MHD and Ionization dynamics and radiation transport models used in simulations

Summary of pre-refurbished Z argon experiments

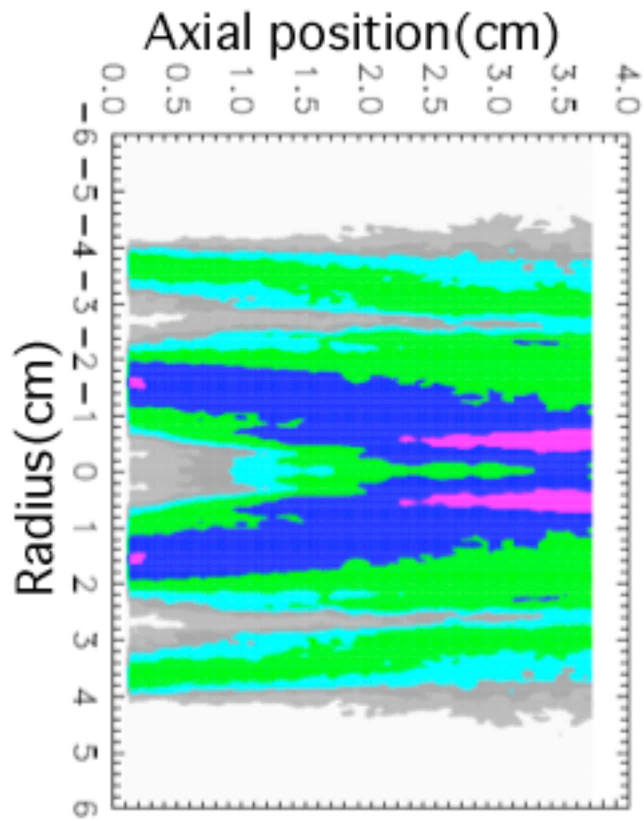
The pre-refurbished Z argon experimental results are well described in [H. Sze, P. L. Coleman, *et. al.*, Physics of Plasmas *Letters*, 8, 3135 (2001).]

Inner annulus
1-2 cm



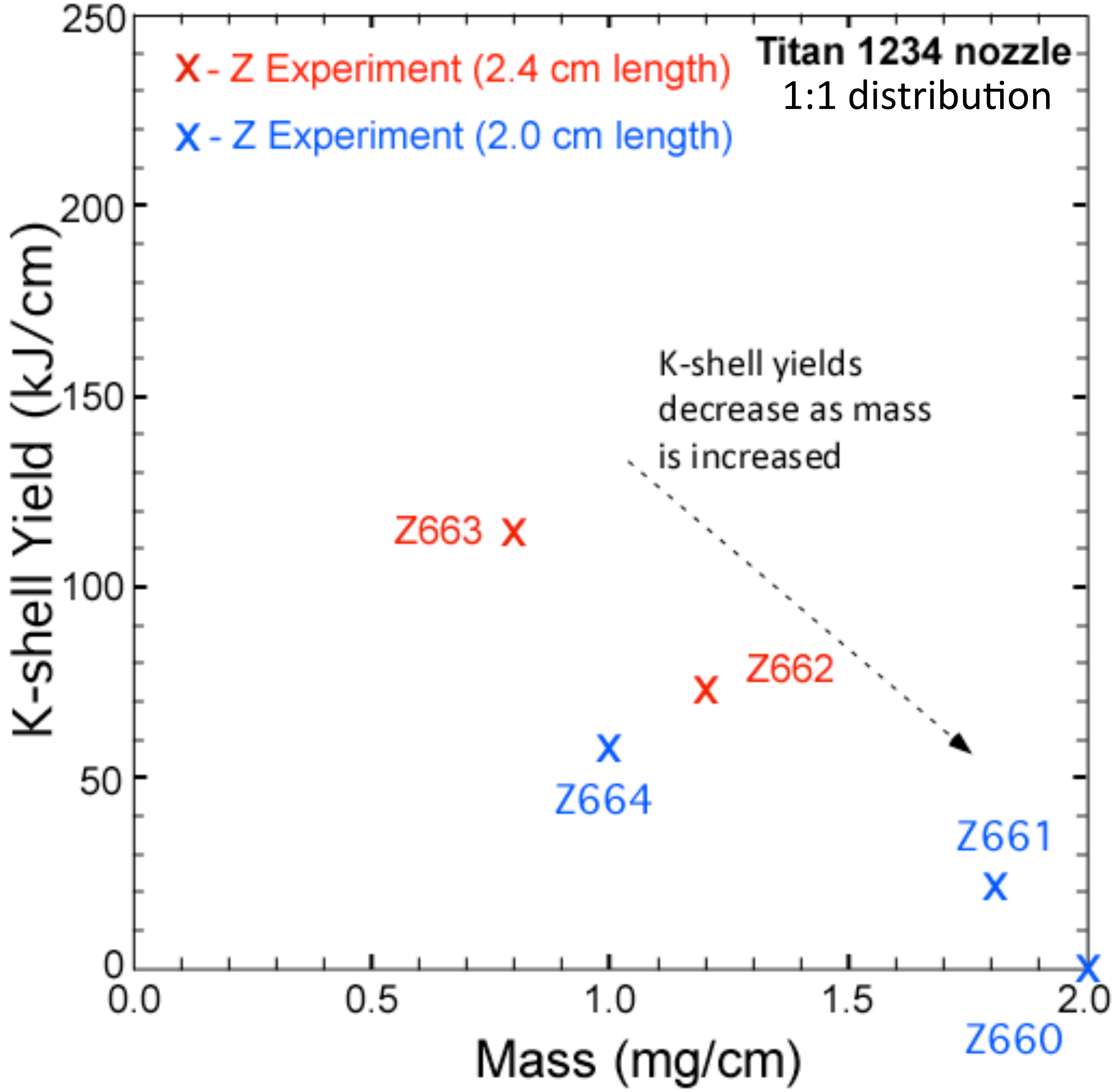
generic nozzle

Outer annulus from
3-4 cm



Titan 1:1 Nozzle
Gas distribution

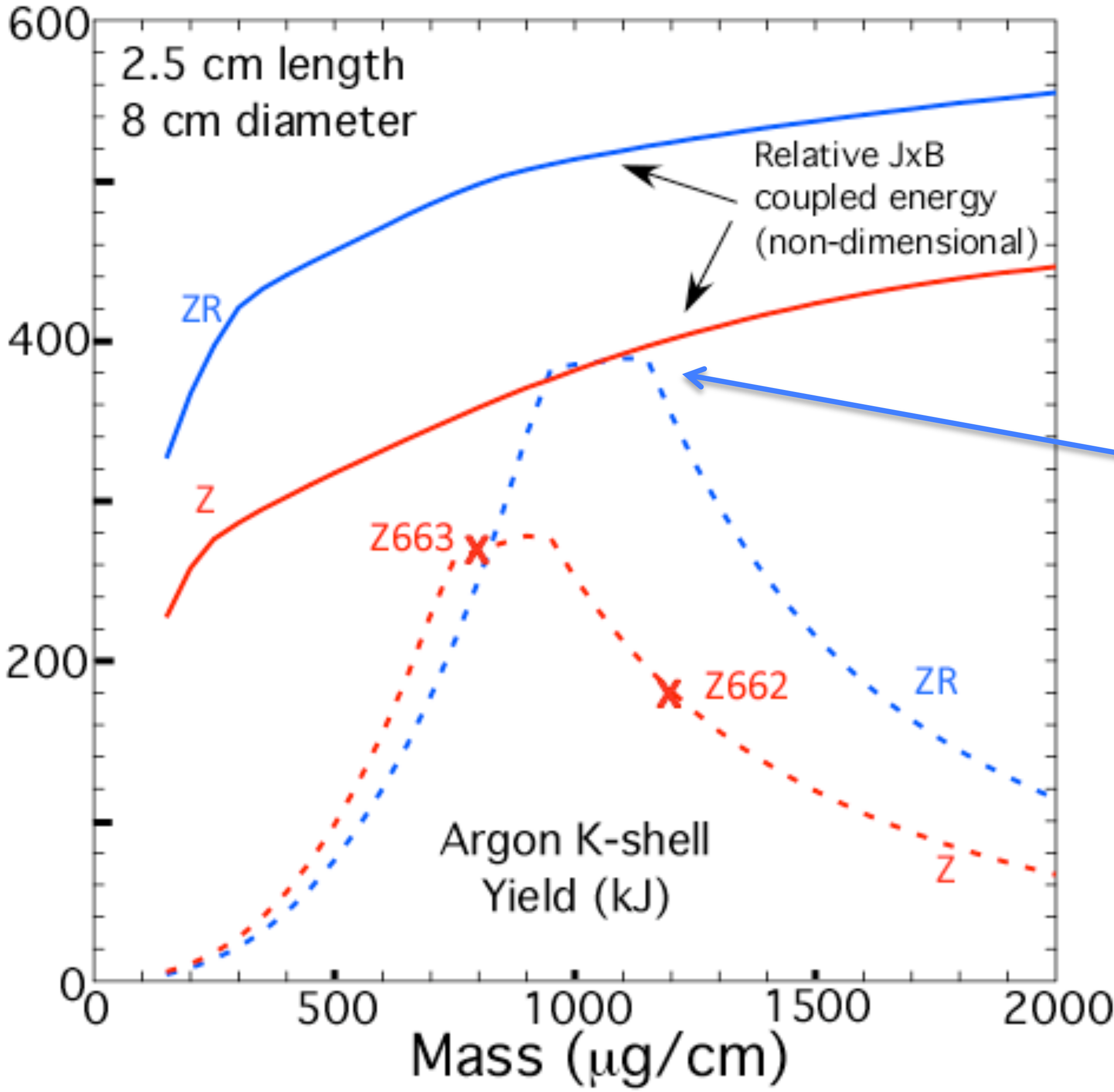
Summary of pre-refurbished Z argon experiments



Current loss was observed in most of these experiments, especially for Z660 the most massive load.

H. Sze's speculation – current loss due to UV light from implosion illuminating the convolute power feed

Expected performance of refurbished Z argon experiments based on past success of Titan 1234 nozzle pre-refurbished Z experiments

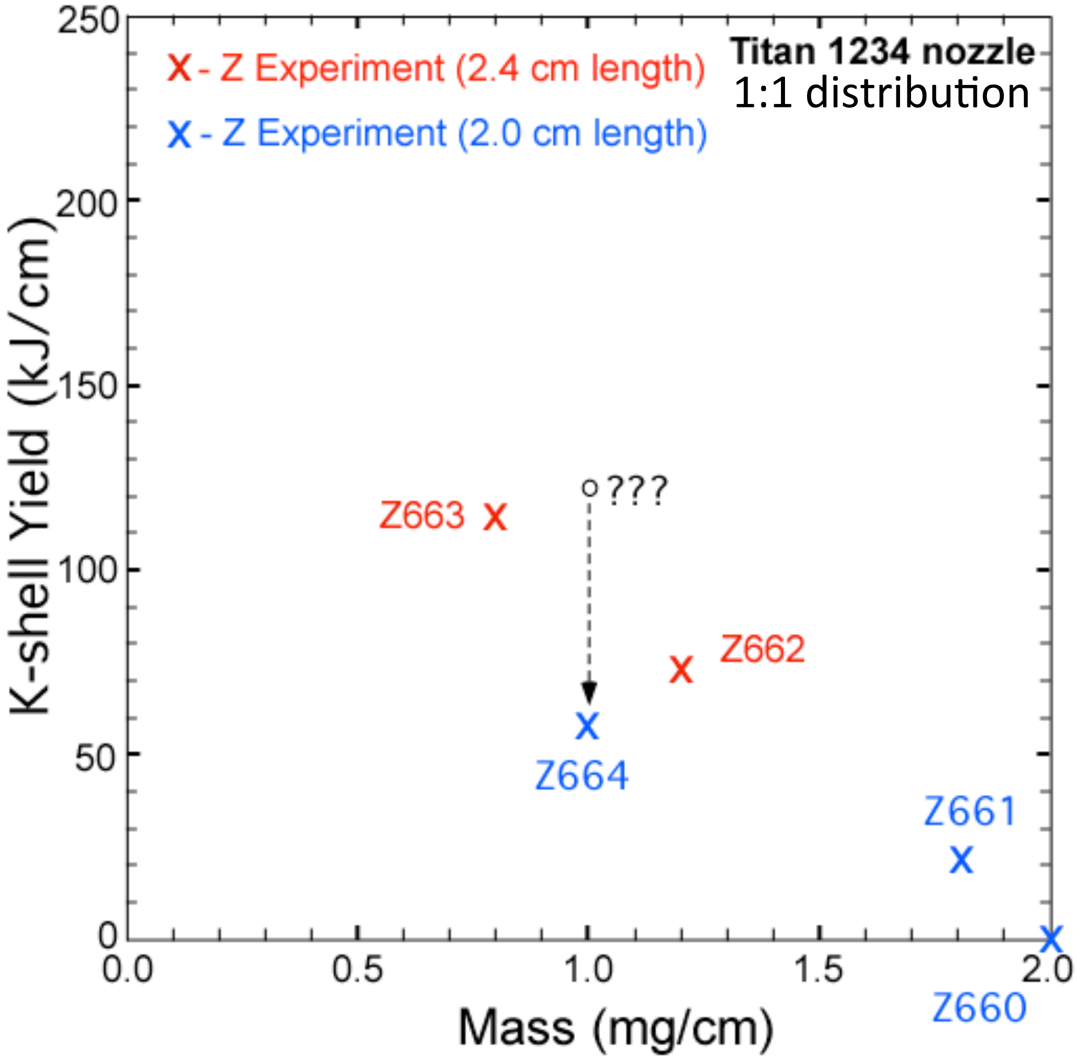


Relative JxB energies are obtained from 0D snowplow model of Titan 1234 nozzle coupled to equivalent circuit model for Z and ZR.

K-yields of ~ 380 kJ are expected on ZR based on energy considerations

Yields are predicted using an empirical scaling model
Y_k = C *f(mass,energy)
(one parameter fit, C),
which here presumes
that the Titan 1234 nozzle
is employed on both machines
[Thornhill *et. al.*, IEEE Trans Plasma Science 34, 2377 (2006)]

Load Instability likely played a role in pre-refurbished Z experiments



Z664 had more energy/cm than Z662, why was K-yield/cm less? H. Sze suspects it is due to axial non-uniformity.

By using a reduced pinch length for Z664 they eliminated the region of the pinch that had radiated best in Z662 (near anode)

Based on earlier Z argon experiments one expects for ZR:

1) **Current loss to be an issue**

2) **K-shell yields of ~380 kJ are attainable on ZR**

3) **Load instability likely played a role in earlier Z experiments and is likely to do so on ZR**

4) **Not clear how the AASC nozzle characteristics will affect K-shell emission** – likely to have different instability properties than did the Titan 1234 nozzle

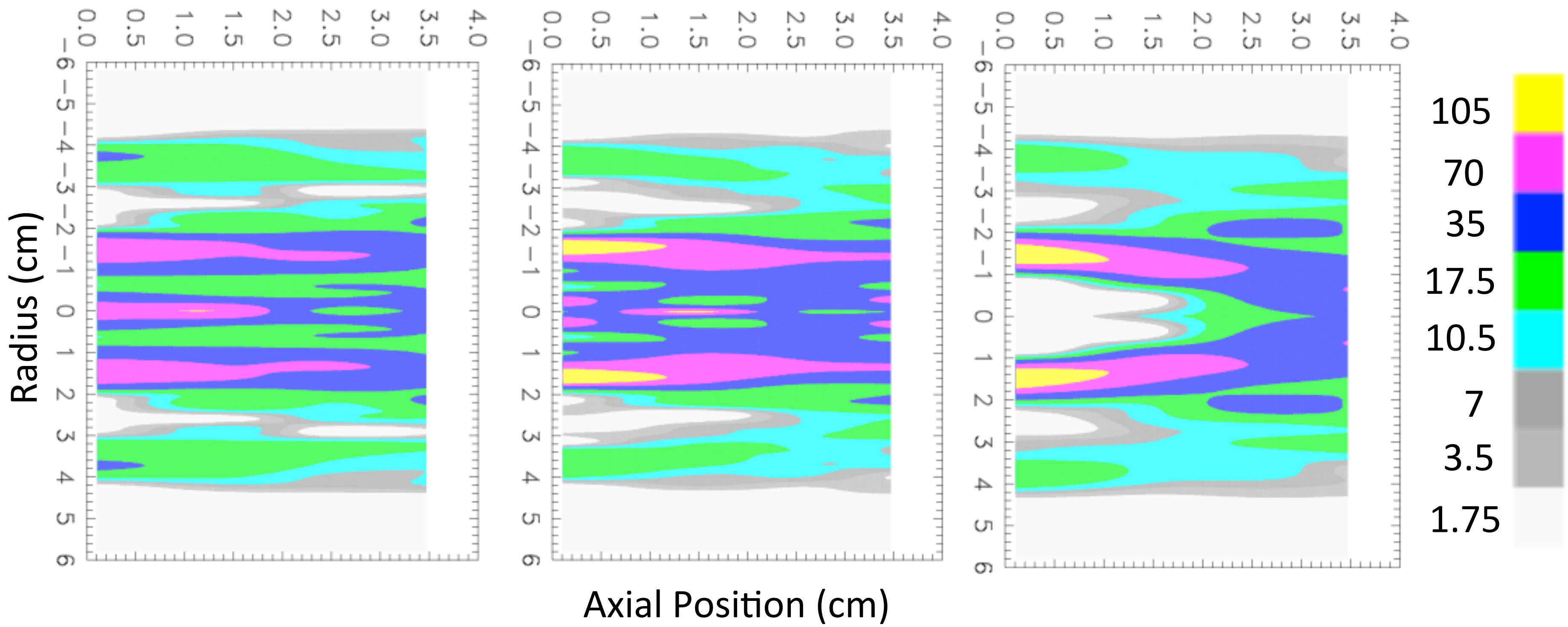
Modeling the K-shell emission and stability properties of the AASC nozzle gas distributions

- To theoretically model the non-linear growth of instabilities and multi-dimensional plasma motion that is present in gas puff implosions we employ *Numerex's* Mach2 – two dimensional magneto-hydrodynamics code.

- To account for the non-LTE state of the high temperature argon plasma, opacity effects, and the non-local transport of radiation that effects the argon atomic populations we incorporated into Mach2 a self-consistent EOS calculation, which includes non-LTE kinetics and a ray-trace based radiation transport. It is called the tabular collisional radiative equilibrium model -TCRE

These Models will be discussed at the end of the talk

Modeling the K-shell emission and stability properties of the AASC nozzle gas distributions



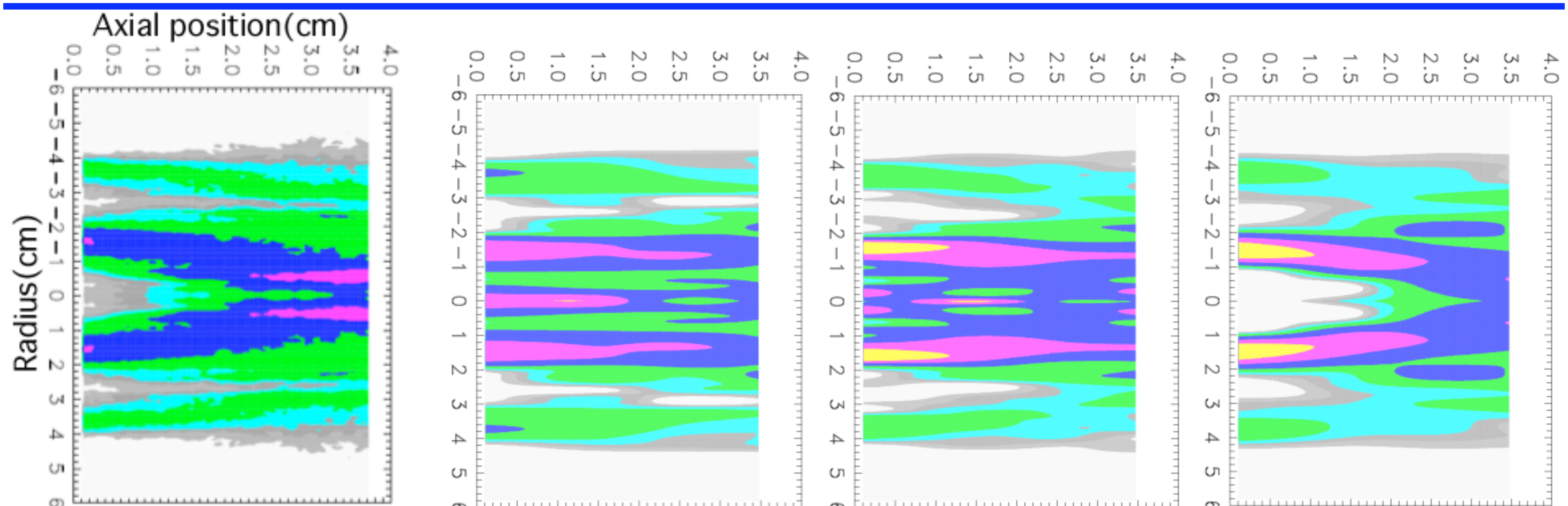
AASC [31_30_250] "1:1"

AASC [22_30_250] "1:1.5"

AASC [31_58_0] "1:2"

- Distributions measured using **F**iber **O**ptic **I**nterferometry
- Measurements taken along 4 axial slices (0.5,1.5,2.5 and 3.5 cm)
- Bicubic spline used to interpolate between data points

Modeling the K-shell emission and stability properties of the AASC nozzle gas distributions

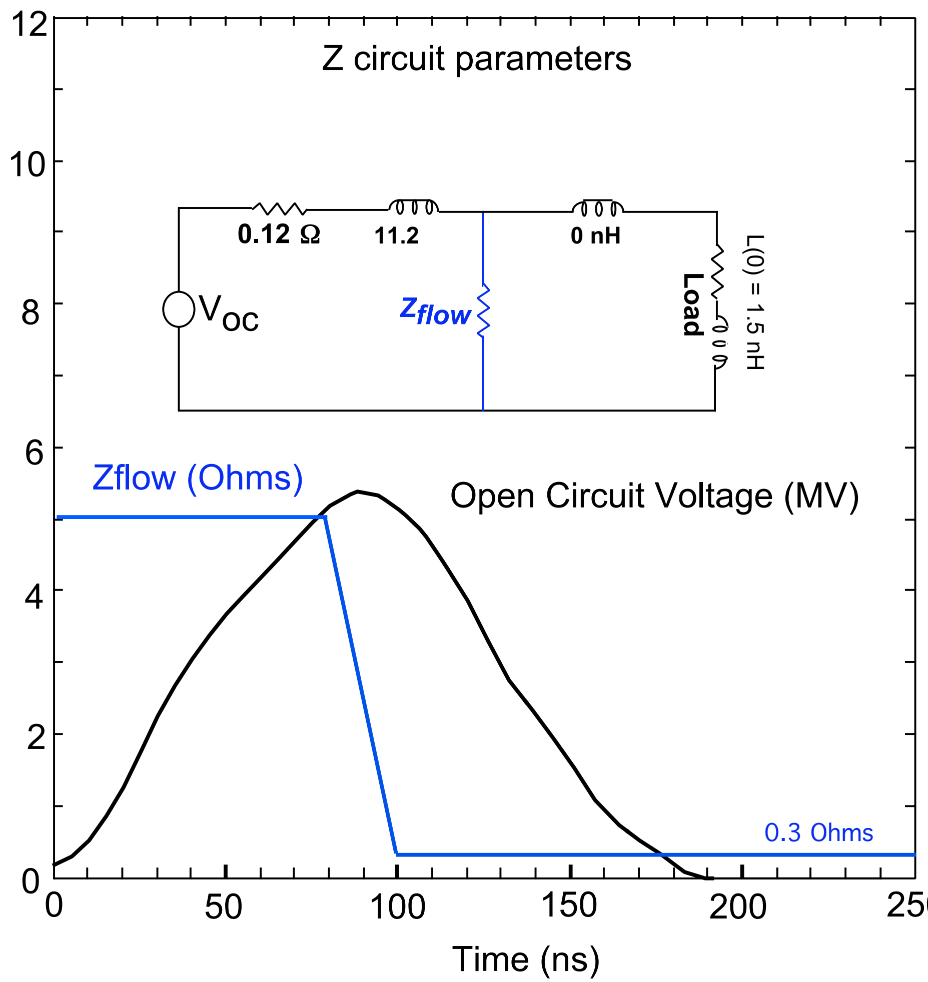


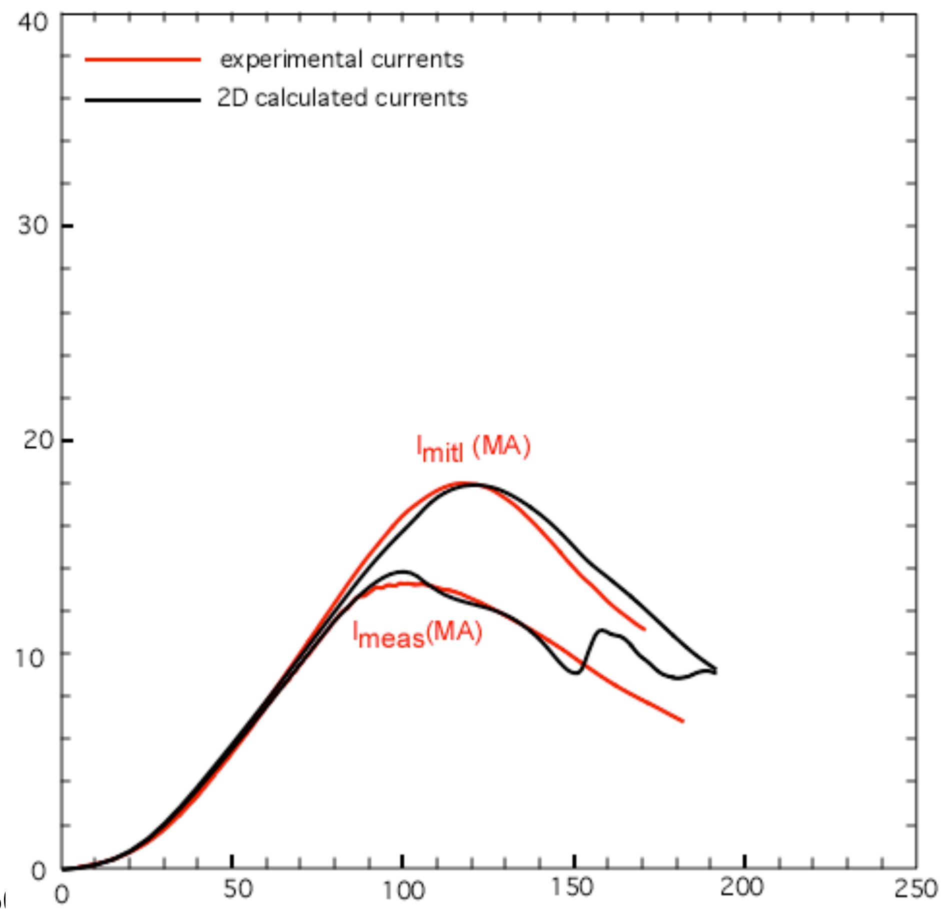
Titan 1:1 | AASC 1:1 | AASC 1:1.5 | AASC 1:2

	Titan 1:1	AASC 1:1	AASC 1:1.5	AASC 1:2
Fraction of mass in outer nozzle region (>2.5 cm) to total mass is ---	1.0	0.83	0.57	0.60
Mass fraction at z=0.5 cm:				
outer/total	0.48	0.46	0.35	0.39
middle/total	0.61	0.51	0.61	0.61
inner/total	0.02	0.03	0.04	0.00

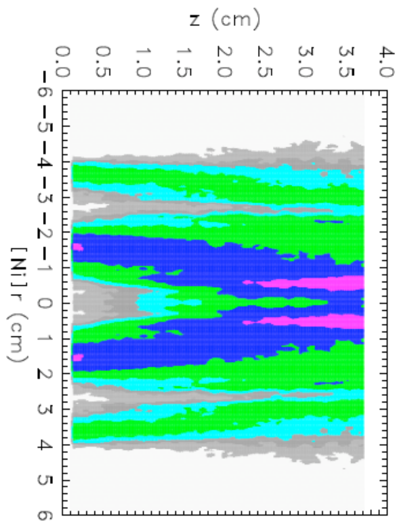
Outer r > 2.5 cm Middle: 2.5 > r >1 cm Inner: r < 1 cm

AASC nozzle performance is compared to Titan1234 theoretical and Experimental performance on pre- Refurbished Z

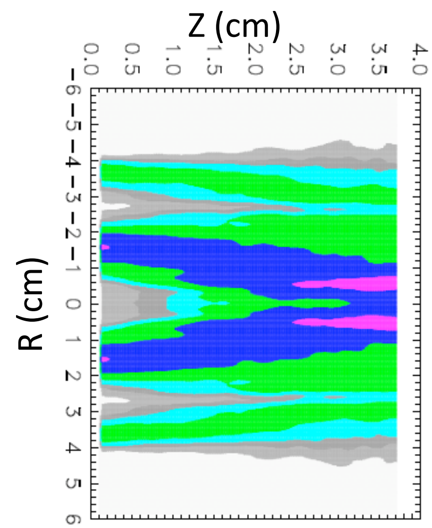




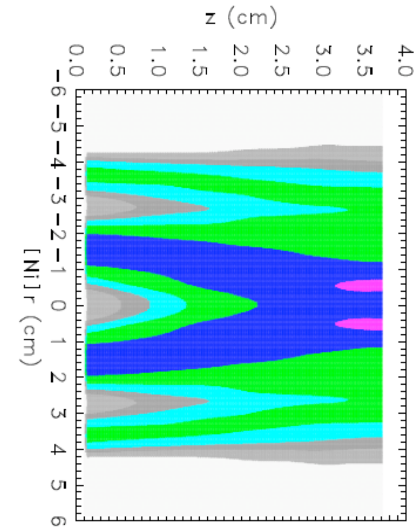
Comparison of Titan 1234 and AASC nozzle performance



Titan 1:1 (no smoothing)

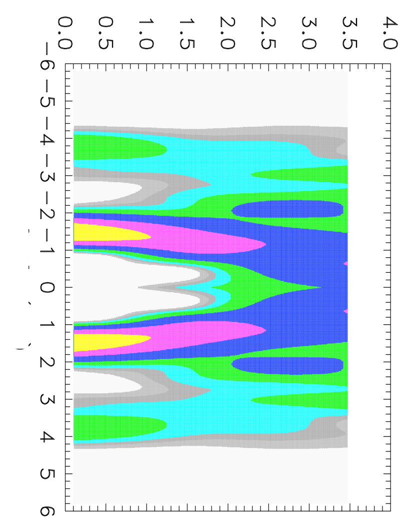


Titan 1:1 (10x)



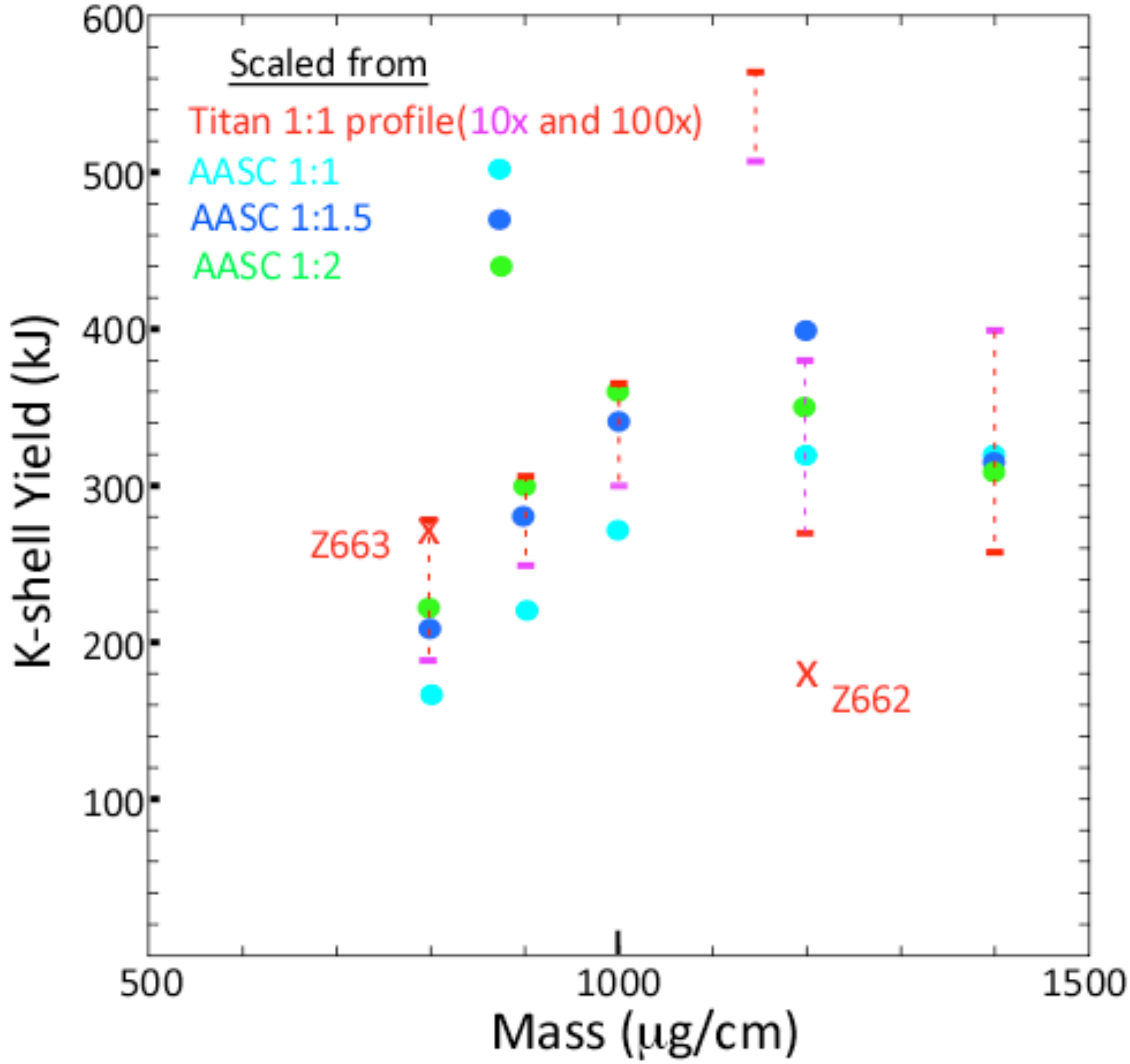
Titan 1:1 (100x)

Titan profile is smoothed (average of zone + nearest neighbors) to compensate for the inherent smooth profile of spline fit AASC distribution. 10x and 100x calculations are performed.

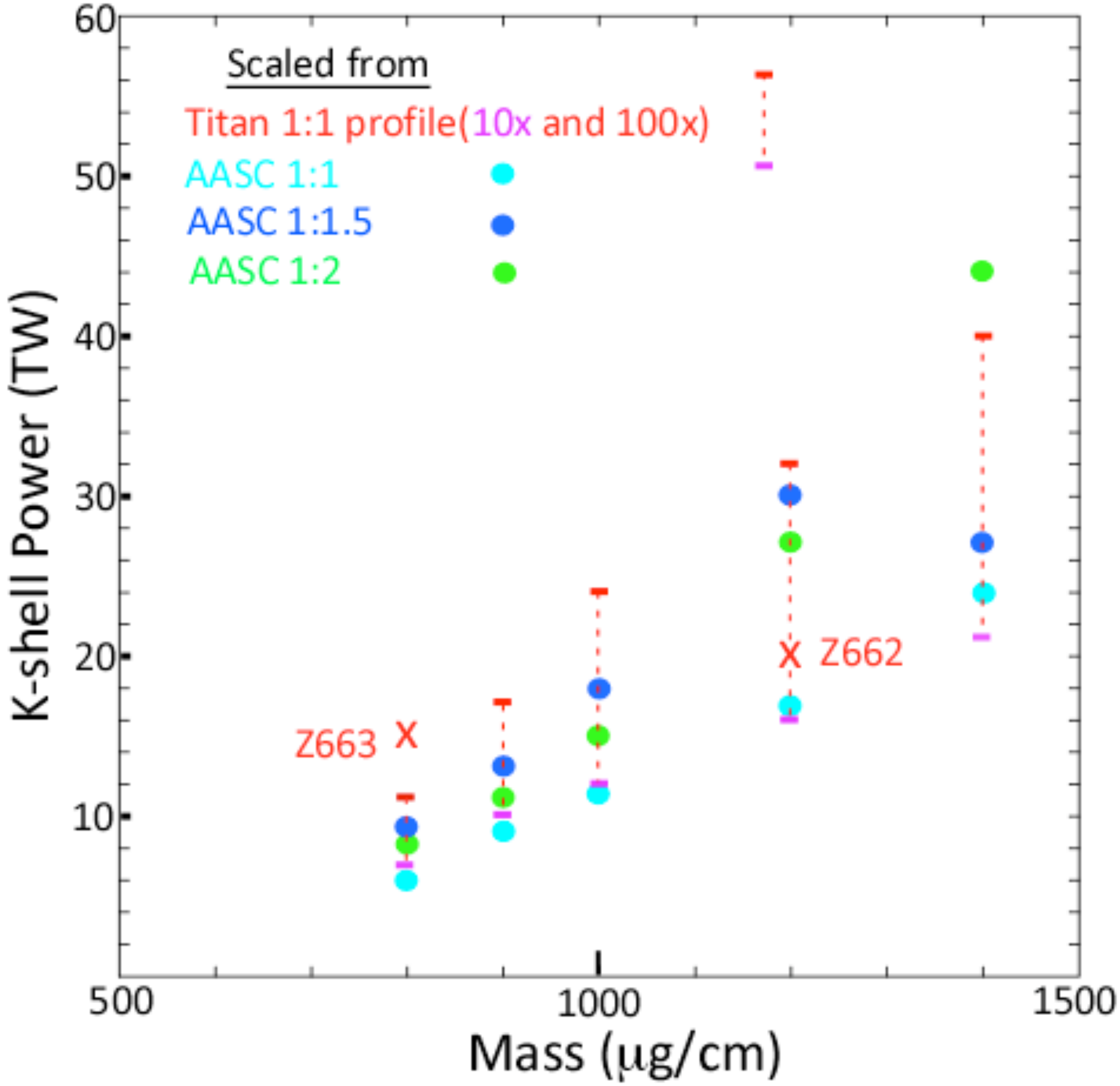


AASC 1:2 - [31_58_0]

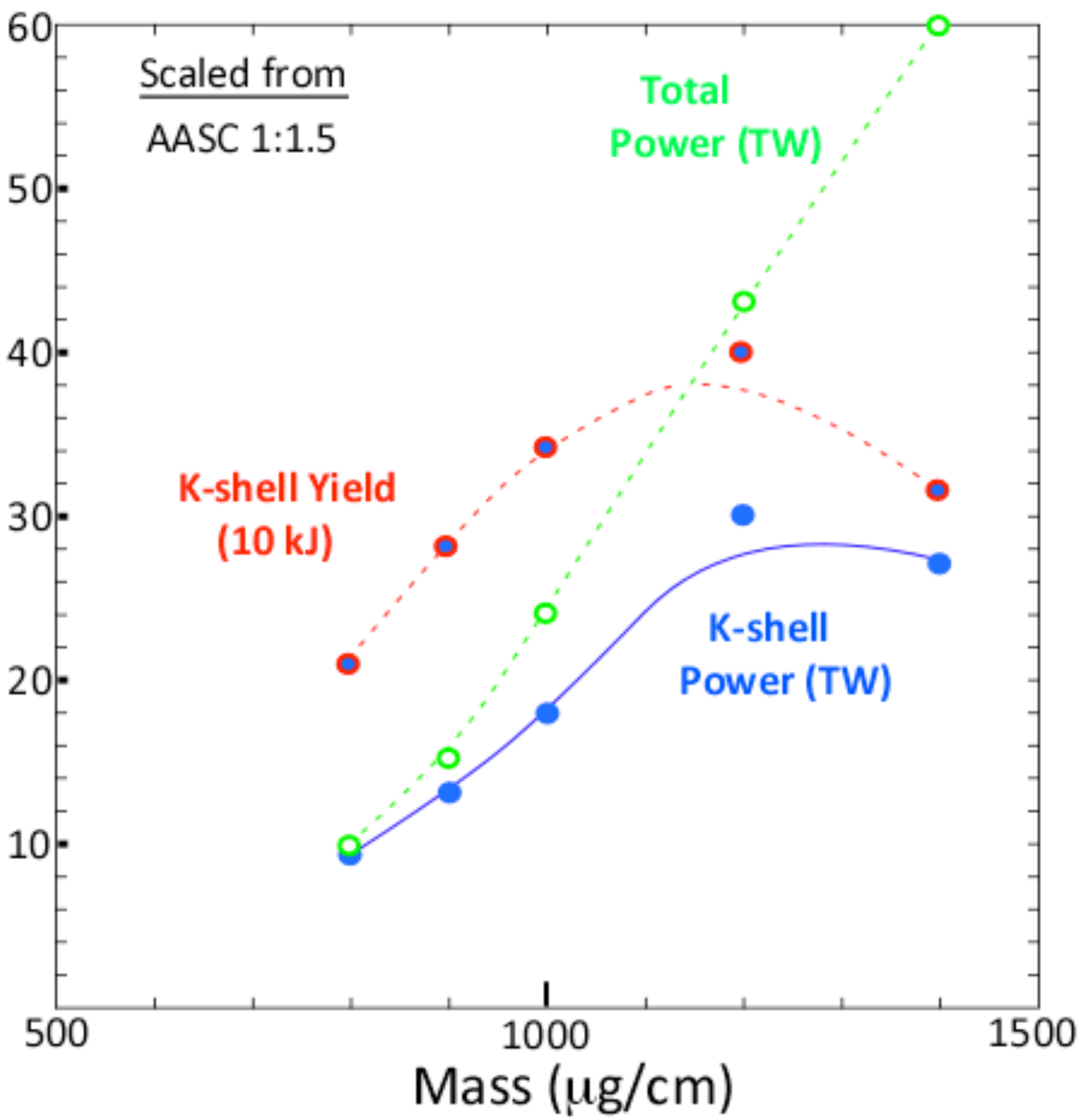
2D Calculated K-yields for Titan 1234 and AASC Nozzles on Pre-refurbished Z



2D Calculated K-shell Power for Titan 1234 and AASC Nozzles on Pre-refurbished Z



As total radiative power increases the plasma cools too much to sustain k-shell emission

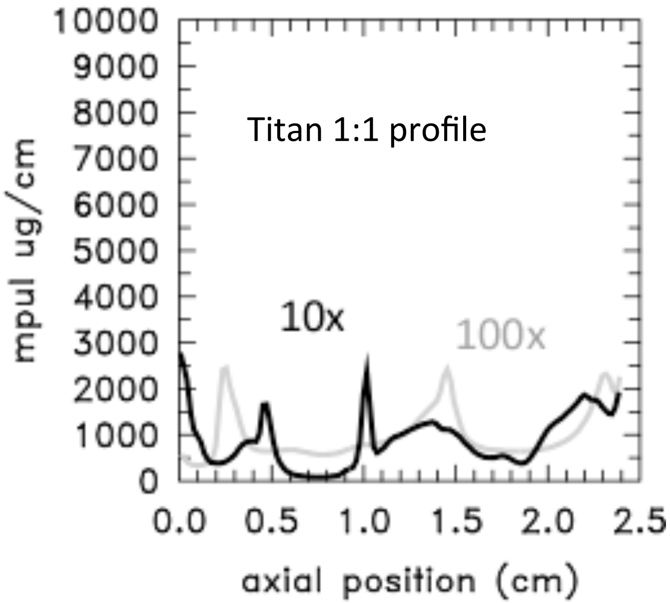


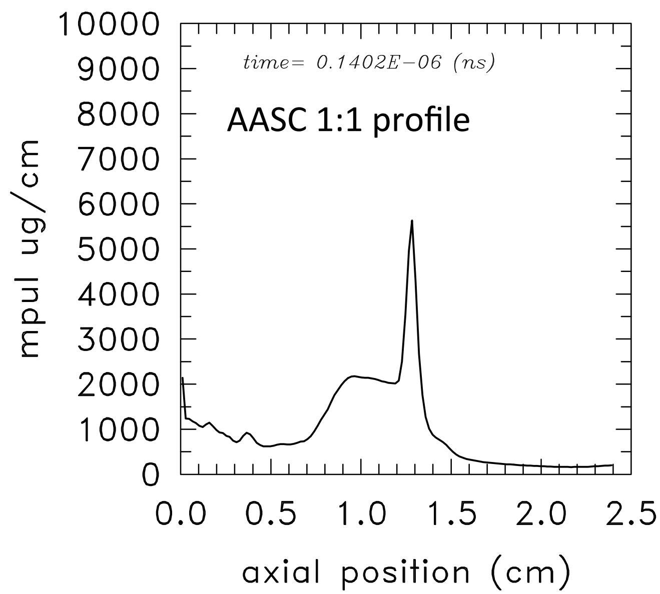
K-shell yield curve turns over when total power is sufficiently large that plasma cools and has difficulty ionizing into the K-shell.

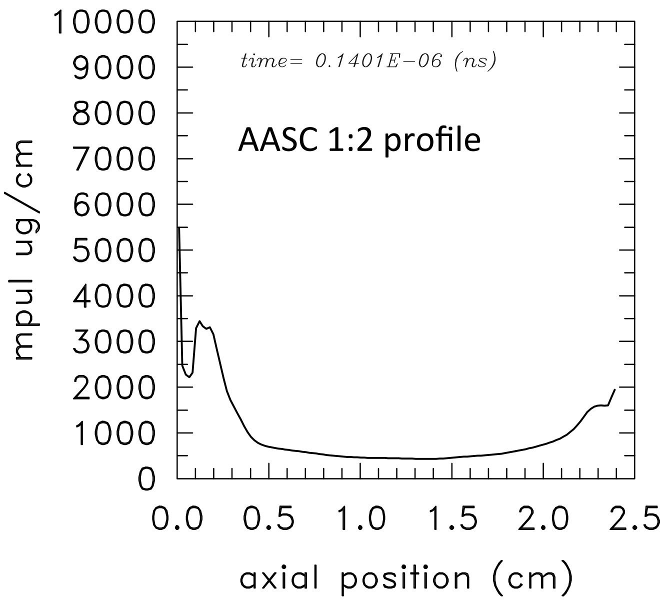
Total power increases ~ Ni^2 or $Mass^2$, any uncertainty in L-shell cooling rates will be magnified at larger mass loads.

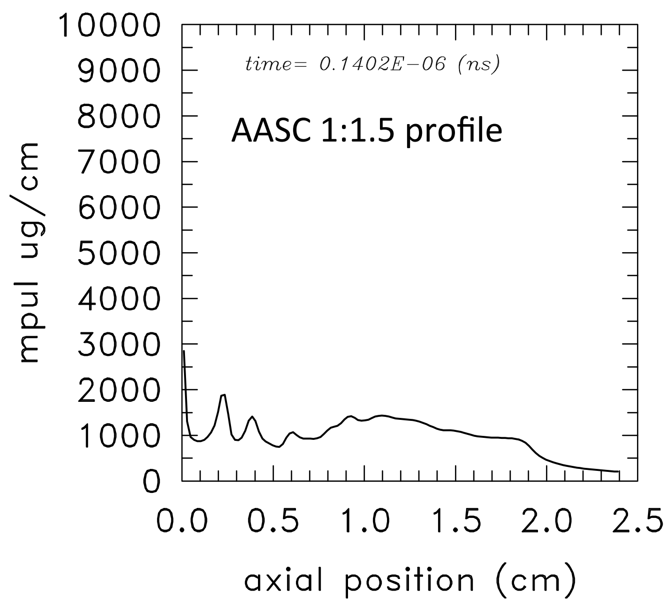
This uncertainty, as well as especially large current losses observed for large mass loads in Z experiments is the reason initial ZR experiments will likely take place in the 800-1200 μg/ cm range.

Stability comparison between Titan 1234 and AASC 2D implosions



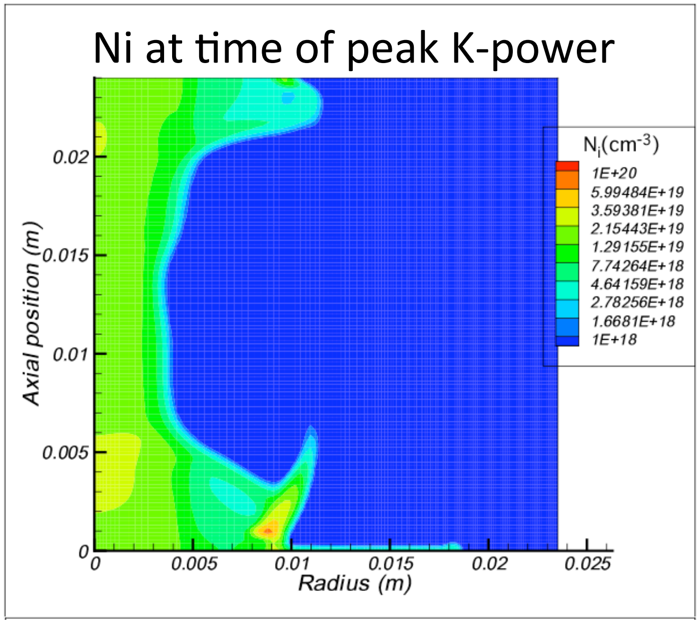


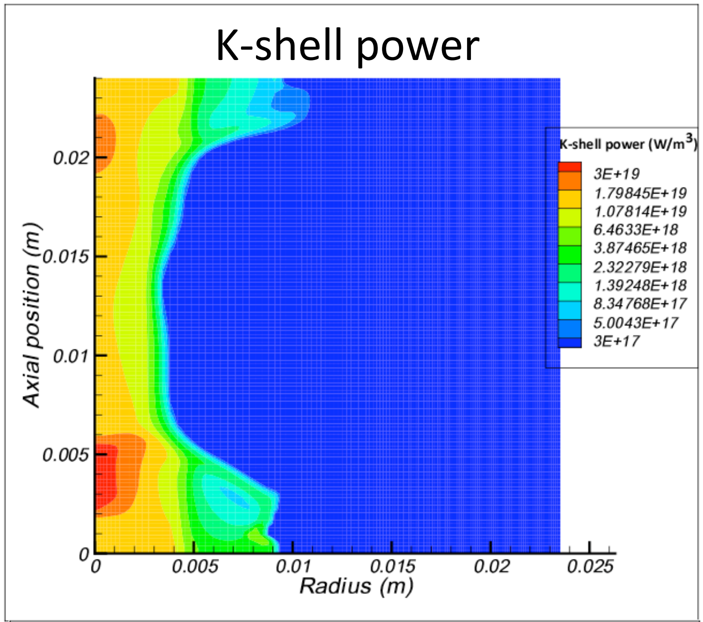




The mass-per-unit-length as a function of axial position – just prior to stagnation. large fluctuations denote an unstable implosion. These calculations were for a 1 mg/cm load.

Stability comparison between AASC 1:1 and 1:2 2D implosions

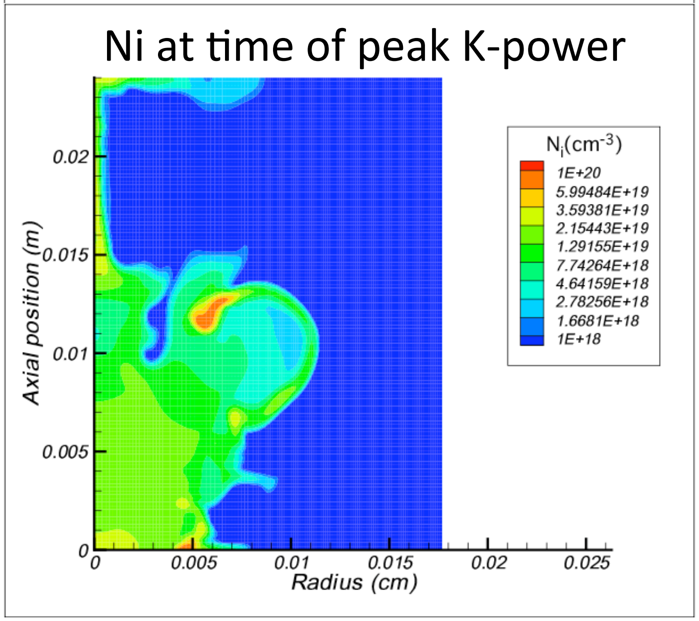


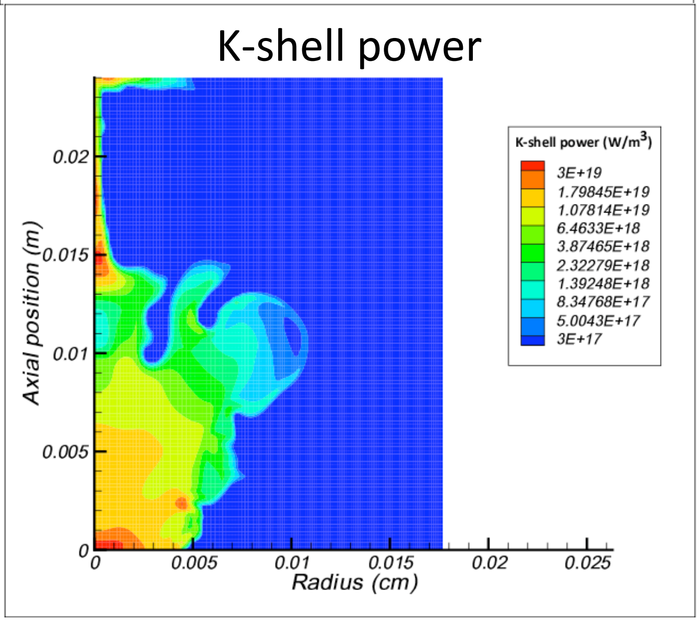


AASC 1:2

2.5 cm length
1 mg/cm

AASC 1:1

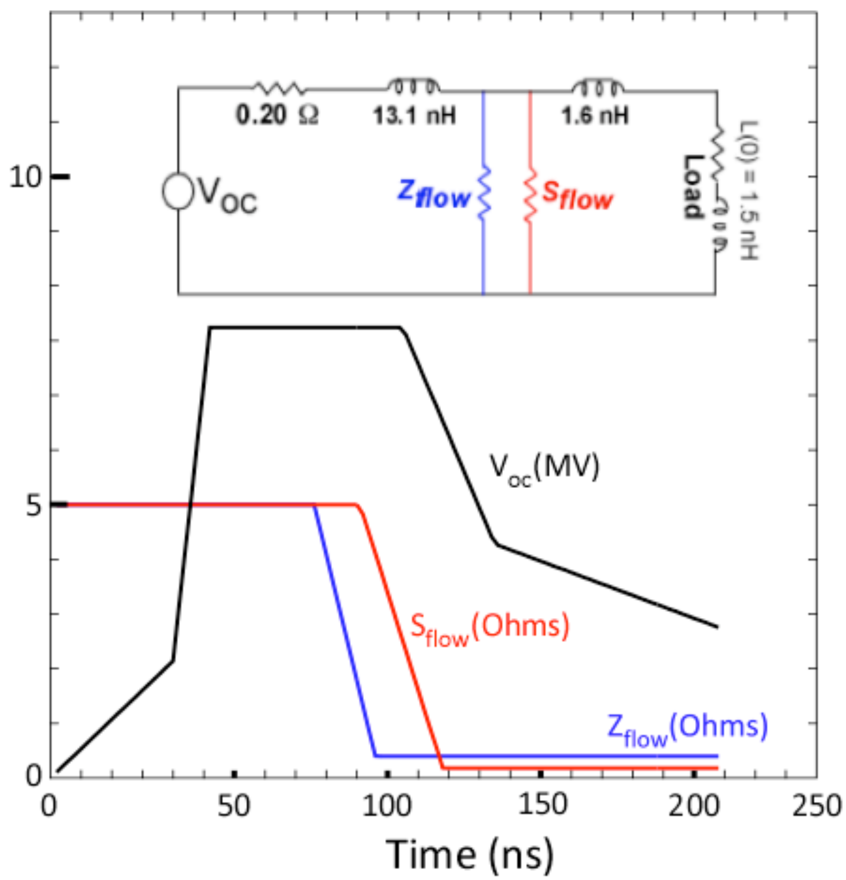


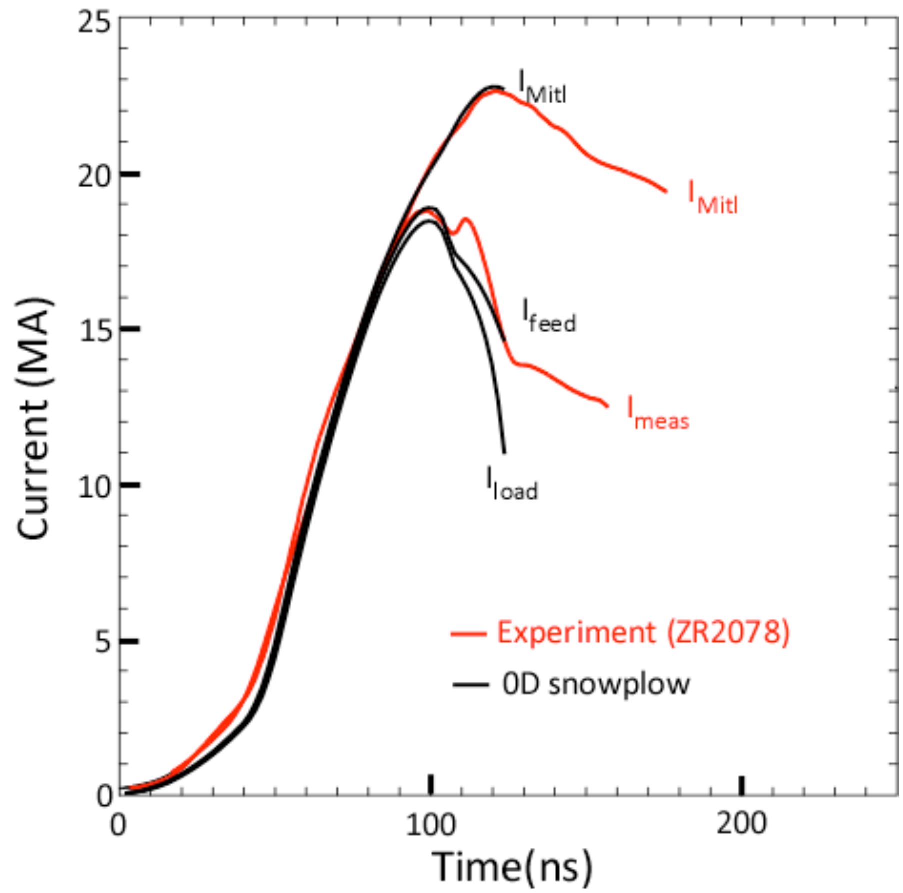


Summary of Titan 1234 and AASC nozzle comparison

Profile	Peak kinetic energy gen-erated in a 2.5 cm length 1 mg/cm calculation	K-yield compared to Titan1234 [0.8-1.2 mg/cm]	K- power compared to Titan1234 [0.8-1.2mg/cm]	Stability Compared to Titan1234 [0.8-1.2 mg/cm]
Titan 1:1	320 kJ			
AASC 1:1 31_30_250	310 kJ	~ less	~less	~worse
AASC 1:1.5 22_30_250	240 kJ	~same	~same	~better
AASC 1:2 31_30_0	240 kJ	~same	~same	~same

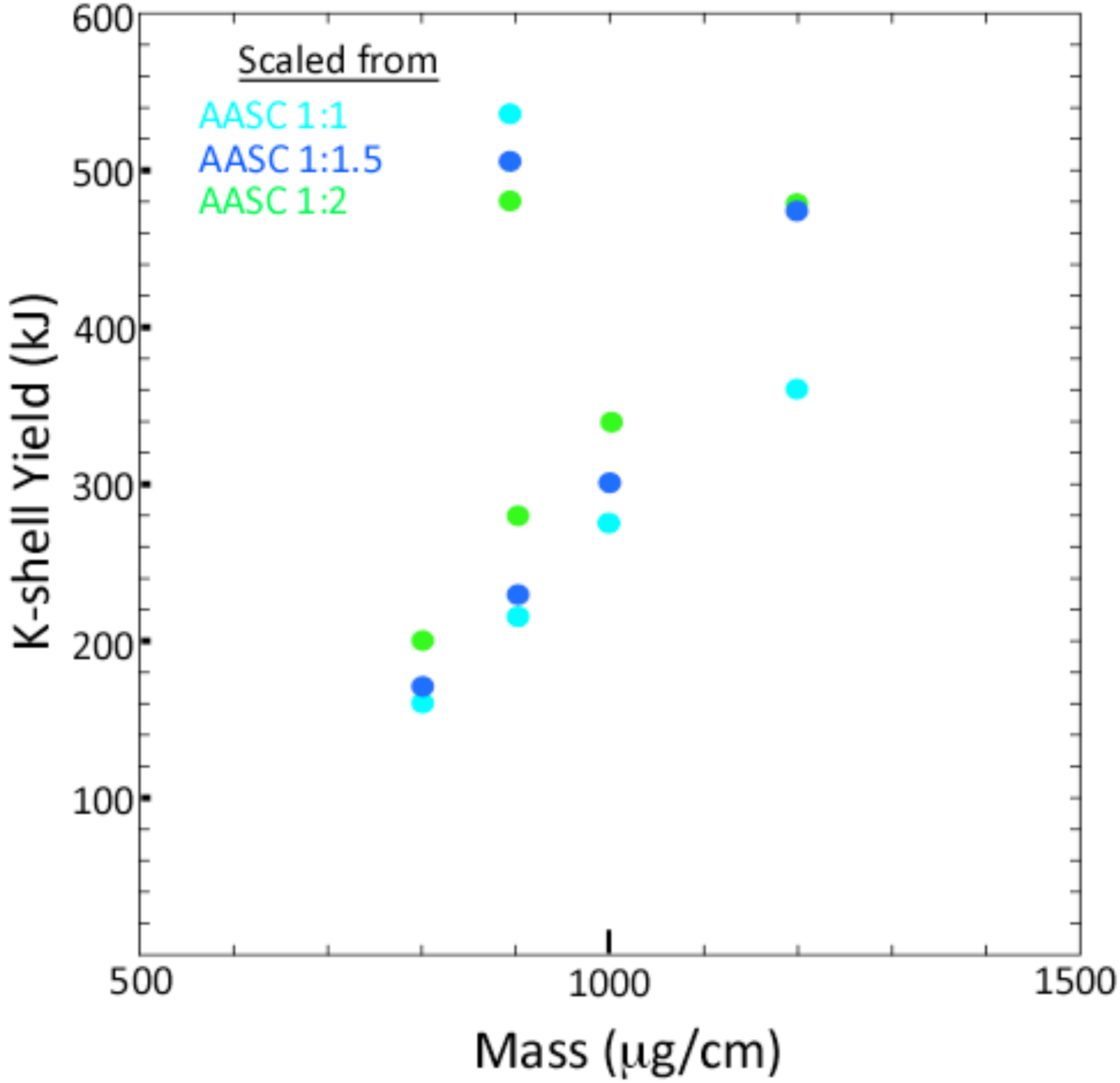
Equivalent Circuit Model for the Refurbished Z machine





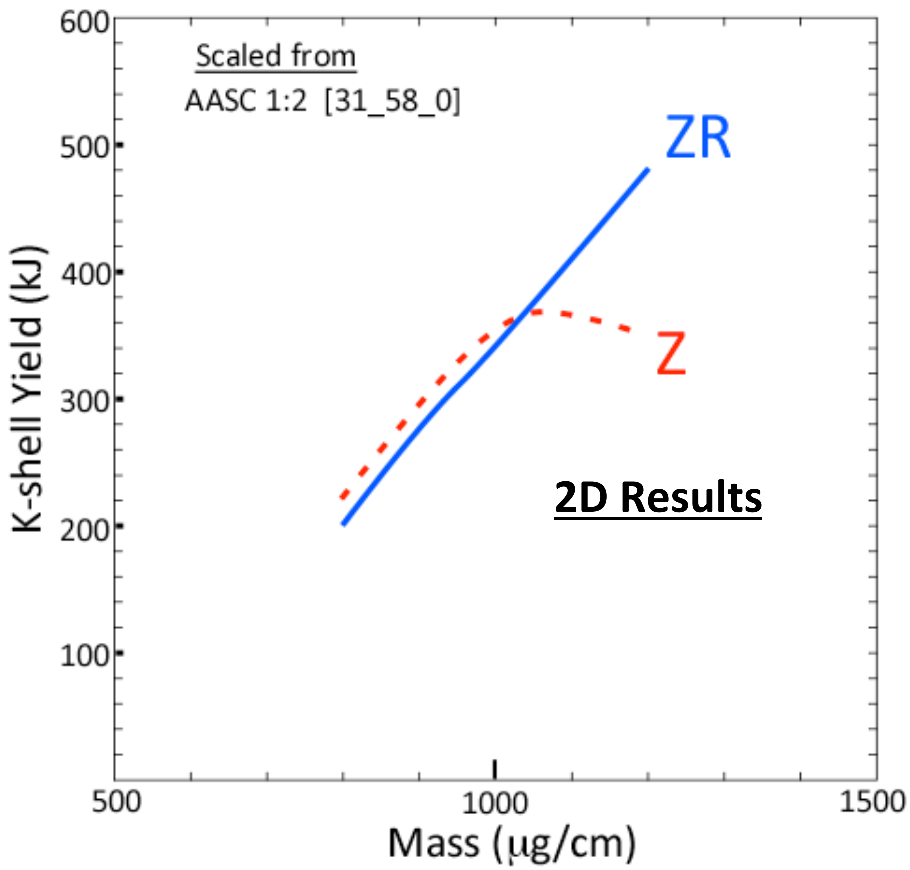
This is considered to be a conservative model for ZR. Understanding of convolute losses (Z_{flow}) and feed losses (S_{flow}) are still active areas of research at Sandia – as is the development of an equivalent circuit model. [C. A. Jennings *et. al.*, Phys. of Plasmas **17**, 092703 (2010)]

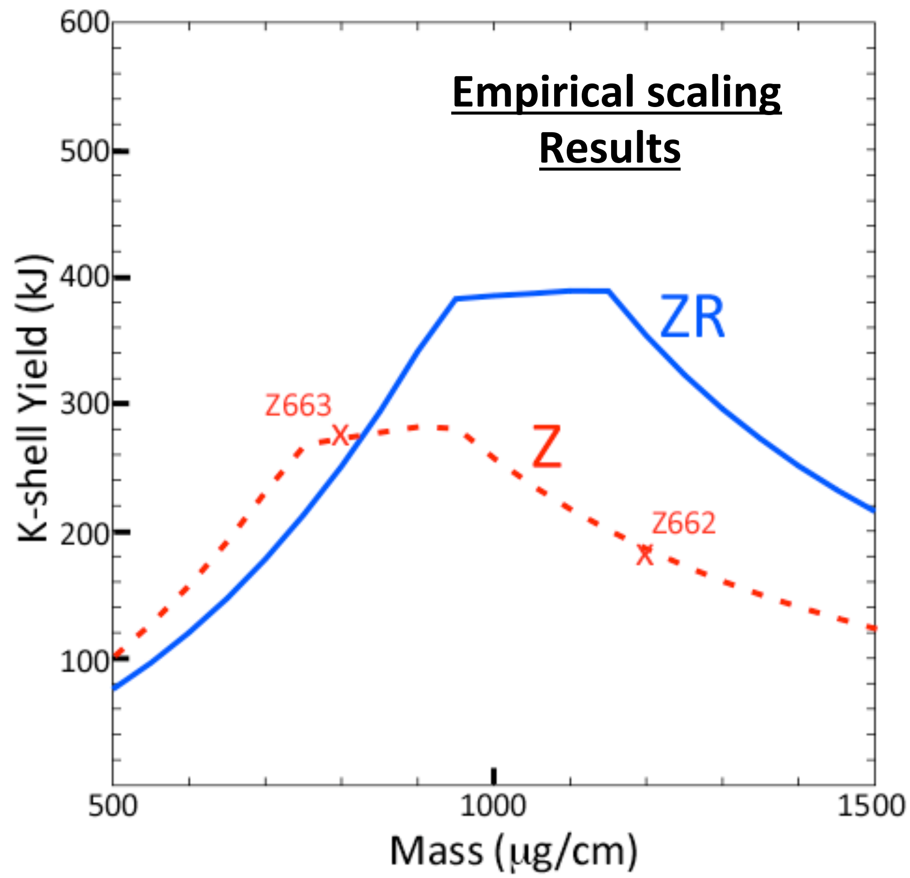
2D calculated K-shell yields for AASC Nozzle Configurations on ZR



2D calculations
Predict 400-500
kJ K-yields on ZR

Comparison of 2D calculated and Empirical Scaling K-Yields





2D calculations predict that ZR K-shell emission will exceed Z predicted K-shell emission at larger mass load than given by empirical scaling ,1.0 mg/cm vs 0.8 mg/cm.

Summary

Issues involving severe current losses at large mass loads due to UV irradiance of the convolute power feed, and overall characterization of convolute and feed losses are still under investigation.

In terms of mass distribution and 2D calculated peak kinetic energy, the AASC 1:1 [31_30_250] provides the best match to the successful Titan 1:1 profile.

However, the stability properties of the AASC 1:1 profile were the worst, resulting in lower calculated K-shell yields and powers than obtained with the 1:1.5 and 1:2 distributions.

There was so little mass in the central jet region, it is not clear that the presence of the jet has much influence on the pinch dynamics. The yields, powers, and stability properties of the AASC 1:1.5 distribution, which had a central jet, were similar to the properties of the AASC 1:2 distribution which did not.

Empirical scaling formulas and 2D calculations predict ~380 kJ K-shell yields on ZR for argon mass loads of 1 mg/cm. Furthermore, the 2D calculations predict even higher yields ~480 kJ for slightly larger mass loads of 1.2 mg/cm.

The Mach2 MHD code coupled with a TCRE argon model is used to model instability and radiation effects present in gas puff implosions with the AASC nozzle

Model Description :MACH2* - a Multiblock Arbitrary Coordinate 2-D Hydromagnetics Model

Time-Dependent, Single Fluid MHD in Cylindrical Symmetry. For PRS: 2T Plasma Model:

•Separate Electron and Ion Energies and Thermal Diffusions

•Analytic Magnetically-inhibited Spitzer Diffusion Coefficients

•Finite Volume Differencing, Energy-Coupled Circuit Model for Z accelerator

•Tabular Collisional Radiative Equilibrium (used for Electron EOS) and radiation transport

•Moving grid employed to increase resolution (128 radial x 128 axial)

**NumerEx*

Collisional Radiative Ionization Dynamics

In order to hydrodynamically calculate the evolution of a plasma one needs to know its state, i.e. temperature, ion density, electron density, radiative cooling/heating rate, etc. Unless the plasma is in LTE, a collisional radiative (CR) model is required to self- consistently solve for the atomic ground state populations, excited state populations and the radiation field that define the state of the plasma.

dn/dt =Local collisional and radiative rates + Non local radiative rates

Local collisional and radiative rates ↓

- Collisional ionization
- Collisional de-excitation
- Collisional ionization
- Collisional recombination
- Dielectronic recombination
- Radiative recombination
- Spontaneous emission

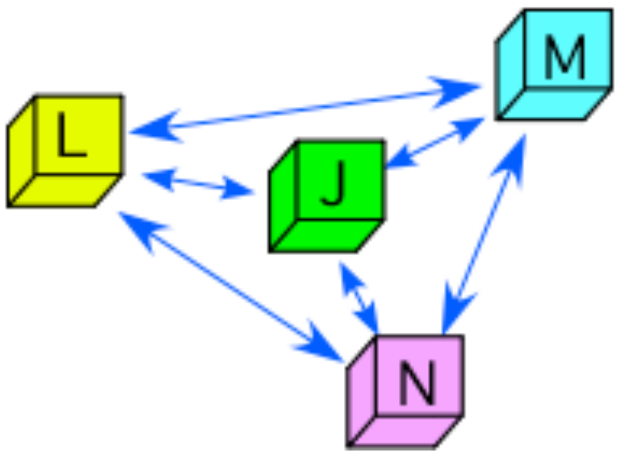
Non local radiative rates ↓

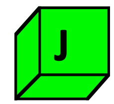
- Line photo-excitation
- Photo ionization

Blue – non-local processes that require radiation transport, all other processes are local functions of (T_e,N_i)

Collisional Radiative Ionization Dynamics

Multi-dimensional plasma



The state of zone 

depends on **local collisional and radiative** processes as well as **non-local radiative** processes.

Solving the EOS from first principles for the ground and excited state populations in each zone, requires solving **the local collisional and radiative rate** equations self-consistent with the **non-local radiative rates.** **Calculation involves:**

1) Solving the equation of radiative transfer for **thousands** of frequencies along enough rays (**hundreds**) to insure that there is good radiative communication between all zones.
2) Iterating on populations (**thousand**) and radiation field to insure self-consistent solution for each zone

Computationally difficult to implement this $\sim N^2$ coupling, where N is the number of zones ($N \sim 10^5$ - 10^7 for multi-dimensional plasma calculations).

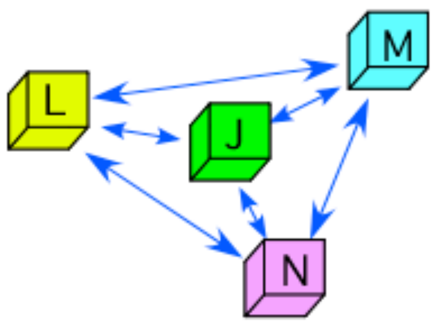
Tabular Collisional Radiative Equilibrium (TCRE) Model

Localized plasma region [J] has a known:

E_{int} - specific internal energy (J/cm^3)

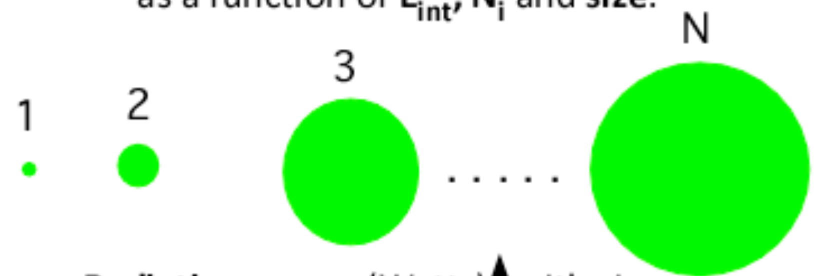
N_i - ion density (cm^{-3})

$P_{He\text{-}\alpha}$ - specific radiative power in the He-α line (W/cm^3)



Uniform plasmas with same E_{int} and N_i

Complete EOS of uniform plasmas are calculated with an extensive collisional radiative model with radiation transport. EOS quantities of interest are **tabulated** as a function of E_{int}, N_i and **size**.



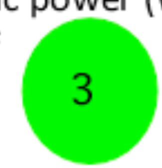
Radiative power (Watts) ↑ with size

Specific radiative power (W/cm^3) ↓ with size

"Uniform plasma" assumption of the TCRE model

If zone [J] of the multi-dimensional plasma has the same $P_{He\text{-}\alpha}$ as does the uniform plasma

, the total specific power (W/cm^3) from all lines in the He-like stage of [J] is taken to be the same as that of



Likewise, representative lines for each of the other ionization stages are used to calculate the total specific line power from that stage

Tabular Collisional Radiative Equilibrium (TCRE) Model

- **Total line specific radiative power** is calculated by summing all the line contributions from each ionization stage as given by the "uniform plasma" assumption.

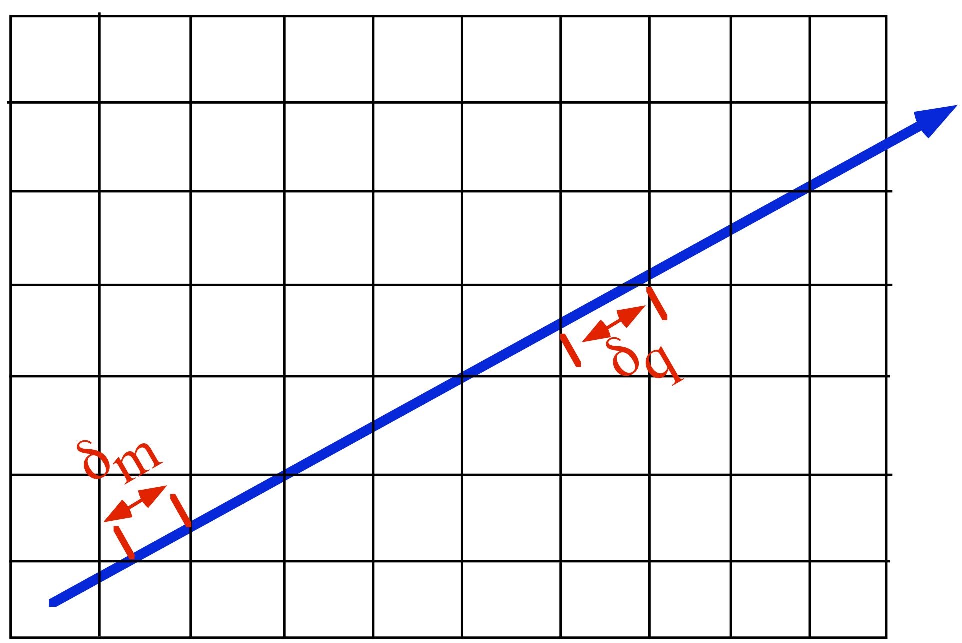
- **Total recombination specific radiative power** is given by the EOS for a uniform plasma that matches the representative line power from the dominant ionization stage. For example, if a local region of argon plasma has an effective charge of 16, its dominant ionization stage is the He-like stage.

- **Updated temperatures and effective charge** and any other EOS quantity of interest is also given by the EOS of the uniform plasma that matches the local plasma's dominant ionization stage line power.

- Since the complete EOS of the uniform plasma is known, the line center absorption coefficients , K (cm^{-1}), of each of the representative lines is known. With this information, one can do a ray trace radiation transport (for each of the representative lines) that couples all the multi-dimensional plasma's zones to update the representative line powers in each plasma zone. Requires a ray trace transport of just a N lines, where N is the atomic number, as opposed to hundreds or thousands. **For now we use "on the spot" transport.**

"On-the-spot" Non-local Radiation transport

The essence of the "on-the-spot" escape probability technique is to have the photon transport impact the ionization dynamics and total radiative cooling by reducing the Einstein ***A*** coefficients by an amount ***A*** $(1-P_{esc})$, where P_{esc} is the probability of escape of the line photon from the plasma. If a photon is absorbed anywhere in the plasma before it escapes, it is assumed to be absorbed in the emitting zone.



The probability of escape of a photon emitted along a given ray is a function of the optical depth τ.

$$\tau = \sum \delta_i K_i$$

where δ_i is the distance traveled by the ray through each zone i and K_i is the zonal absorption coefficient for the photon.

D.E. Osterbrock, Astrophysics of Gaseous Nebulae (W. H. Freeman, San Francisco, 1974),p. 19

J. P. Apruzese, et. al., J. Quant. Spectrosc. Radiat. Transfer **23**, 479 (1980).