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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

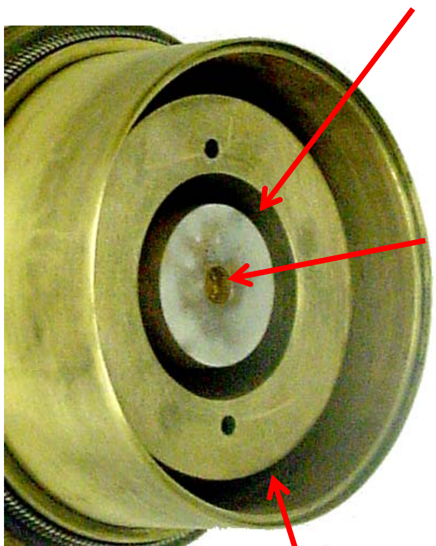
In the near future scientists at Sandia National Laboratories will be performing, for the first time, argon gas puff experiments on the refurbished Z machine. As part of the effort to determine the initial argon loads to be deployed, we theoretically assess the K-shell emission and stability properties 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 compare the stability and K-shell emission properties of gas distributions generated by the new nozzle with the distribution used in the pre-refurbished Z experiments (Titan1234 nozzle).
- 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.
- Summarize results of this argon gas puff assessment for ZR
- Motivate Ar on deuterium gas puff experiments for neutron generation

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).]

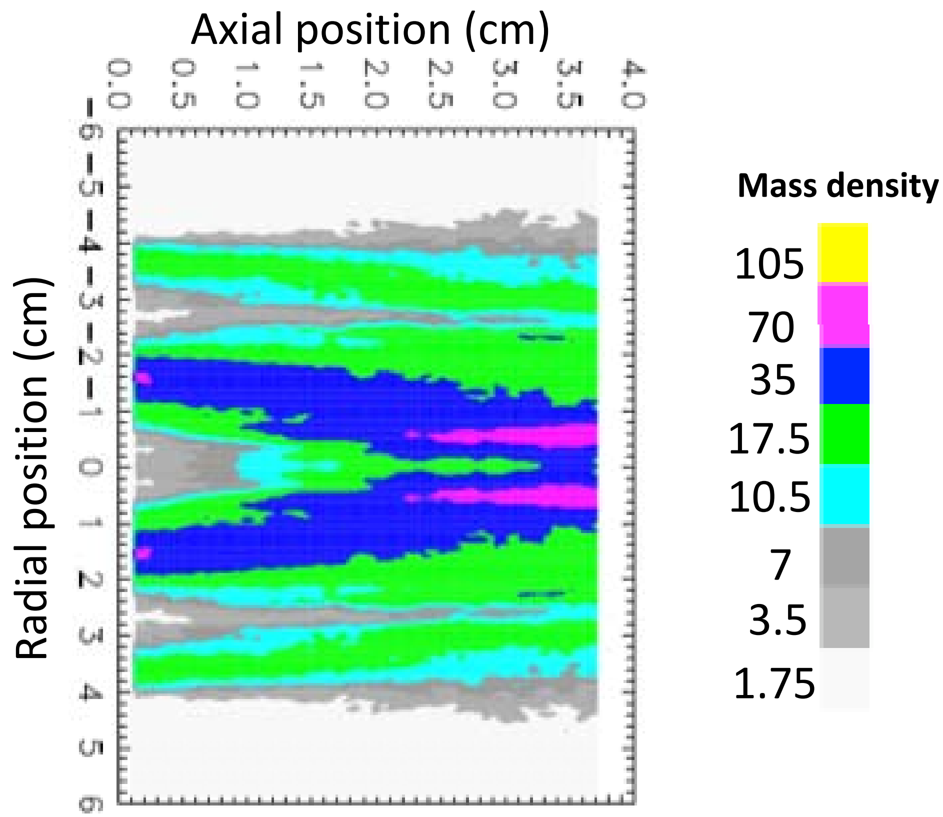
Inner annulus



Central jet

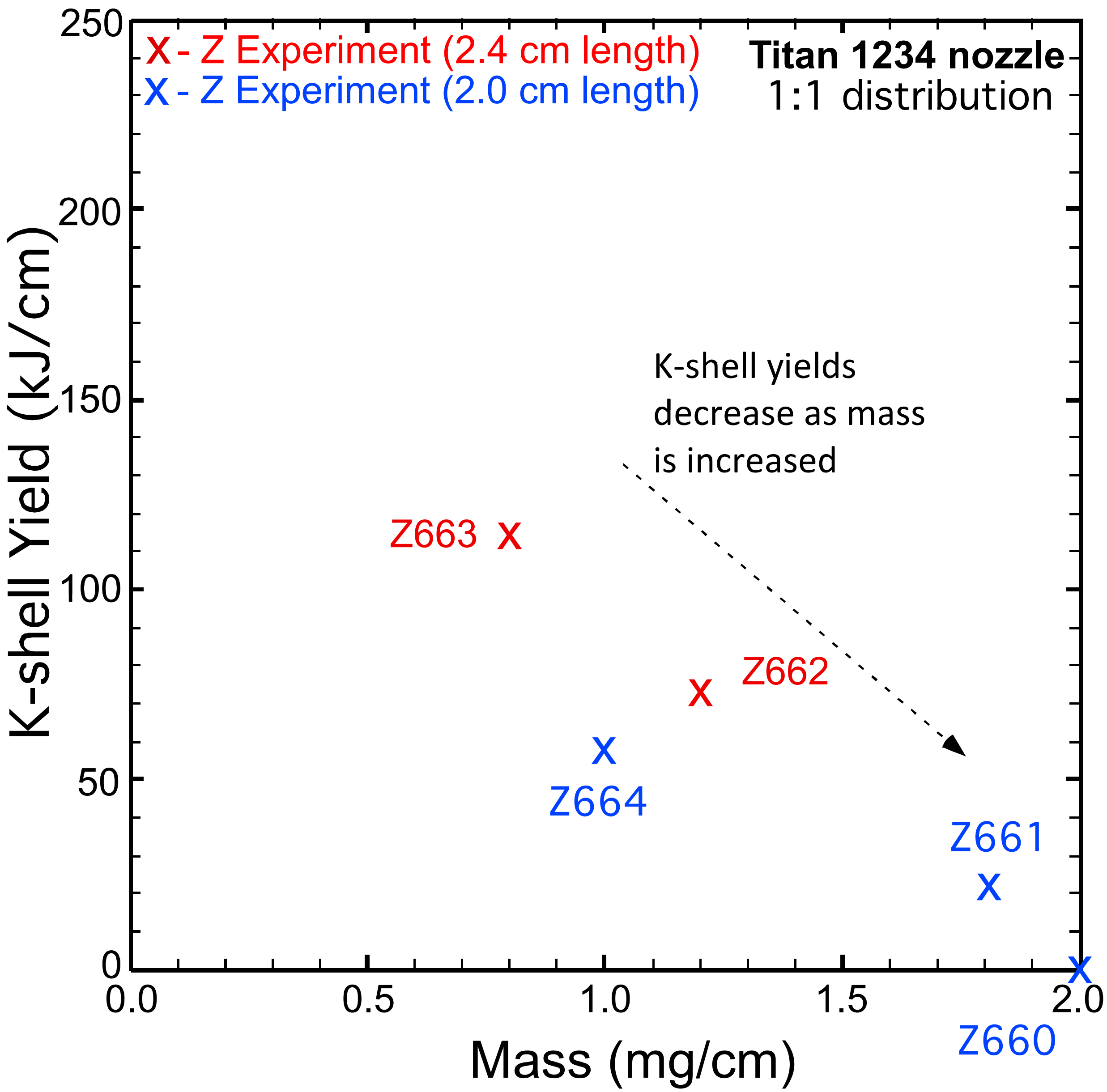
Outer annulus

Generic 8 cm diameter multiple shell nozzle



8 cm diameter, Titan 1234 Nozzle - 1:1 gas distribution

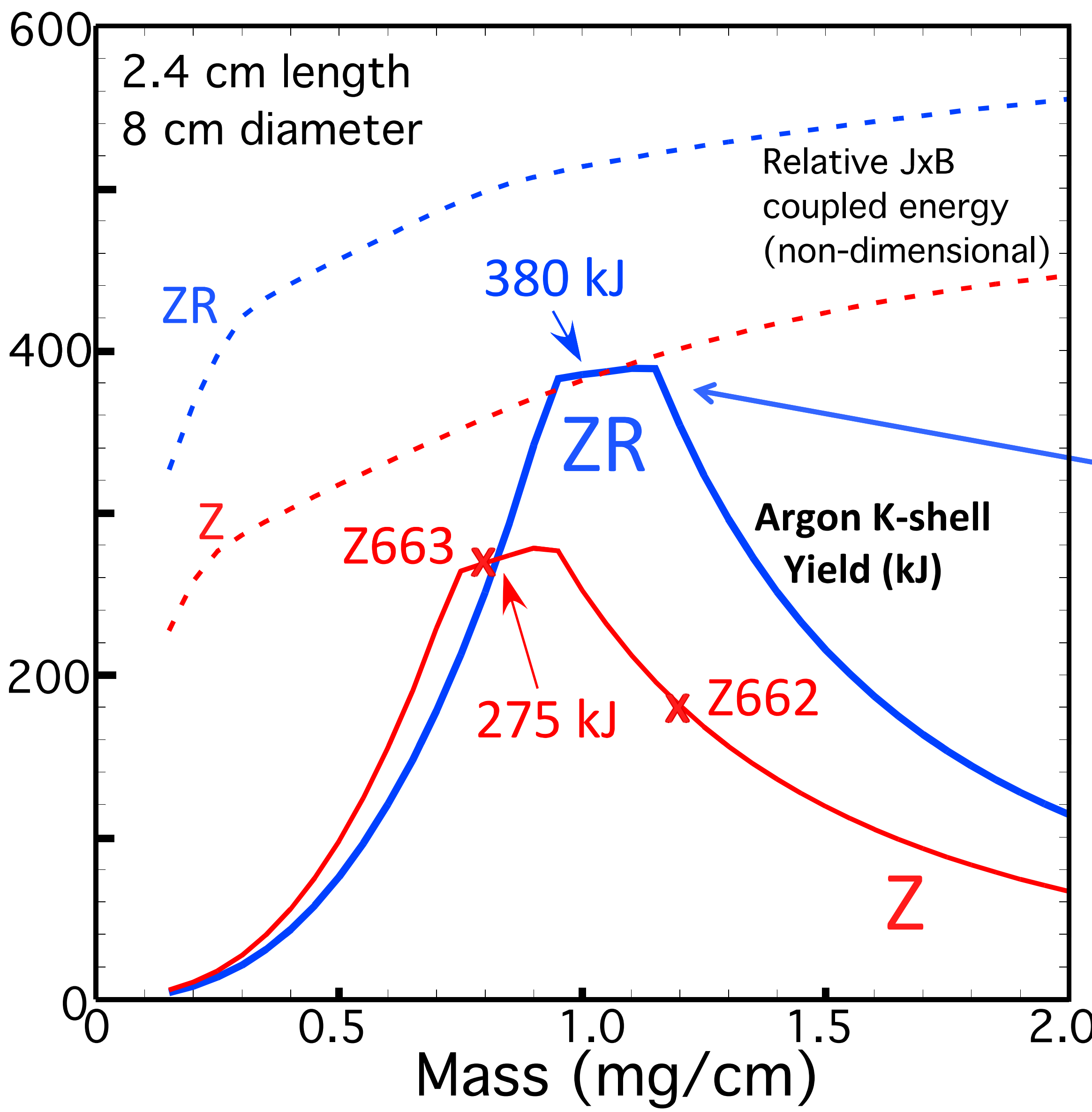
Summary of pre-refurbished Z argon experiments



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

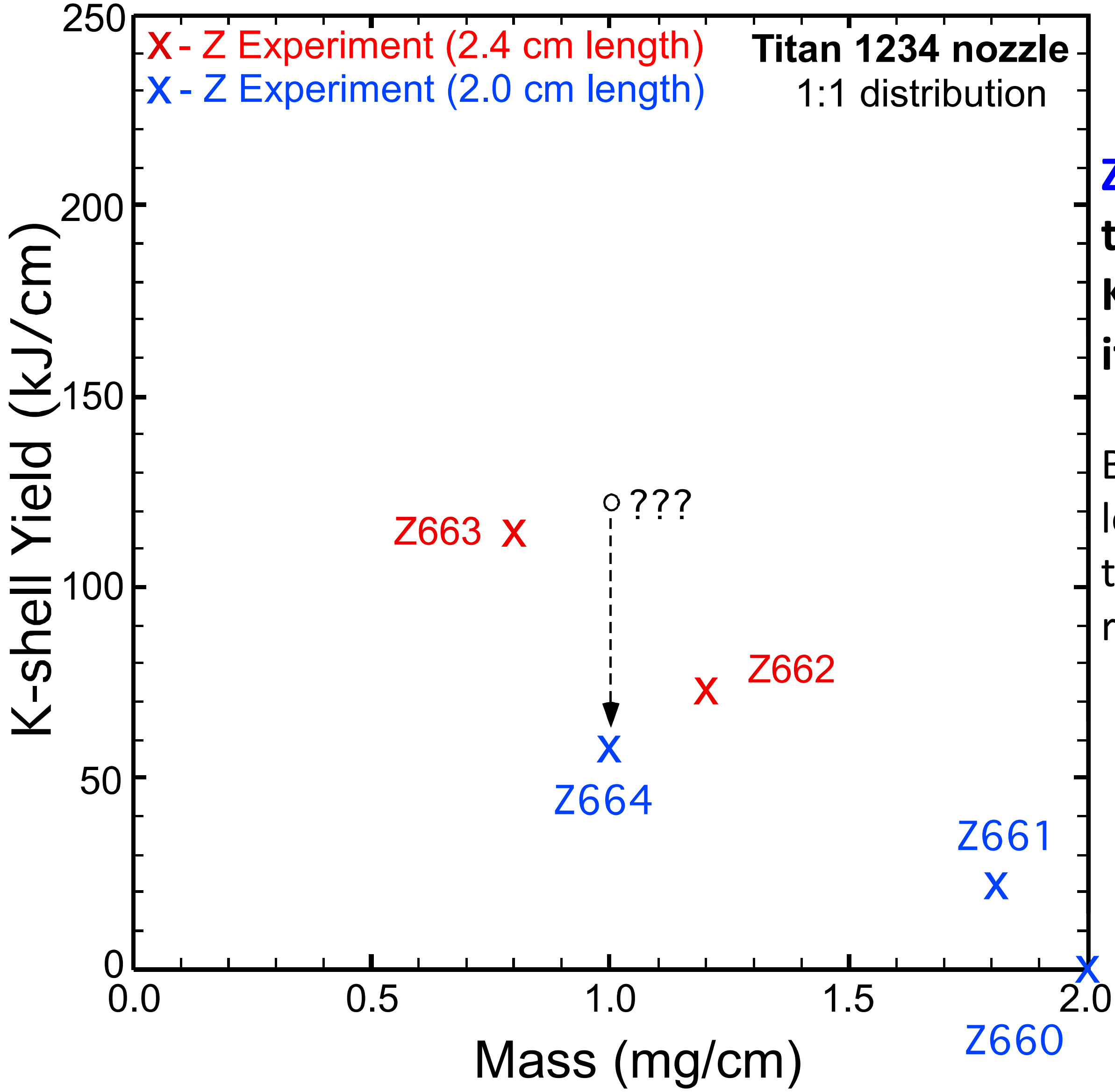


Relative JxB energies are obtained from 0D snowplow model of Titan 1234 nozzle coupled to equivalent circuit model for Z and ZR.

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 could be an issue, especially at large mass**

2) **K-shell yields of ~380 kJ are attainable on ZR based on an empirical extrapolation of ~275 kJ yields obtained on pre-refurbished Z**

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 kinetics, opacity , and non-local transport of radiation that affect the atomic populations of these high temperature K-shell emitting plasmas we incorporated into the Mach2 code a self-consistent EOS calculation that models this physics. It is called the tabular collisional radiative equilibrium model -TCRE

Mach2 reference – R. E. Peterkin, M. H. Frese, and C. Sovienc, J. Comput. Phys. **140**,148 (1998).
TCRE reference – J. W. Thornhill, J. P. Apruzese , *et. al*., Phys. Plasmas **8**, 3480 (2001).

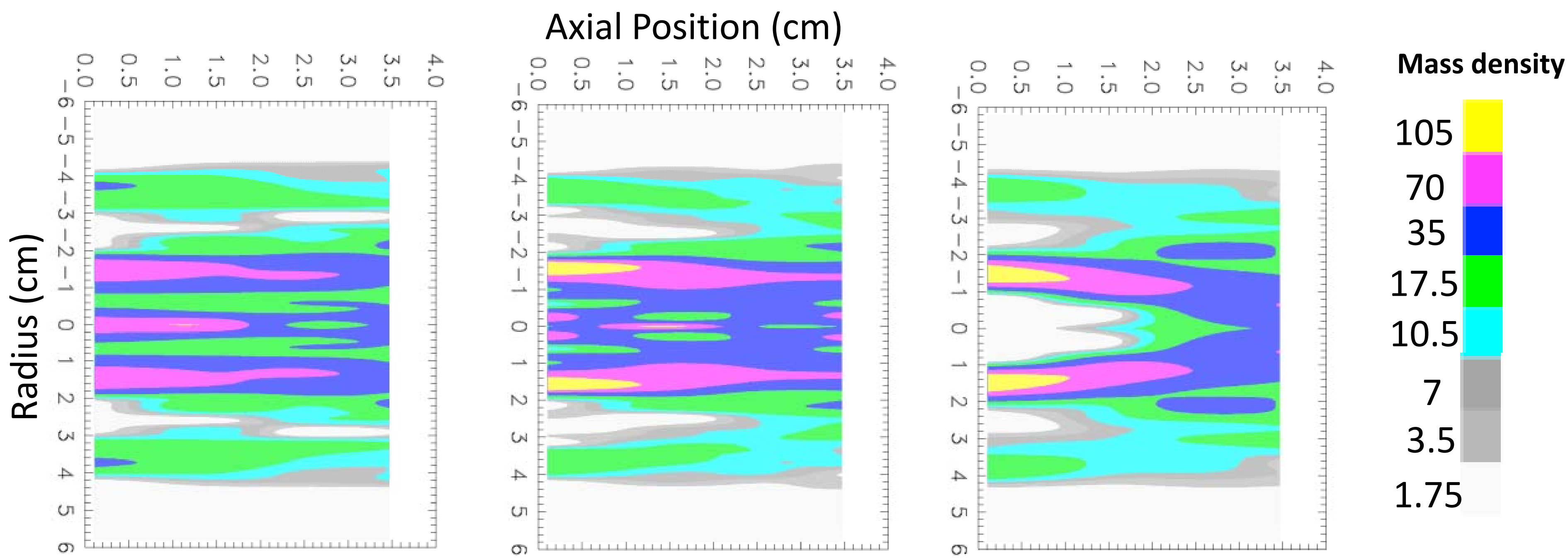
Modeling the K-shell emission and stability properties of the AASC nozzle gas distributions

There are three measured gas distributions analyzed to characterize the stability and K-shell emission properties of the AASC nozzle

1) AASC **[31_30_250]**
2) AASC **[22_30_250]**
3) AASC **[31_58_0]** --------No central jet

Pressure (psi) in **outer** annulus	Pressure (psi) in **inner** annulus	Pressure in **central jet**

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



AASC [31_30_250] "1:1"   AASC [22_30_250] "1:1.4"   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) @ ~20 radial positions
- Bicubic spline used to interpolate between data points
- The load mass is varied in the calculations by renormalizing each of the above three distributions to the mass of interest.

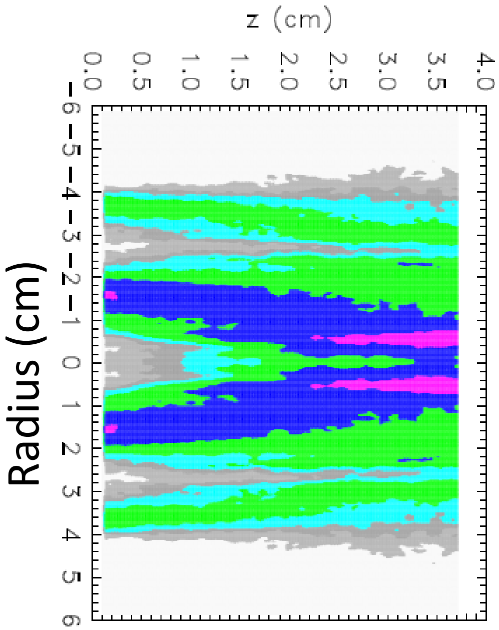
General properties of the AASC gas distributions

	Titan 1:1	AASC 1:1	AASC 1:1.4	AASC 1:2
Fraction of total mass in outer nozzle region (>2.5 cm)	0.5	0.43	0.38	0.38
Mass fraction at z=0.5 cm for: outer/total inner/total c. jet /total	 0.49 0.49 0.02	 0.46 0.52 0.02	 0.37 0.61 0.02	 0.39 0.61 0.00

Outer: r > 2.5 cm; Inner: 2.5 > r > 0.5 cm; Cent. jet : r < 0.5 cm

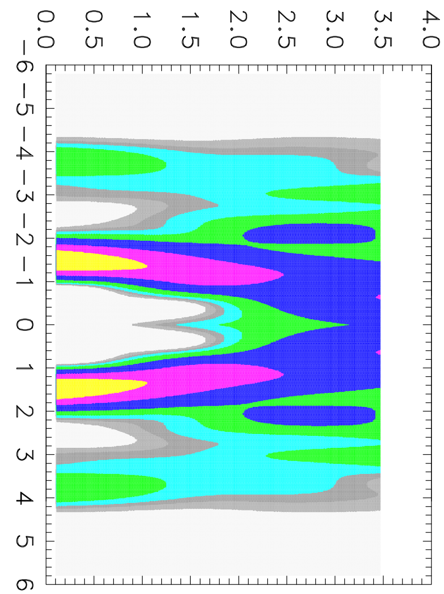
- The AASC 1:1 distribution is the closest match to the Titan 1:1 distribution used in pre-refurbished Z experiments.
- Little mass in the central jet region of the pinch ~2%.

Comparison of the Titan 1234 and AASC gas distribution's K-shell and stability properties



Titan 1:1

Laser induced fluorescence
(120 axial x 540 radial)



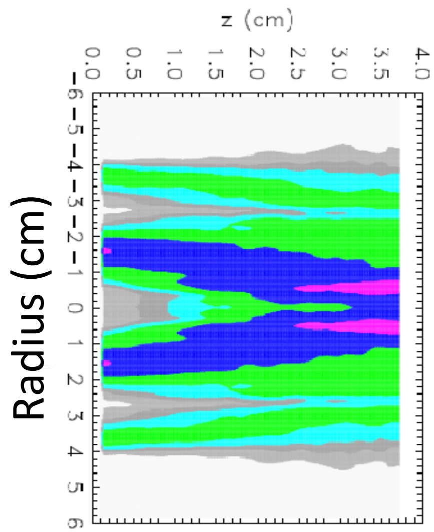
AASC 1:2

Fiber optic interferometry
(4 axial x 20 radial)

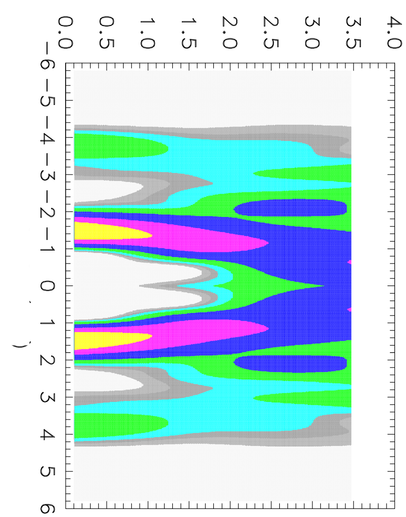
The AASC gas distribution is inherently "smoothed" due to bicubic spline interpolation of data

Comparison of the Titan 1234 and AASC gas distribution's K-shell and stability properties

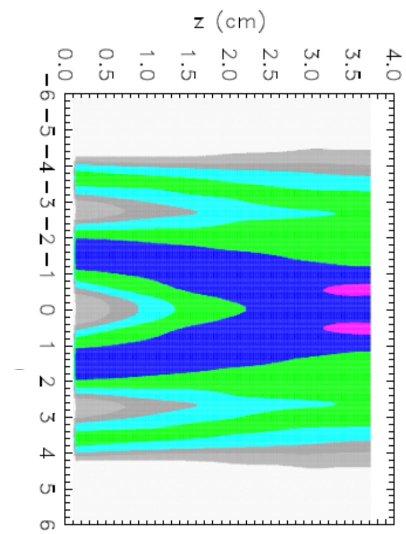
To make for a "fair" comparison with the inherently "smoothed" AASC distributions, the Titan gas distribution is "smoothed" by averaging over nearest neighbor data points successive times. Calculations are performed using a **10x** and **100x** Titan gas distribution.



Titan 1:1 (**10x**)

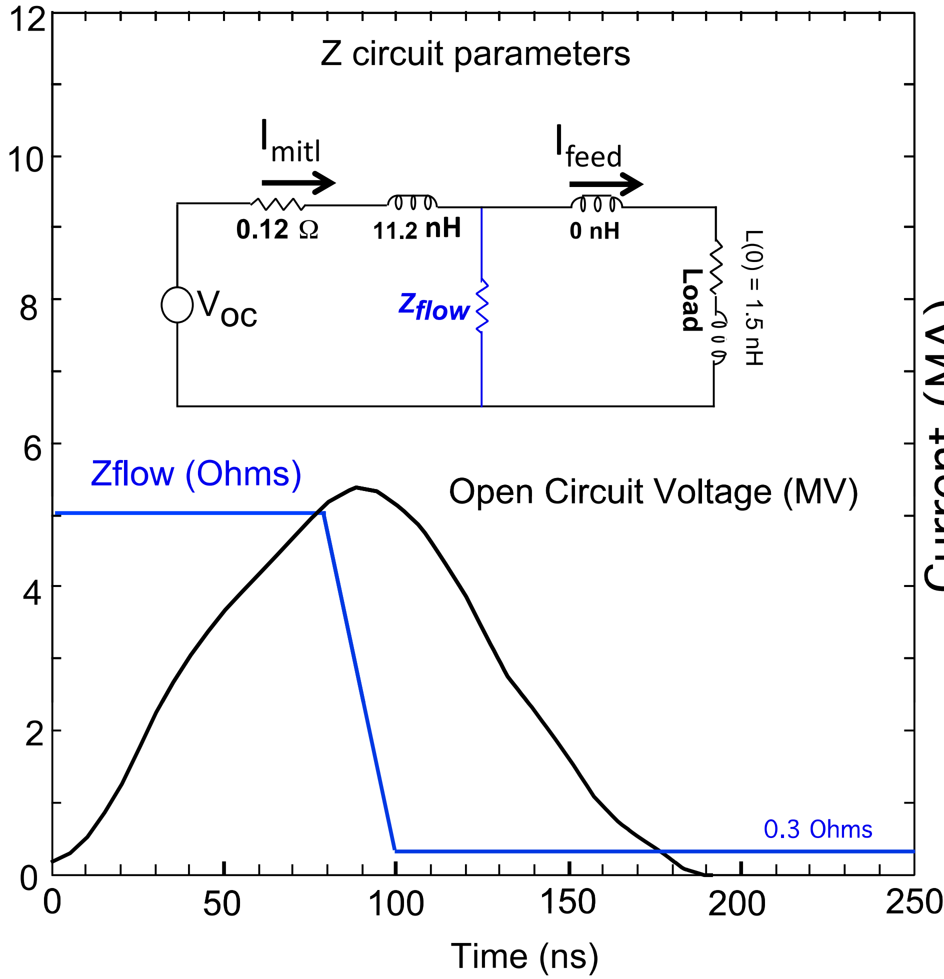


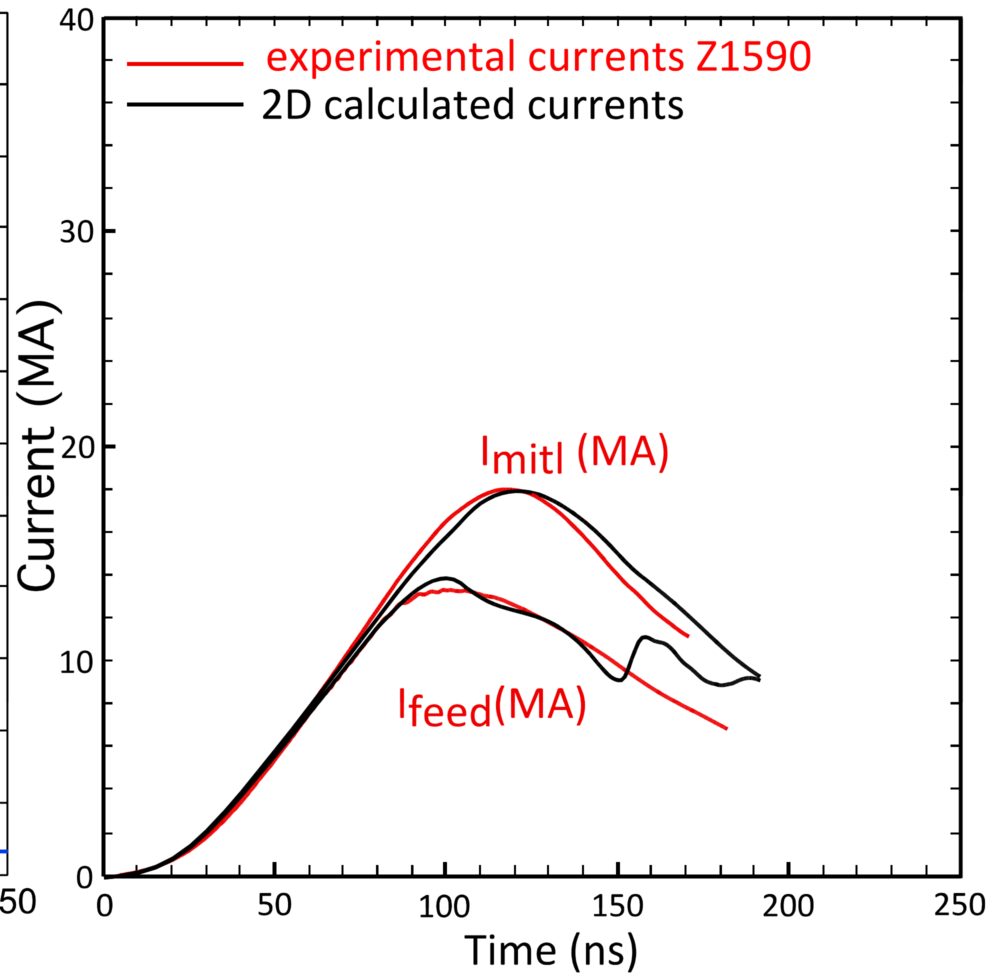
AASC 1:2



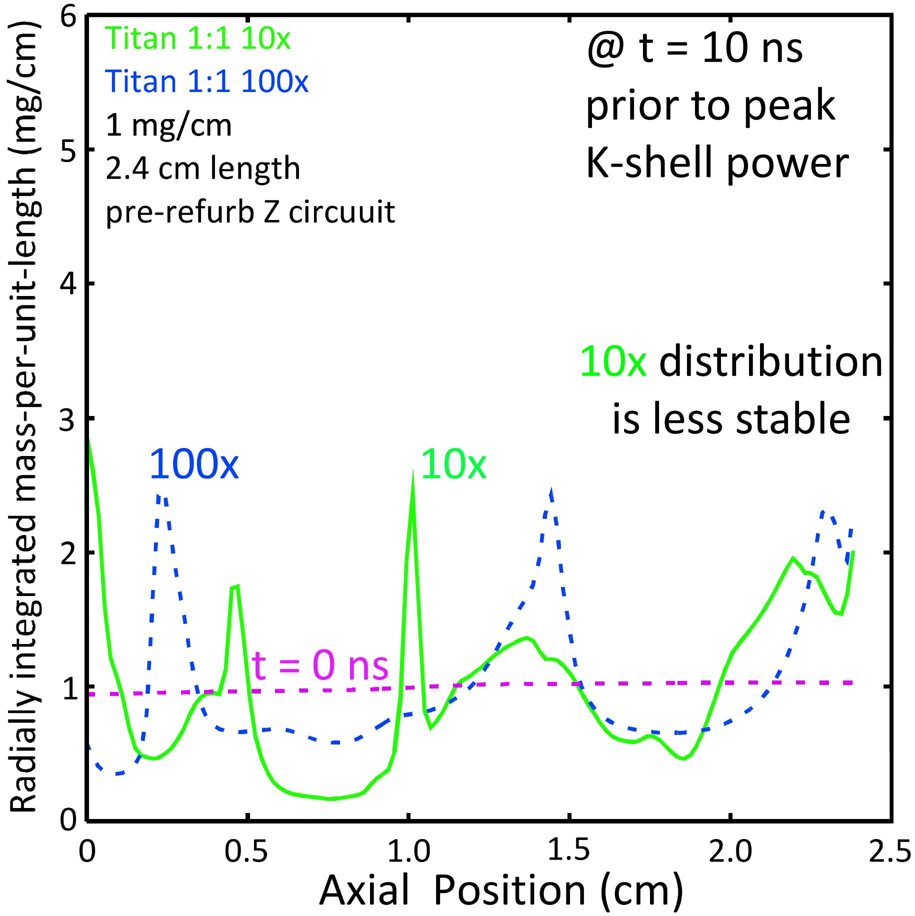
Titan 1:1 (**100x**)

Comparison of the Titan 1234 and AASC gas distribution's K-shell and stability properties on pre-ref. Z

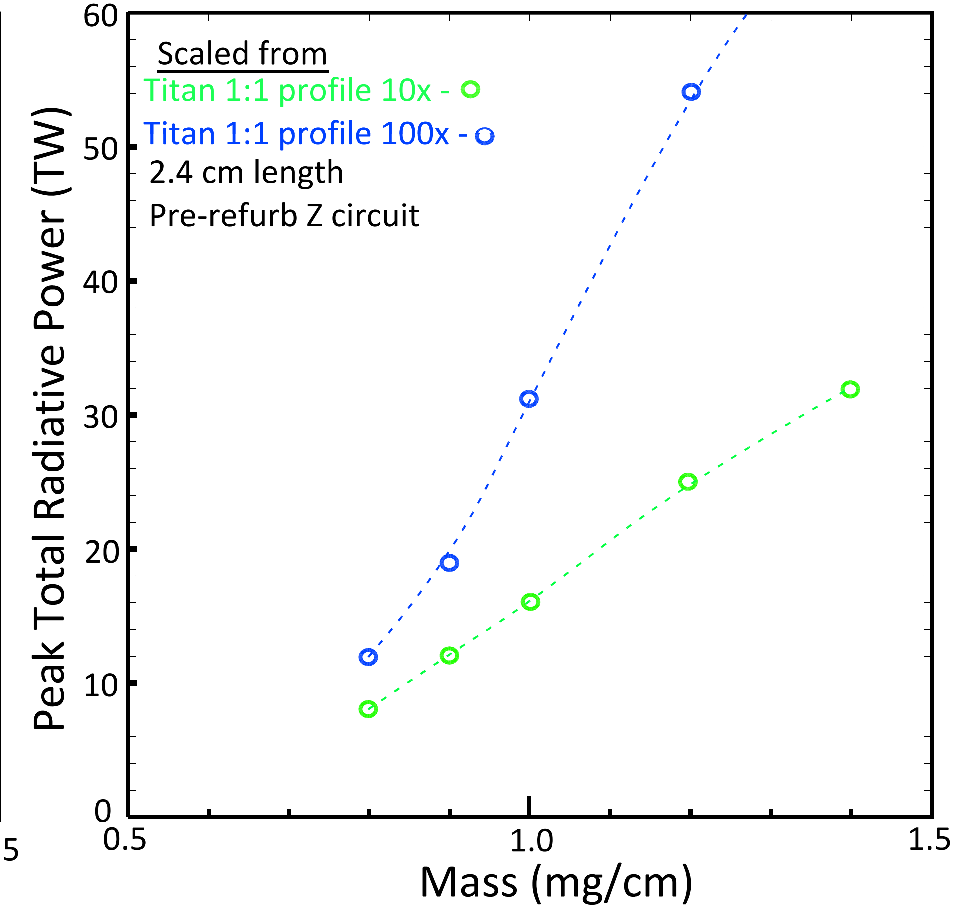




Greater stability of Titan 100x distribution gives rise to higher radiative powers than 10x distribution

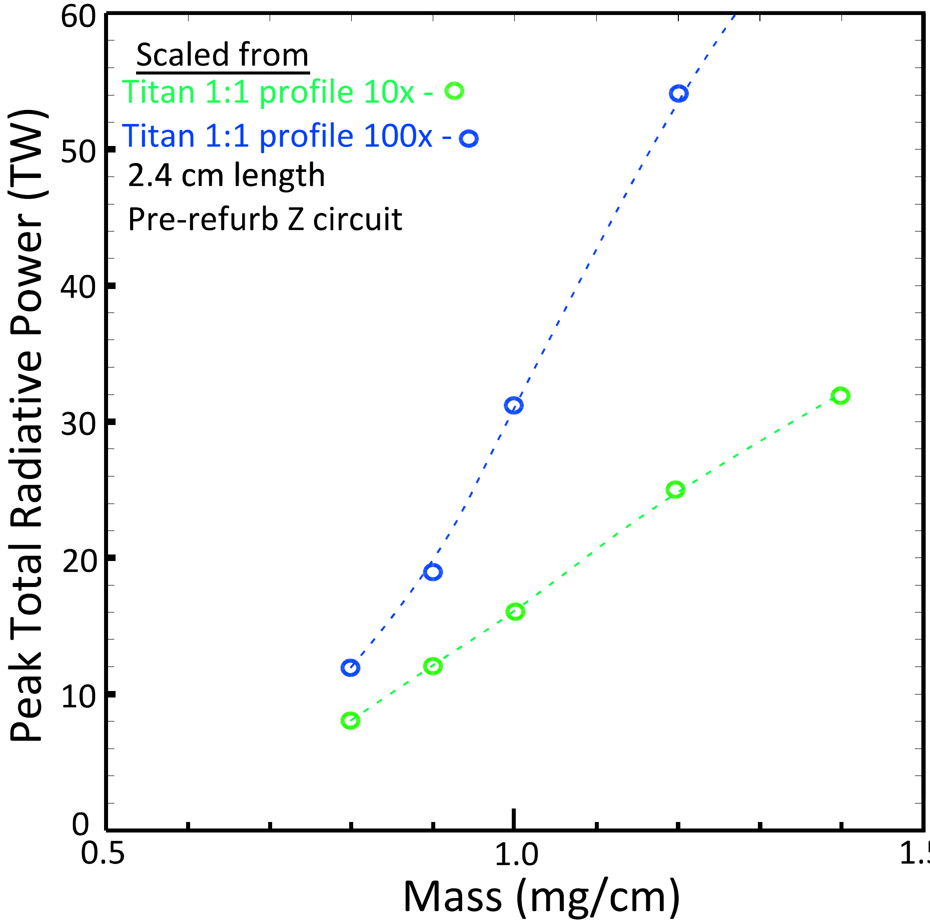


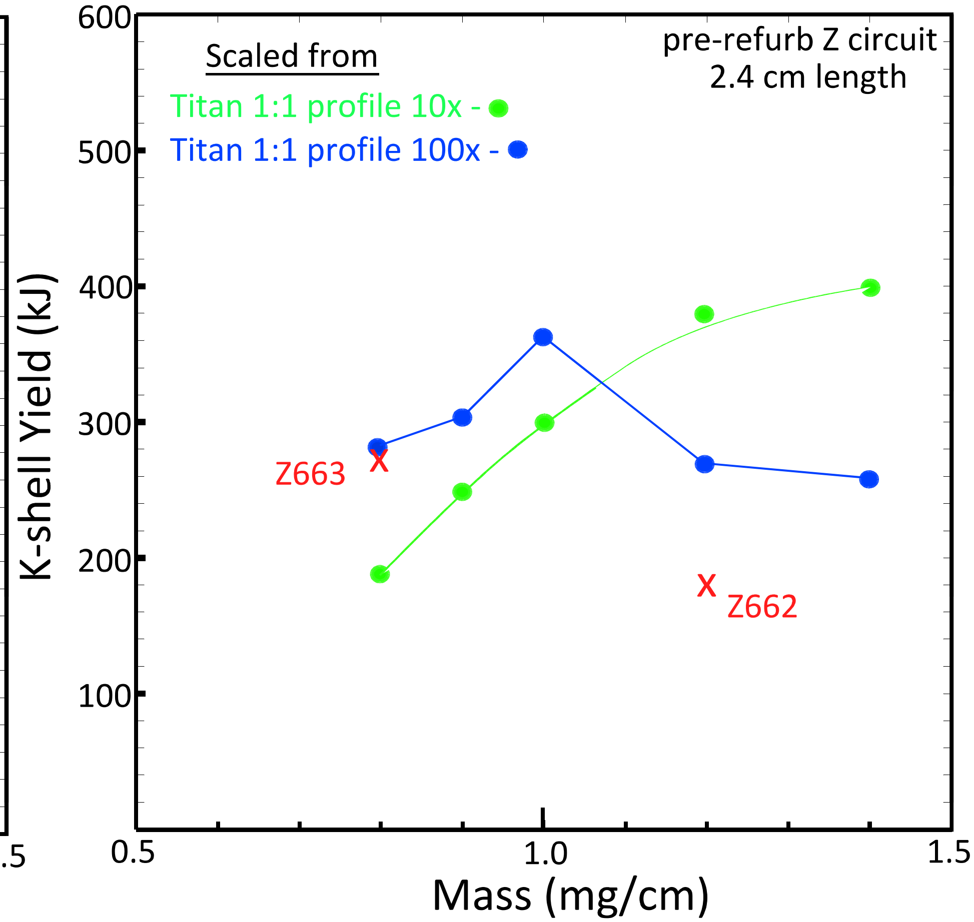
At each axial location, the mass is radially integrated. Large fluctuations denote an unstable implosion.



Lower powers of 10 x distribution are due to increased axial non-uniformity

2D Calculated K-yields and total radiative powers for Titan 1234 10x and 100x smoothed gas distribution :Pre-refurbished Z circuit

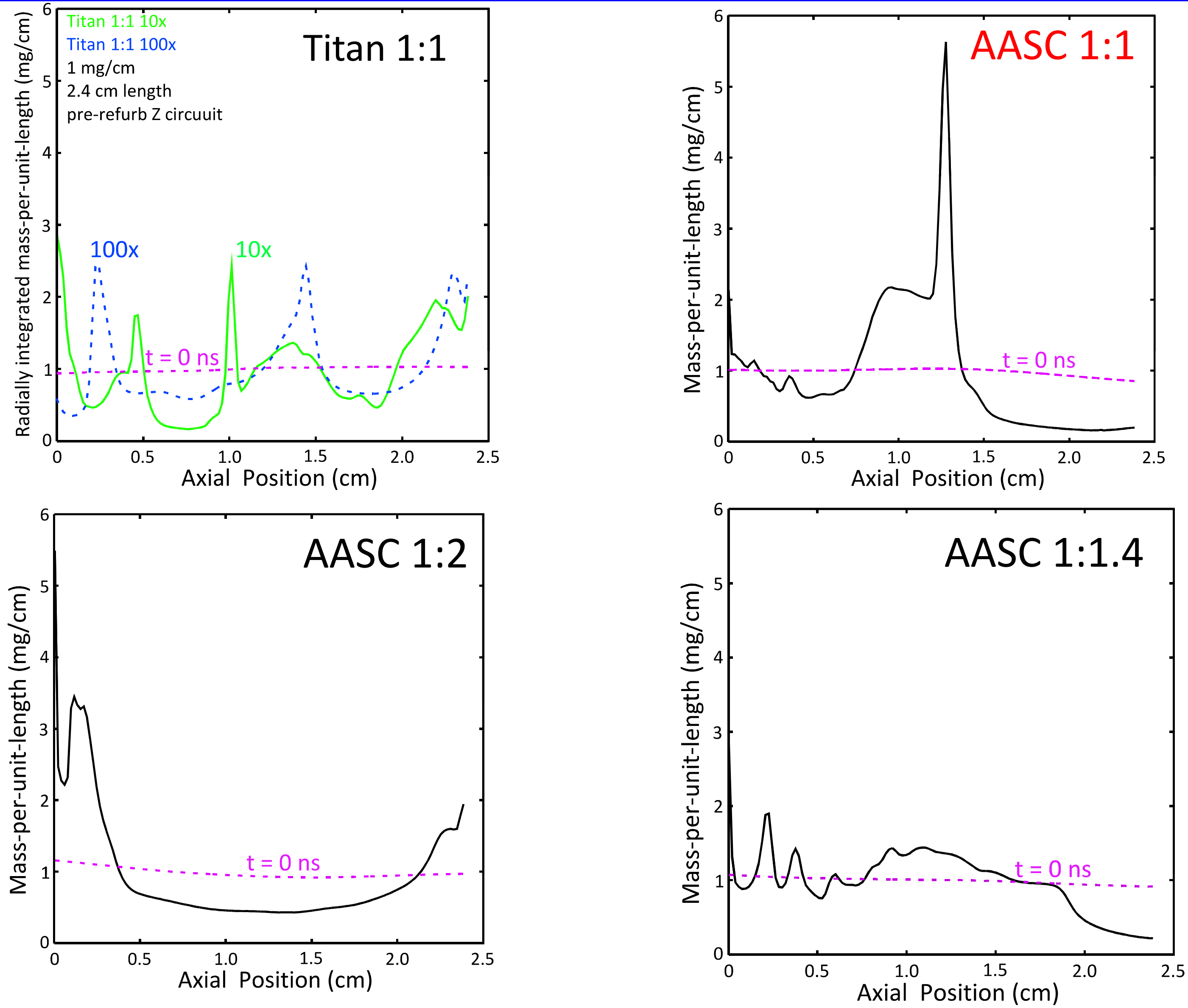




K-shell yield curve turns over when total power is sufficiently large that the plasma cools too rapidly to sustain K-shell emission

- 100 x profile best matches pre-refurbished Z experiments.
- 10 x profile has higher yield at large mass because of less radiative cooling.

The AASC 1:1 gas distribution is the least stable

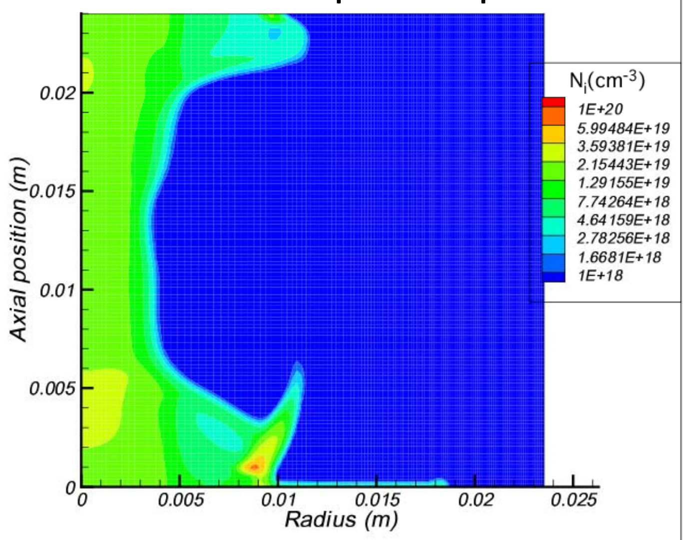


The radially integrated mass-per- unit-length as a function of axial position – 10 ns prior to stagnation. large fluctuations denote an unstable implosion. These calculations were for a 2.4 cm length, 1 mg/cm load driven by the pre-refurbished Z circuit.

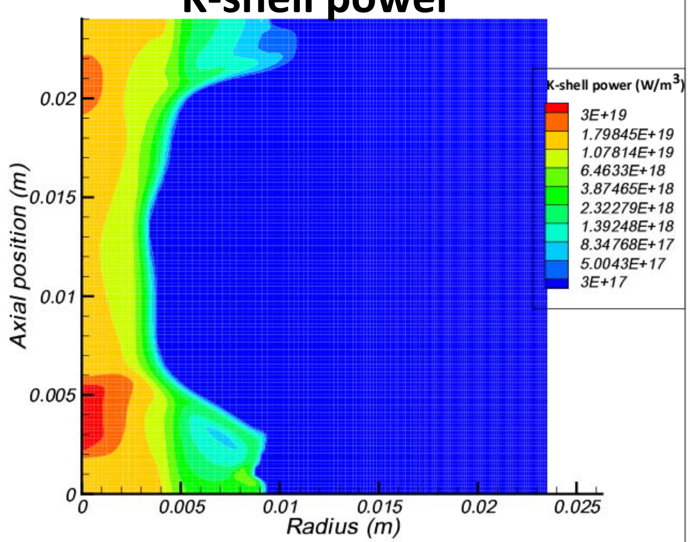
Stability comparison between AASC 1:1 and 1:2 2D implosions

AASC 1:2

Ni at time of peak K-power



K-shell power

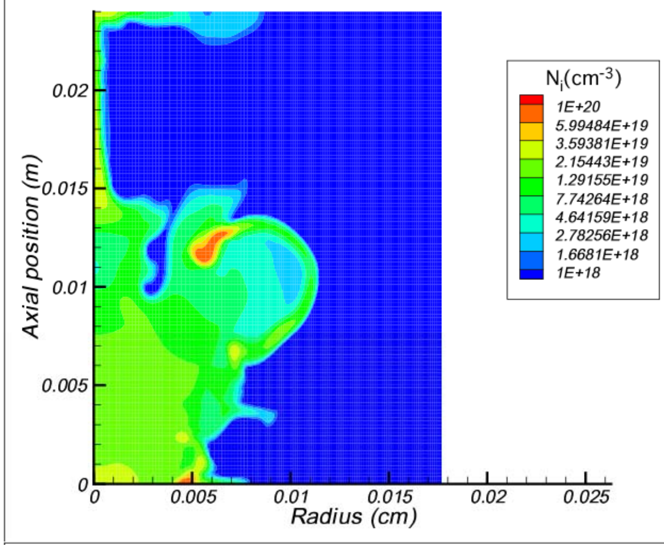


2D (r,z) profiles for Ni and K-shell power @ time of peak K-shell power

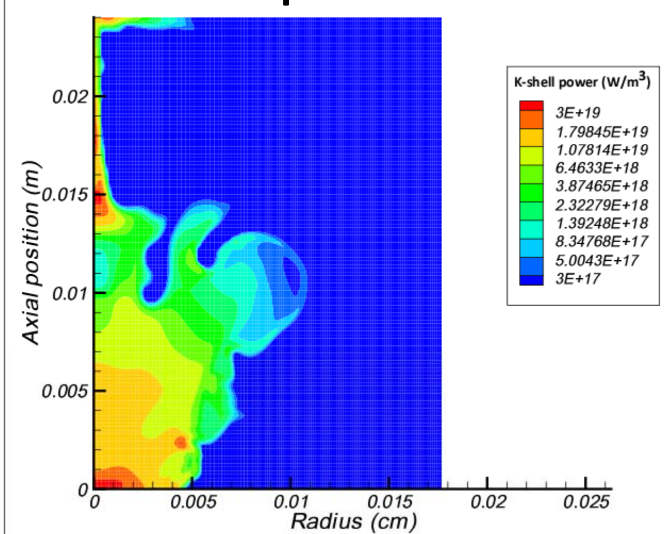
2.4 cm length
1 mg/cm
Pre-refurb Z circuit

AASC 1:1

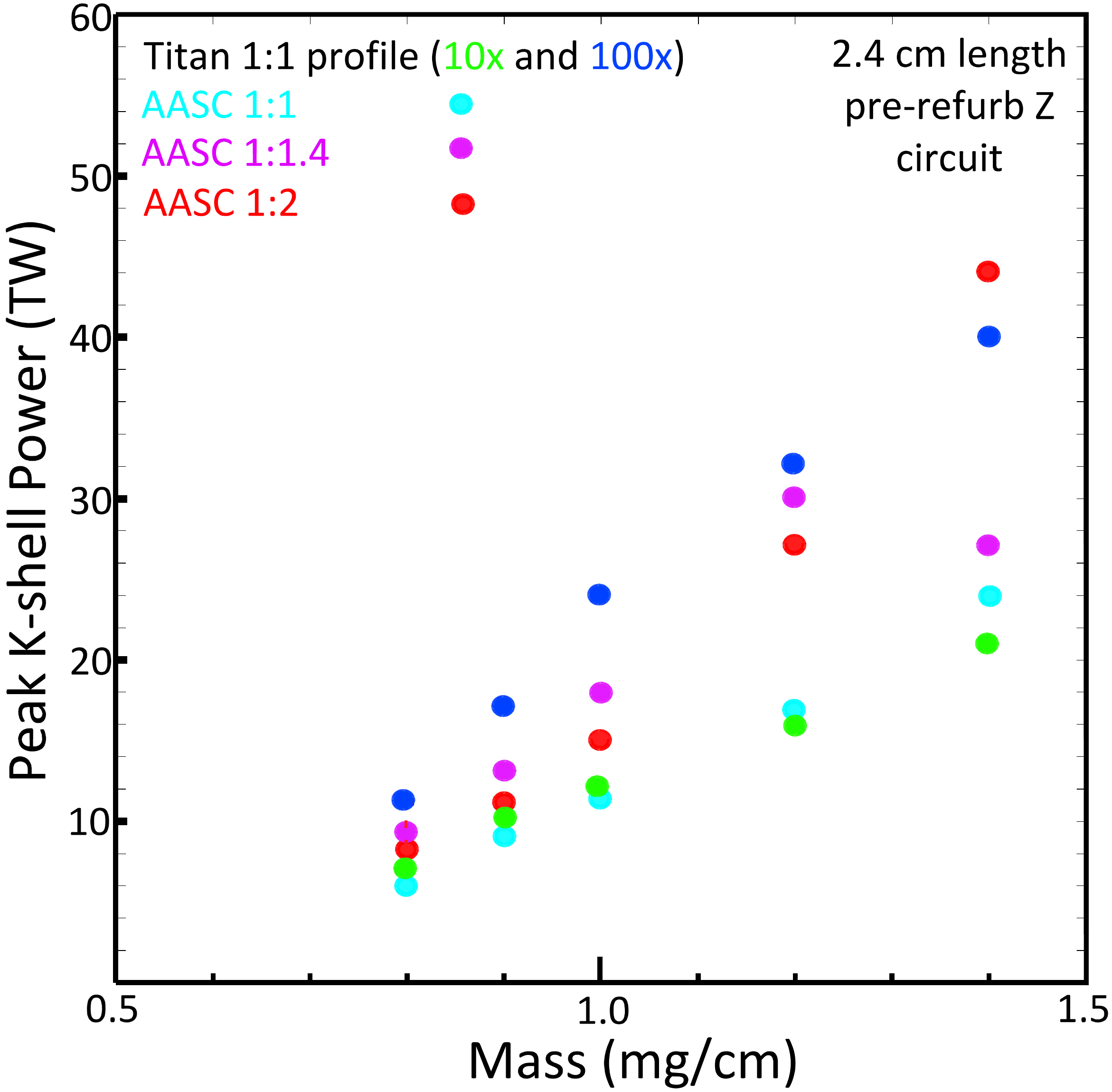
Ni at time of peak K-power



K-shell power

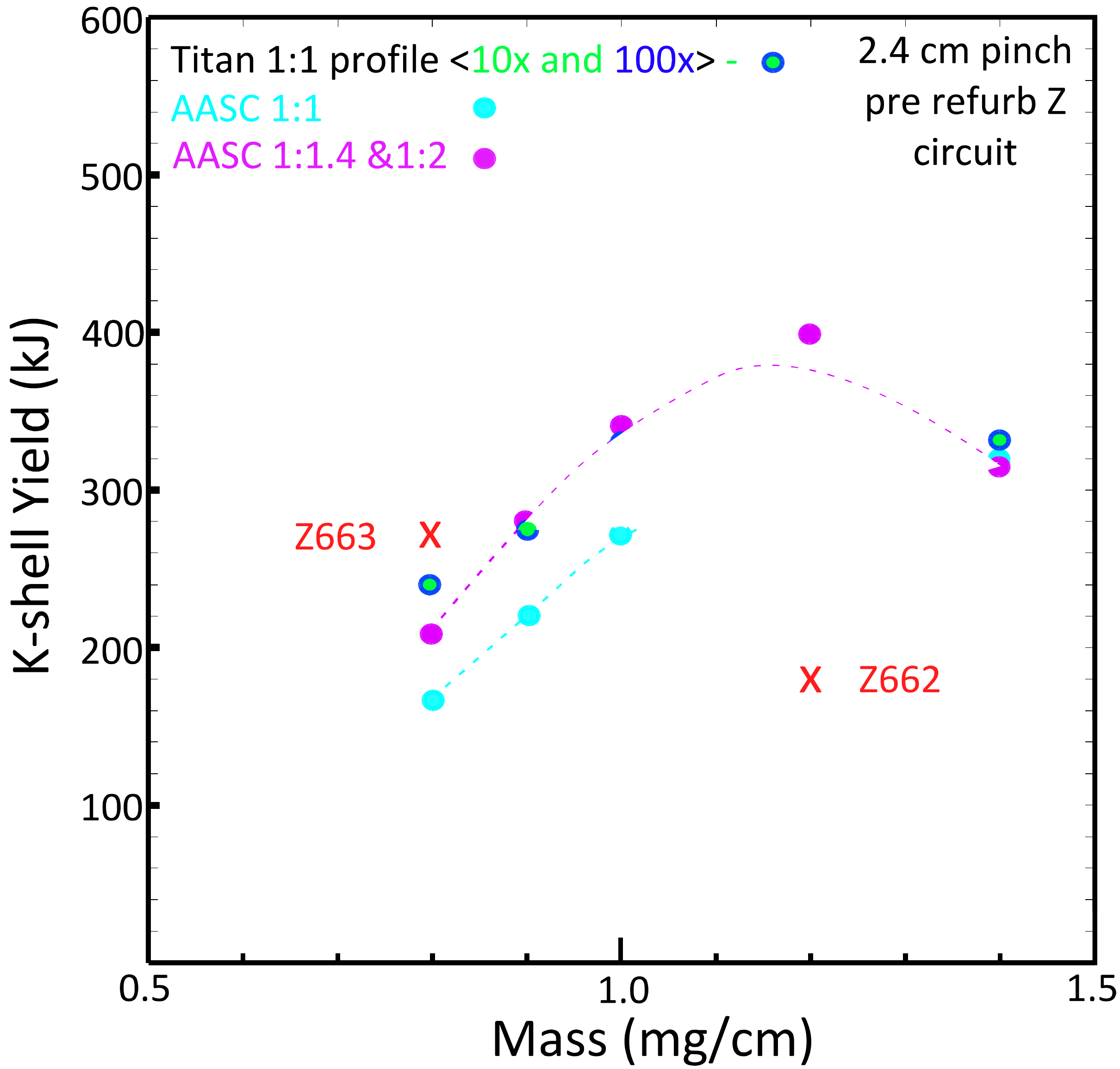


2D Calculated K-shell Power for Titan 1234 and AASC Nozzles on Pre-refurbished Z



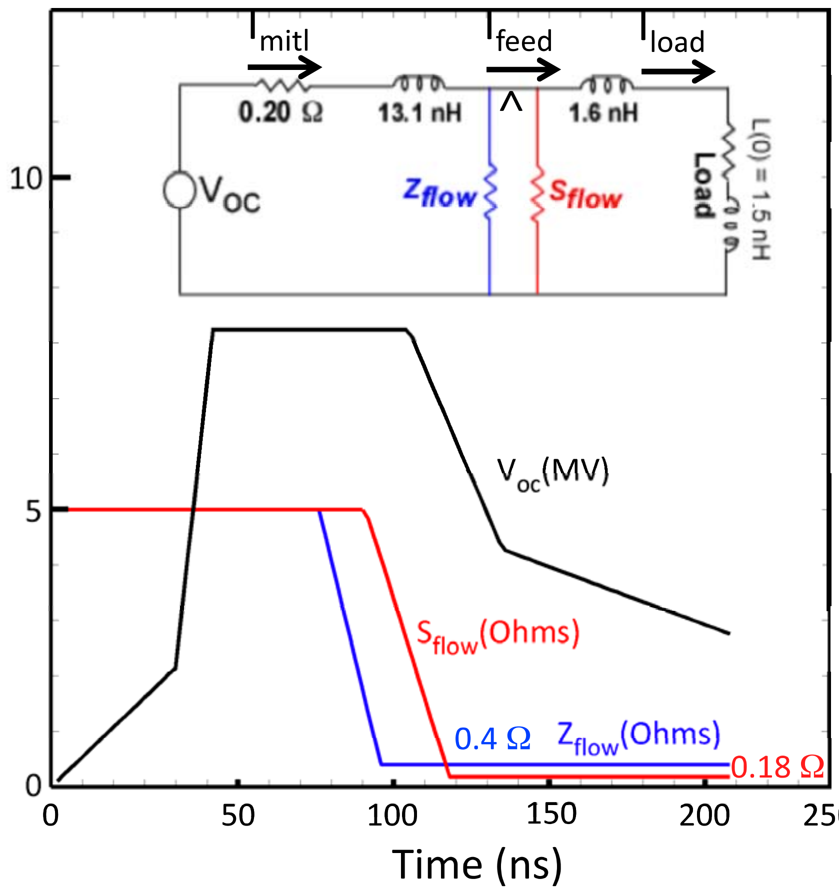
The Titan 100x, and AASC 1:1.4 and 1:2 distributions are the most stable and they have the highest K-shell and total powers.

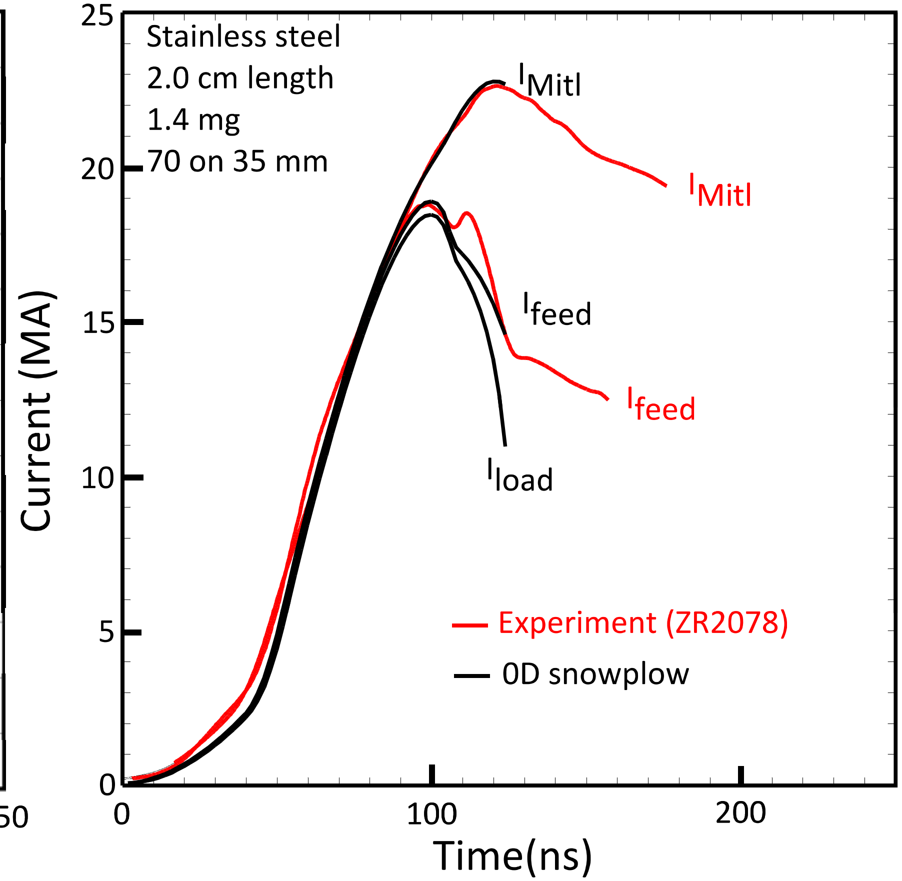
2D Calculated K-yields for Titan 1234 and AASC Nozzles on Pre-refurbished Z



Clearly, the AASC 1:1.4 and 1:2 loads outperform the 1:1 load – especially in the range 0.8 – 1.2 mg/cm, where ZR experiments will likely take place.

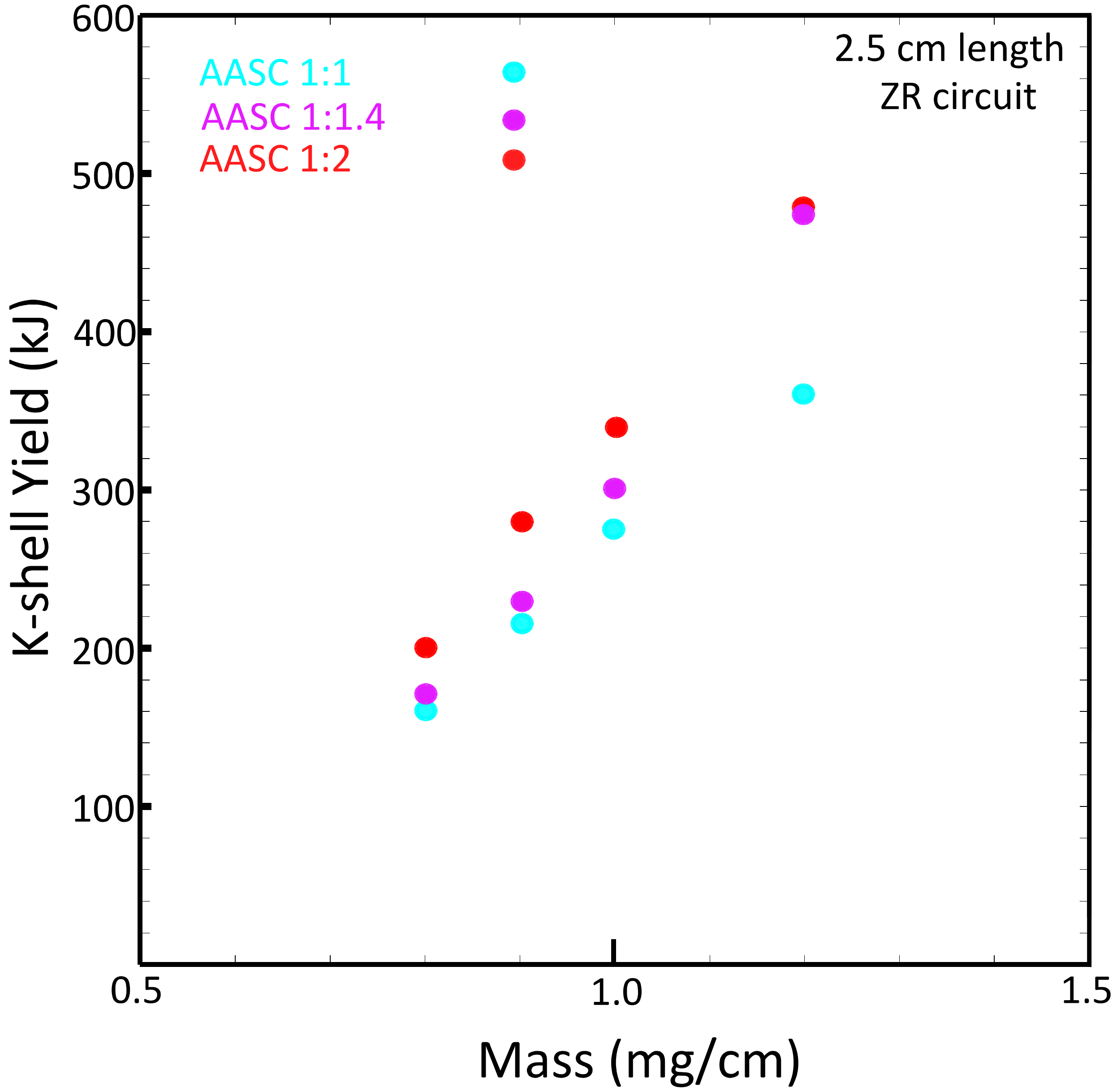
Equivalent Circuit Model for the Refurbished Z machine





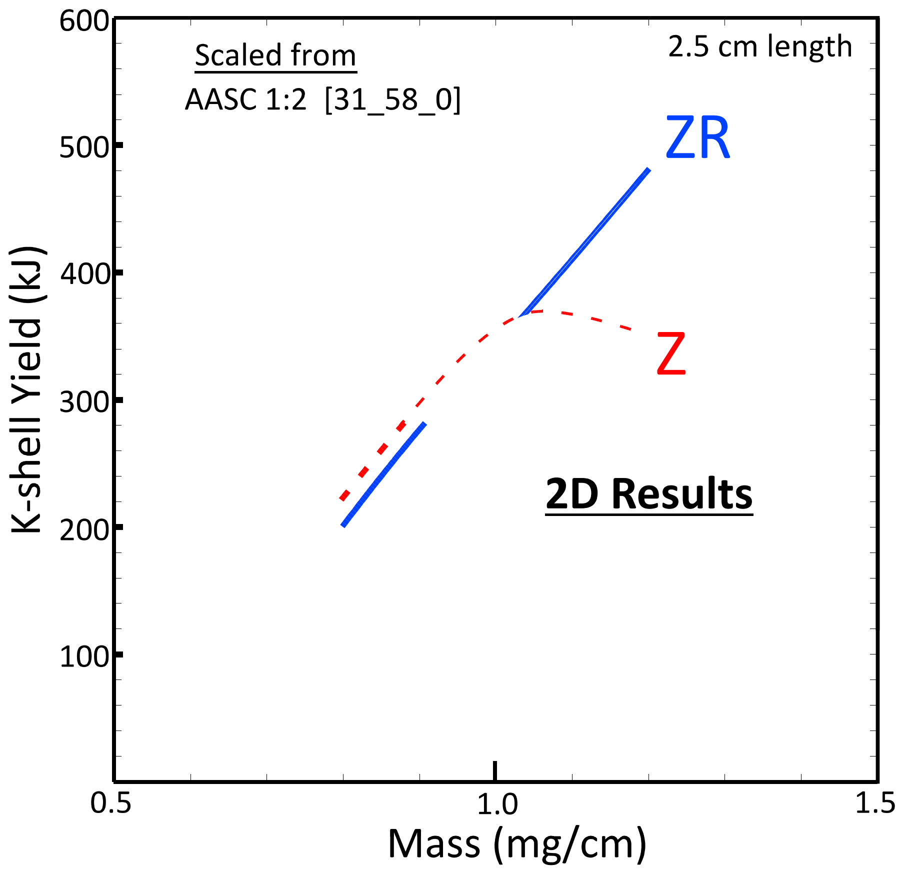
This is considered to be a conservative model for ZR. Understanding of convolute losses (Z_{flow}) and feed losses (S_{flow}) are still active areas of research at Sandia – as is the development of an equivalent circuit model. [C. A. Jennings *et. al.*, Phys. of Plasmas **17**, 092703 (2010)]

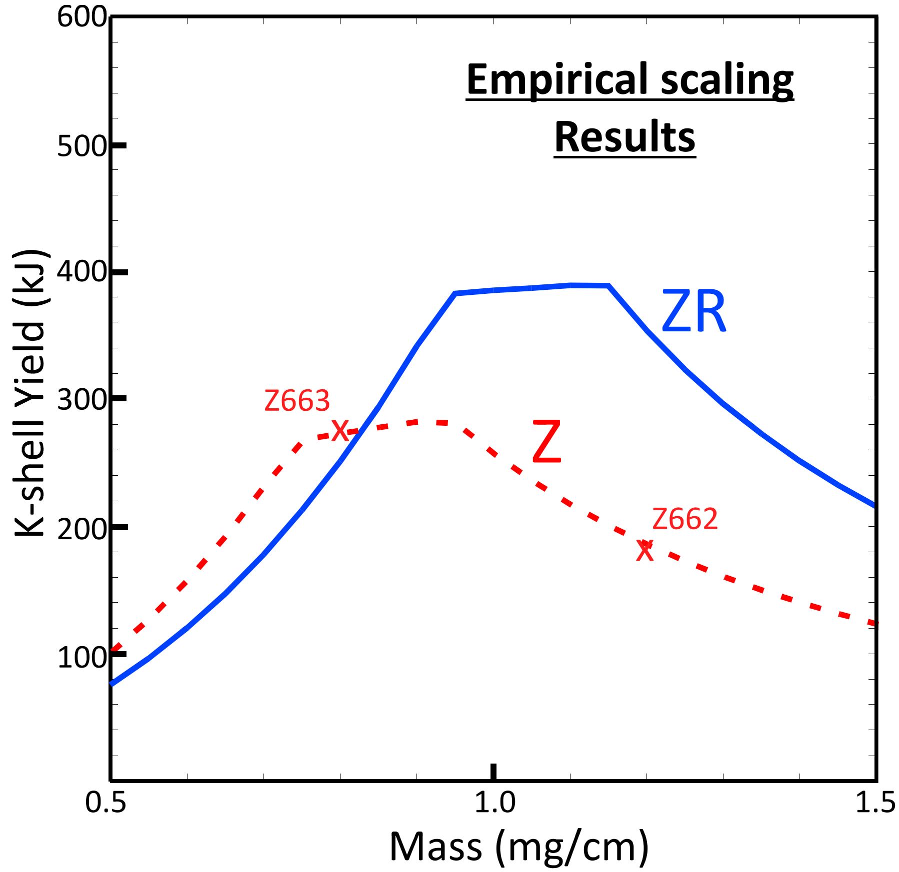
2D calculated K-shell yields for AASC Nozzle Configurations on ZR



2D calculations predict **400-500 kJ K-yield** on ZR for AASC 1:1.4 and AASC 1:2 distributions.

Comparison of 2D calculated and Empirical Scaling K-Yields





Both **2D** and **Empirical scaling** models predict ~**380 kJ** K-yields for ~**1 mg/cm** load on ZR

Summary

The issues of severe current losses due to UV irradiance of the convolute power feed, and overall characterization of convolute and feed losses are still under investigation.

AASC 1:1 distribution is closest to the pre-refurbished Z Titan distribution in terms of general gas distribution properties – i.e. has more mass at large radius as does the Titan distribution. Because of this, higher peak kinetic energies are calculated for the AASC 1:1 and Titan distribution (30% higher than the AASC 1:1.4 and 1:2 distributions) [worth mentioning, because historically experiments have supported the idea that thermalization of high kinetic energies are necessary to insure rapid plasma heating and ionizing into the K-shell]

Stability properties of the AASC 1:1 profile were the worst, resulting in lower calculated K-shell yields and powers than obtained with the AASC 1:1.4, 1:2, and Titan distributions.

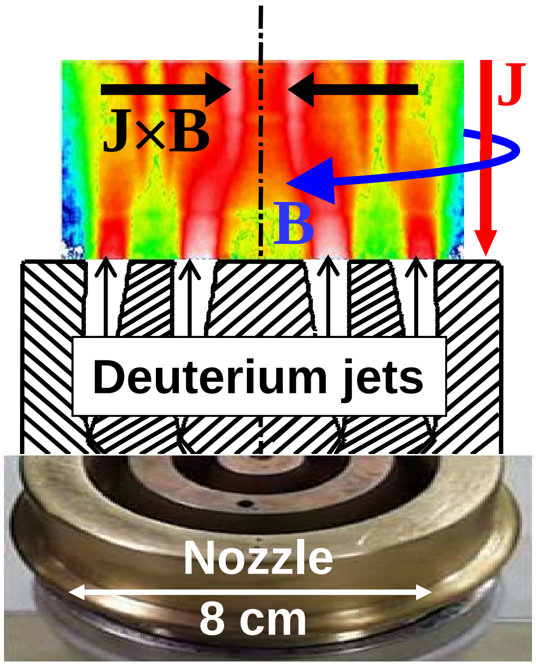
So little mass in the central jet region, not clear that the central jet has much influence on the dynamics.

Modeled stability of the AASC 1:1.4 and 1.2 distributions was as good as that of the modeled Titan distribution – instabilities no more of a limiting factor of K-yield than they were in the pre-refurbished Z experiments with the Titan nozzle.

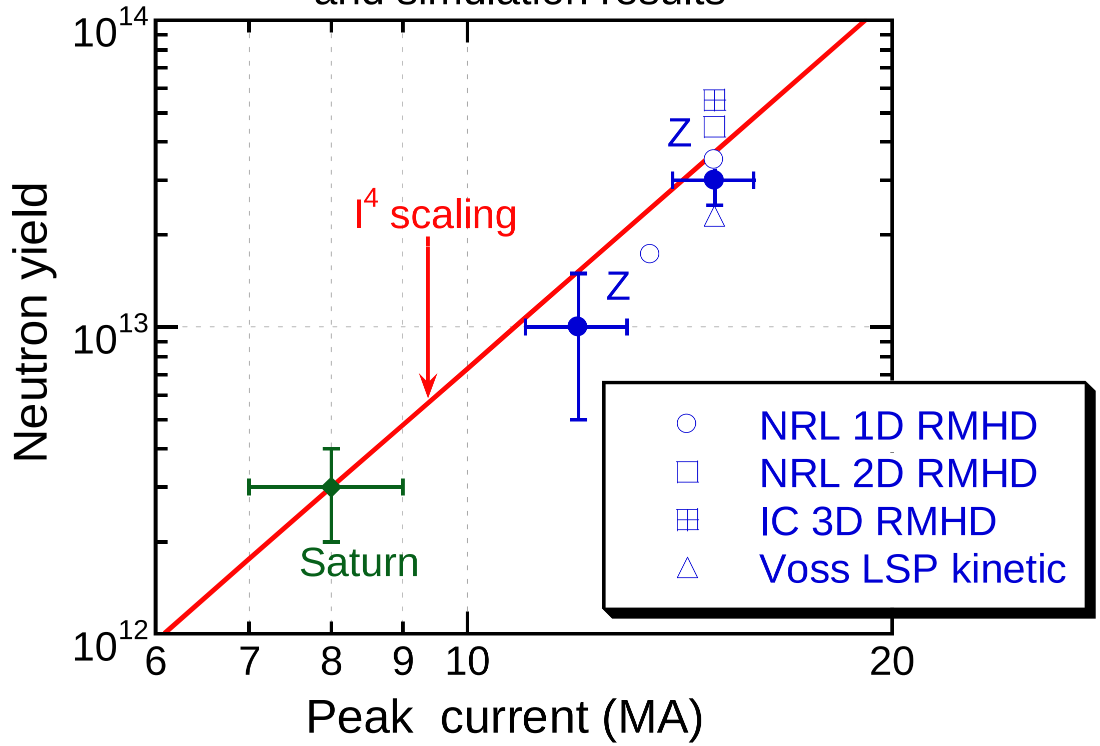
The “True” AASC gas distributions are probably not as stable as the modeled bicubic spline interpolated (“smoothed”) AASC gas distributions analyzed here – would lead to lower calculated yields than shown in this analysis.

2D and **empirical** models indicate that K-yields of ~**380 kJ** are attainable on ZR for mass loads of ~ **1 mg/cm** using the AASC1:1.4 and 1:2 distributions [pre-ref. Z produced 275 kJ]

High DD fusion neutron yields have been obtained in gas-puff shots on Z before refurbishment



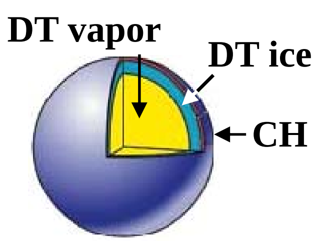
Data obtained before Z refurbishment and simulation results

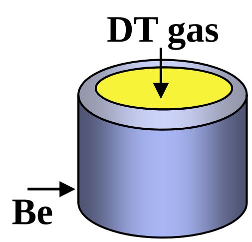


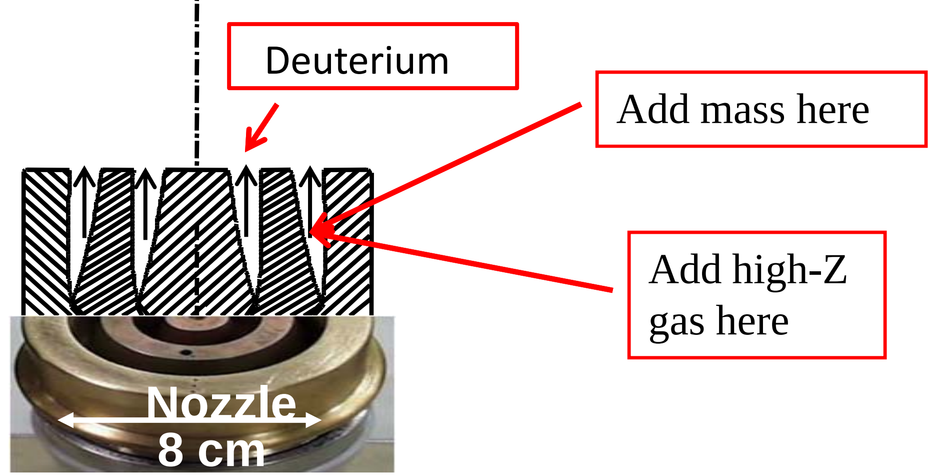
C. A. Coverdale *et al*., Phys. Plasmas **14**, 022706 (2007); Phys. Plasmas **14**, 056309 (2007).
A. L. Velikovich *et al*., Phys. Plasmas **14**, 022701 (2007).
D. Welch *et al*., Phys. Rev. Lett. **103**, 255002 (2009); this conf. 1D-7 Monday, 11:30

What can we do to increase the DD neutron yield on refurbished Z?

We want to compress and heat deuterium as in a direct-drive laser fusion target or pulsed-power-driven liner





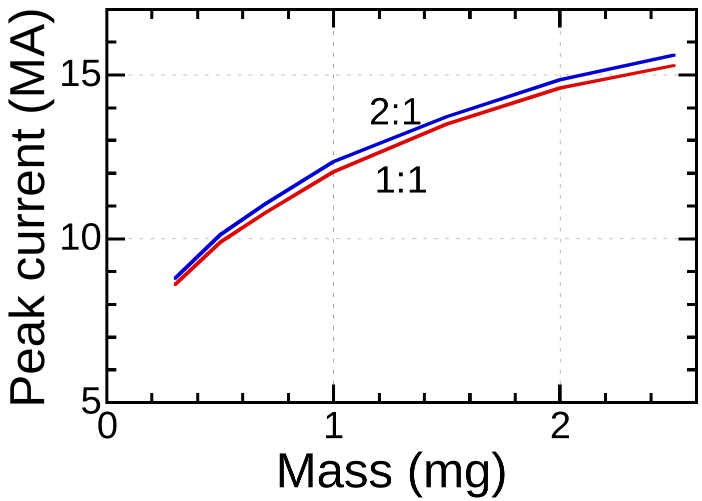


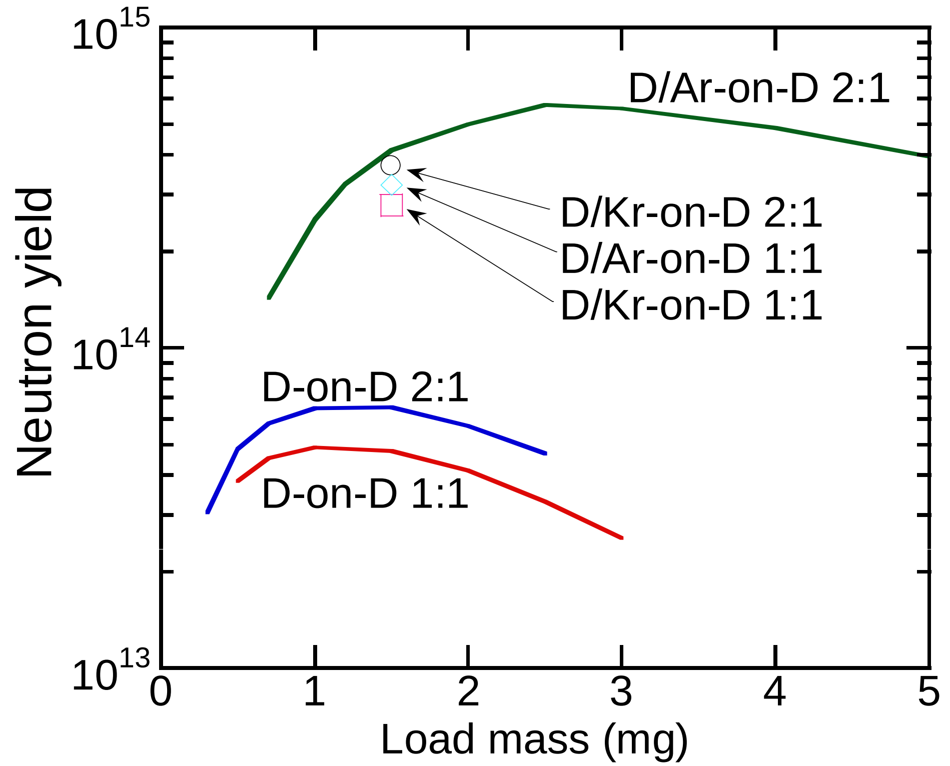
- Problem: deuterium gas-puff does not make a good (compact, heavy) pusher because it does not compress well
- Solution : add substantial amount of strongly radiating gas, Ar or Kr, to the outer shell
  - Radiation makes the outer shell thin and dense
  - Substantial increase of 1D clean DD neutron yield

A. Chuvatin *et al*., IEEE Trans. Plasma Sci. **33**, 739 (2005); S. A. Slutz *et al*., Phys. Plasmas **17**, 056303 (2010).

P. L. Coleman *et al*., in *Dense Z-pinches*, AIP Conf. Proc. **651**, 113 (2002).

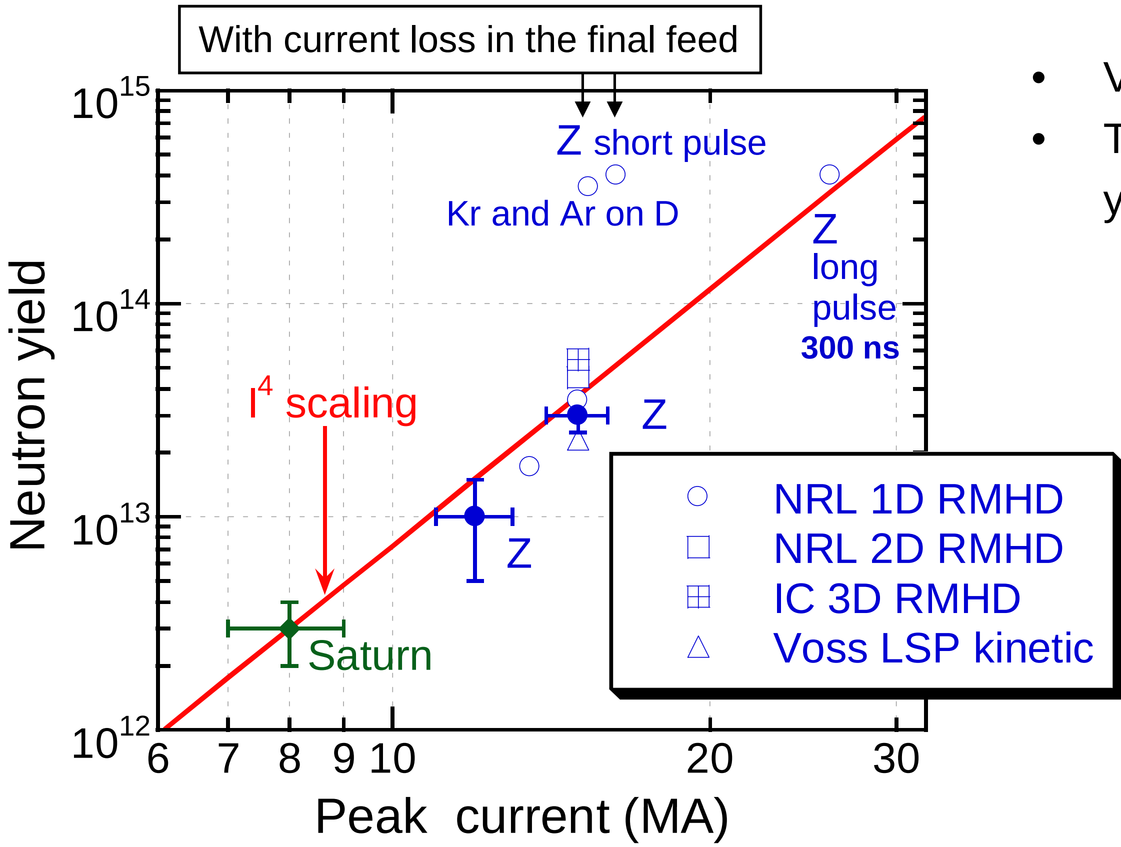
High-Z pusher makes the difference





Simulation results for pinch length 2.4 cm
50-50 by ion number D/Ar or D/Kr mixture in the outer shell

Adding strongly radiating gas to the outer shell can significantly increase the clean* 1D neutron yield on refurbished Z



- Very large clean yields
- Translates into DT yields (same ρ and T):
  - 1.7×10^{16} neutrons
  - 50 kJ of fusion energy

*Simulated for a perfect 1D implosion, no instability