ANS Winter Meeting & Expo

2018

Joining Forces to Advance Nuclear

Computational Optimization of TEX Critical Experiment Design

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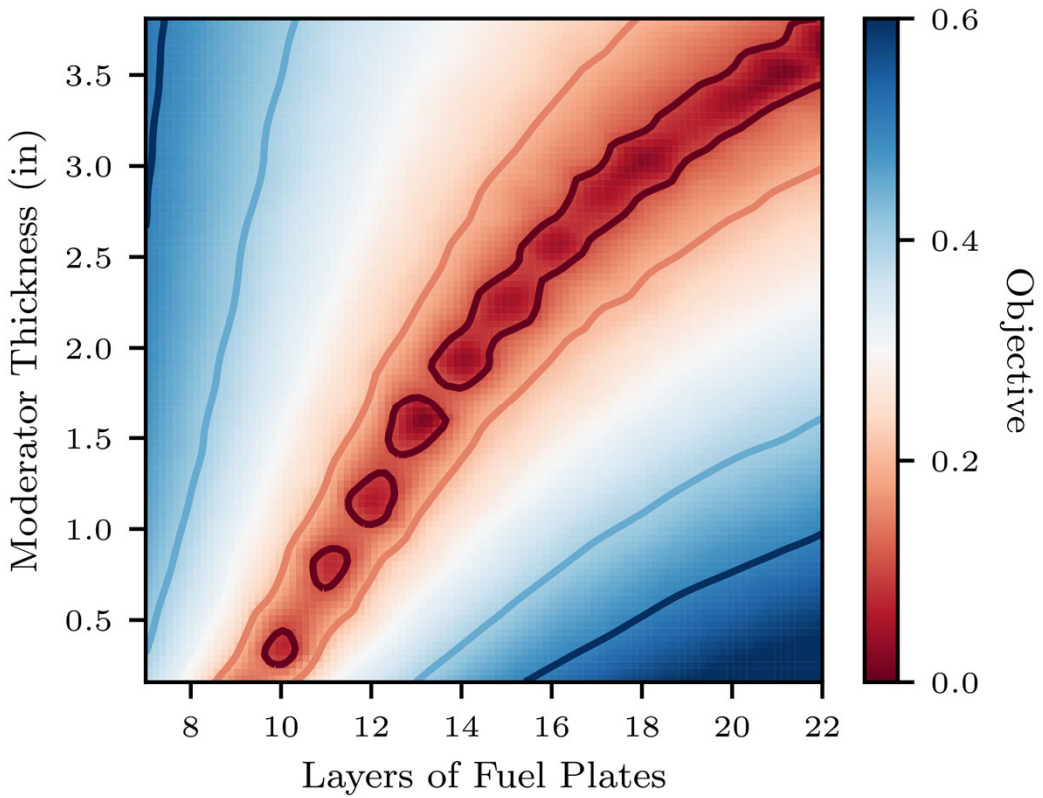
LLNL-PRES-761298

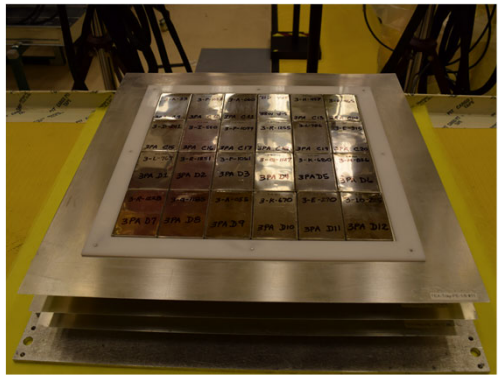
Outline

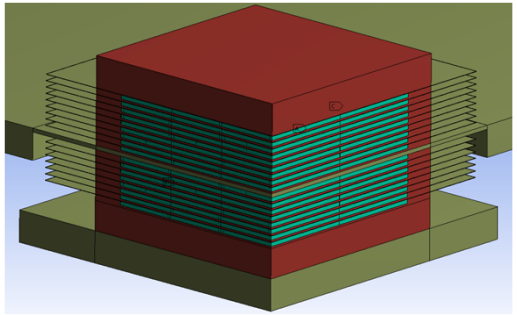
- Thermal/Epithermal eXperiments
- ^{239}Pu/Alumina & ^{233}U/Polyethylene TEX
- Optimus for Experiment Design
- Critical Configuration Results

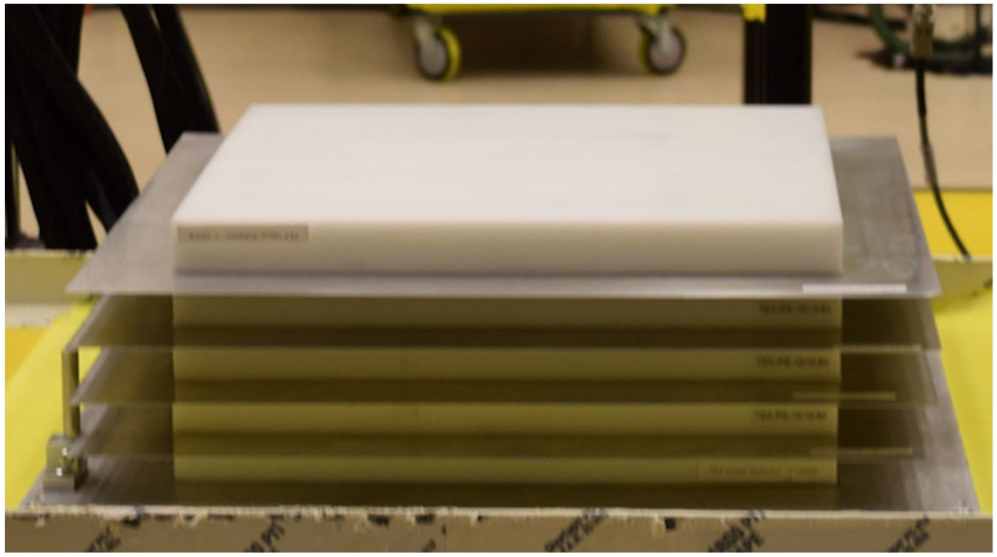


Thermal/Epithermal eXperiments (TEX)

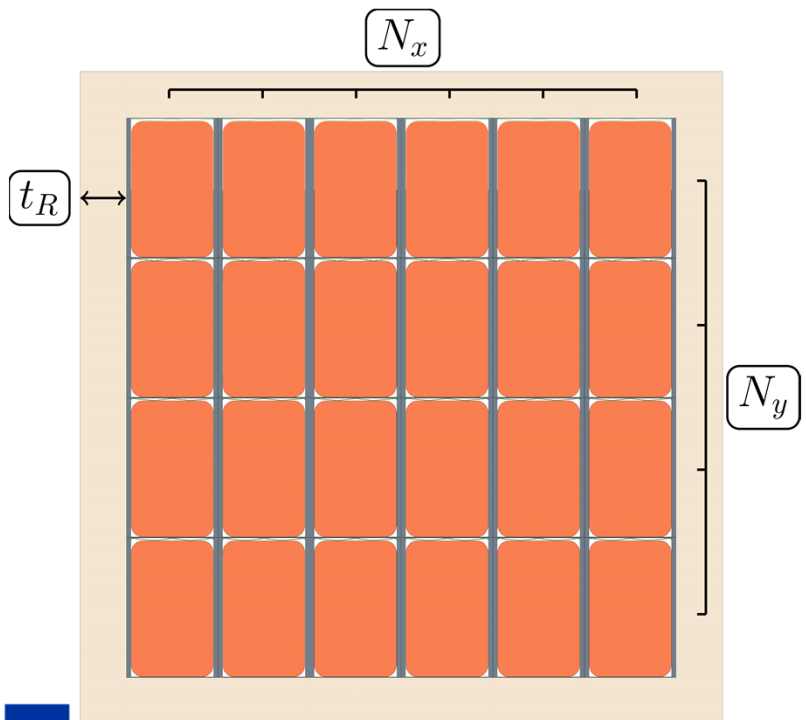
- Design and execute new critical experiments to address high priority nuclear data needs with an emphasis on the intermediate energy range
  - $0.625\ eV < E < 100\ keV$
- IER-184 TEX preliminary design using ^{239}Pu and Polyethylene
- IER-329 using ^{233}U and Polyethylene

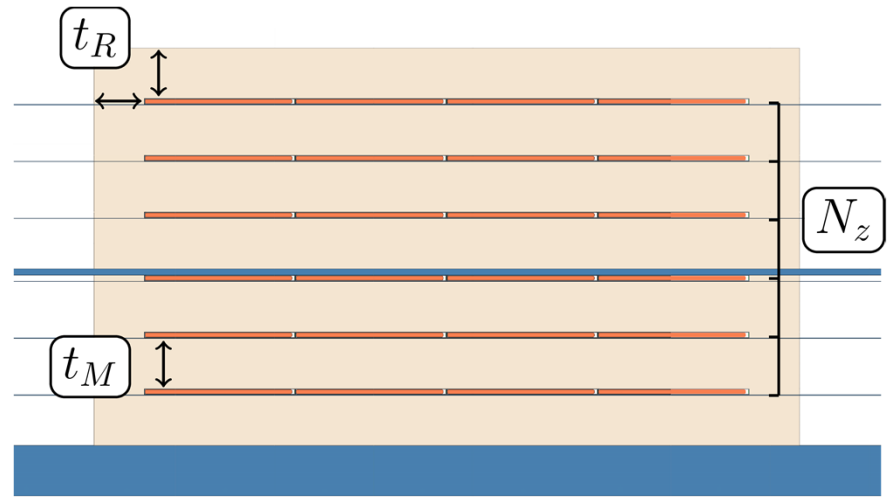


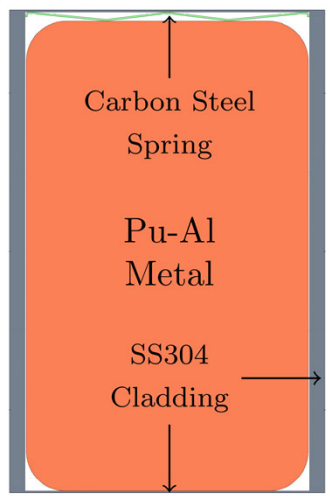


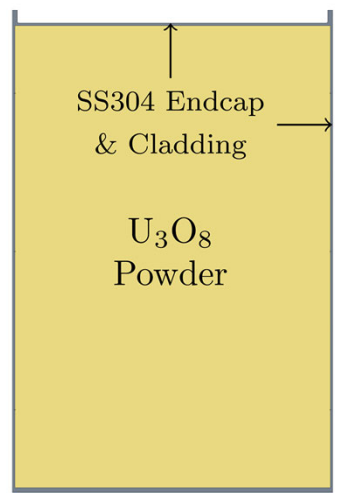


TEX Configuration & Model

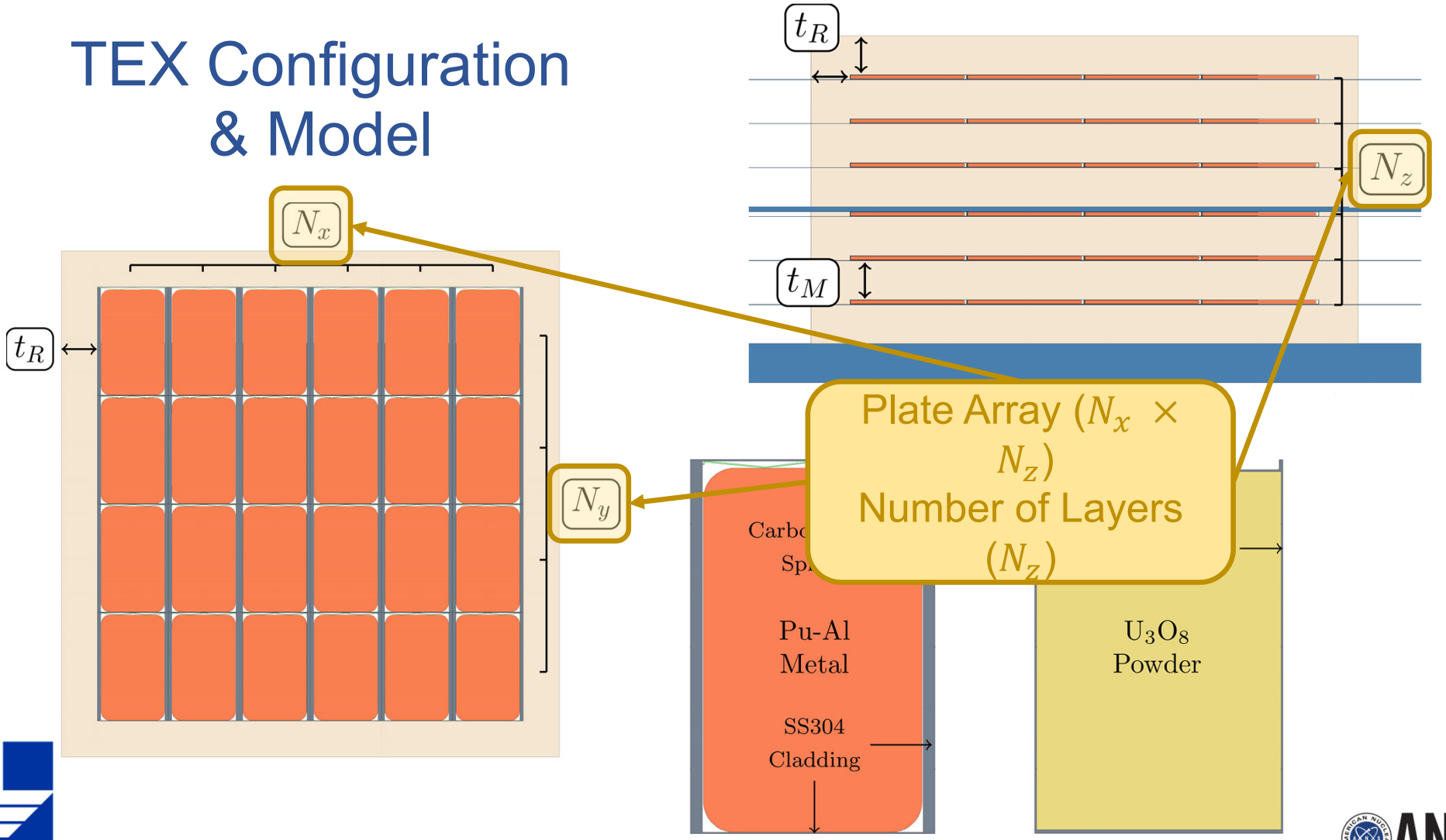




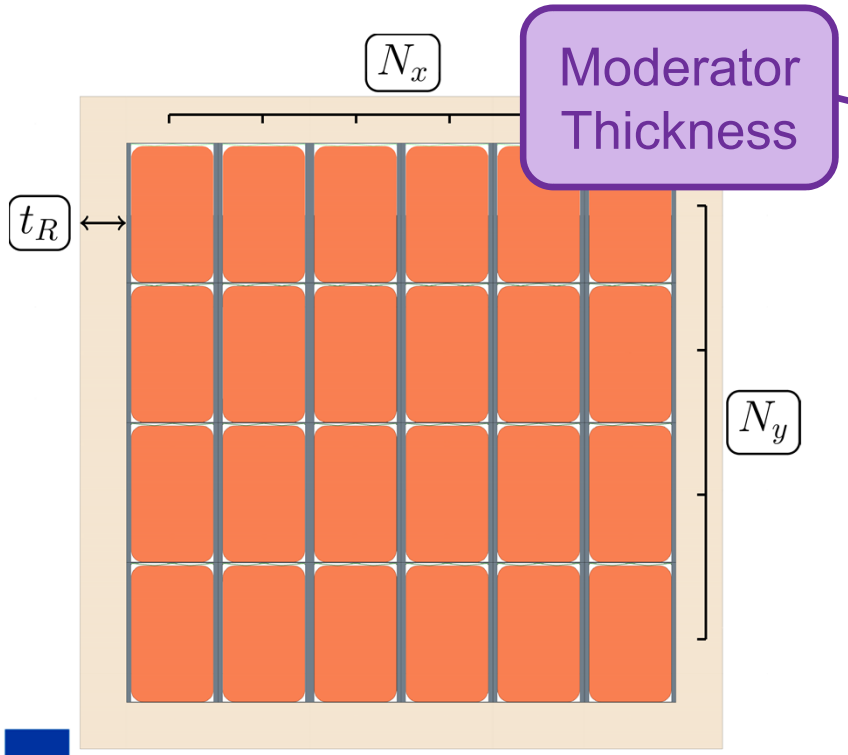




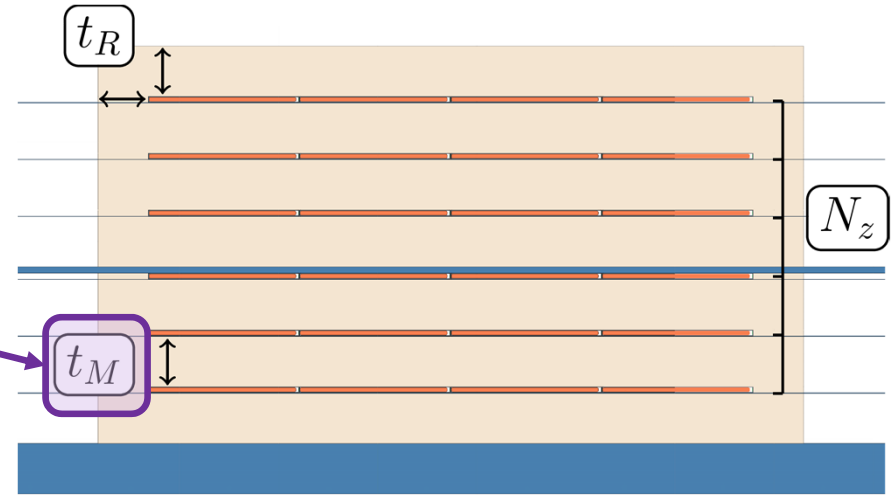
TEX Configuration & Model

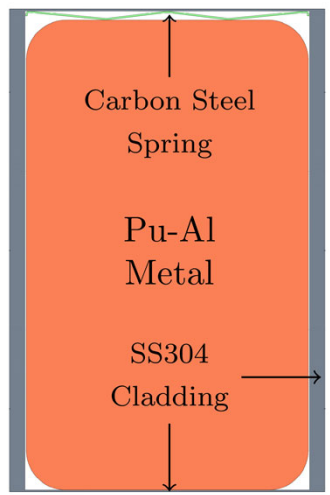


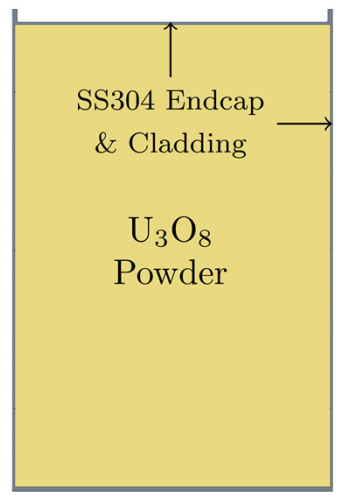
TEX Configuration & Model



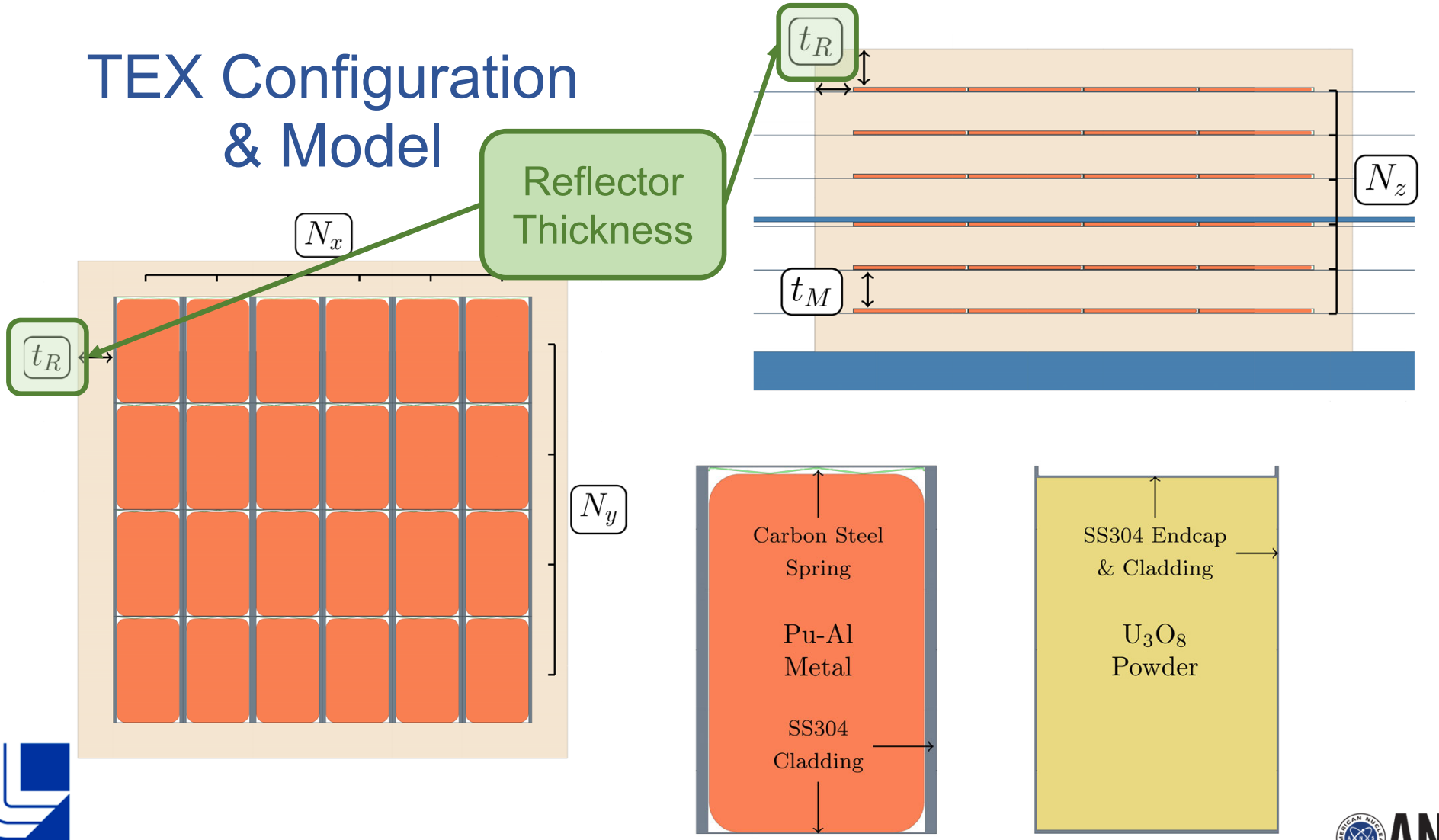
Moderator Thickness



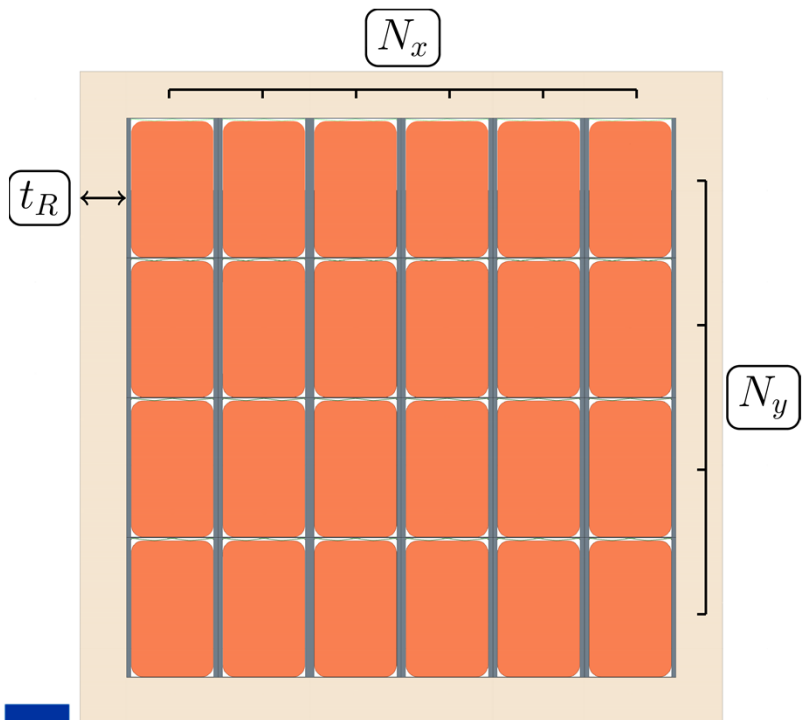


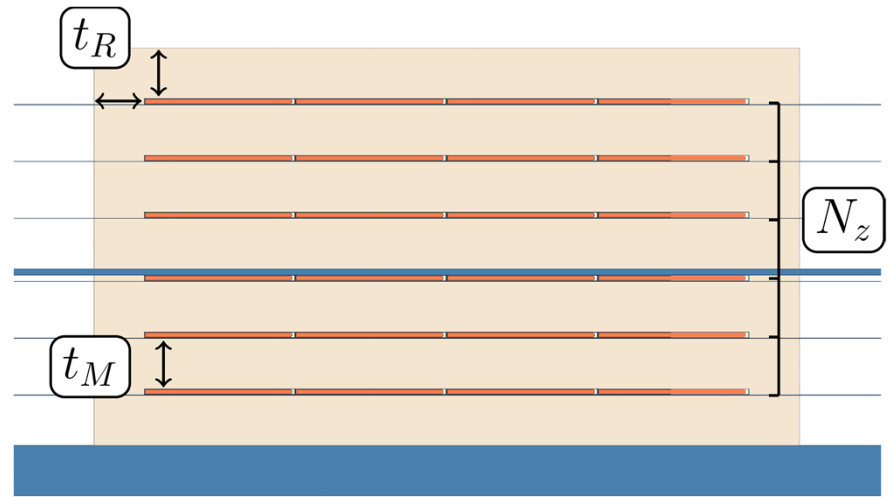


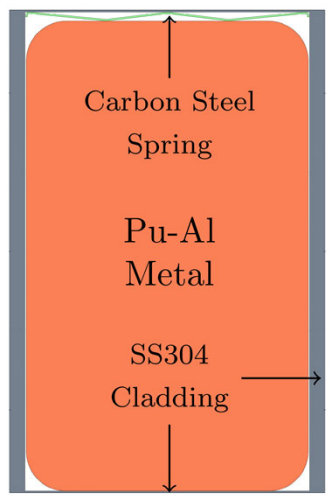
TEX Configuration & Model

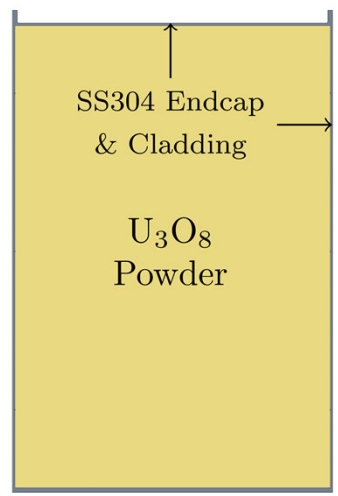


TEX Configuration & Model









Fuel Plates from Zero Power Physics Reactor (ZPPR)

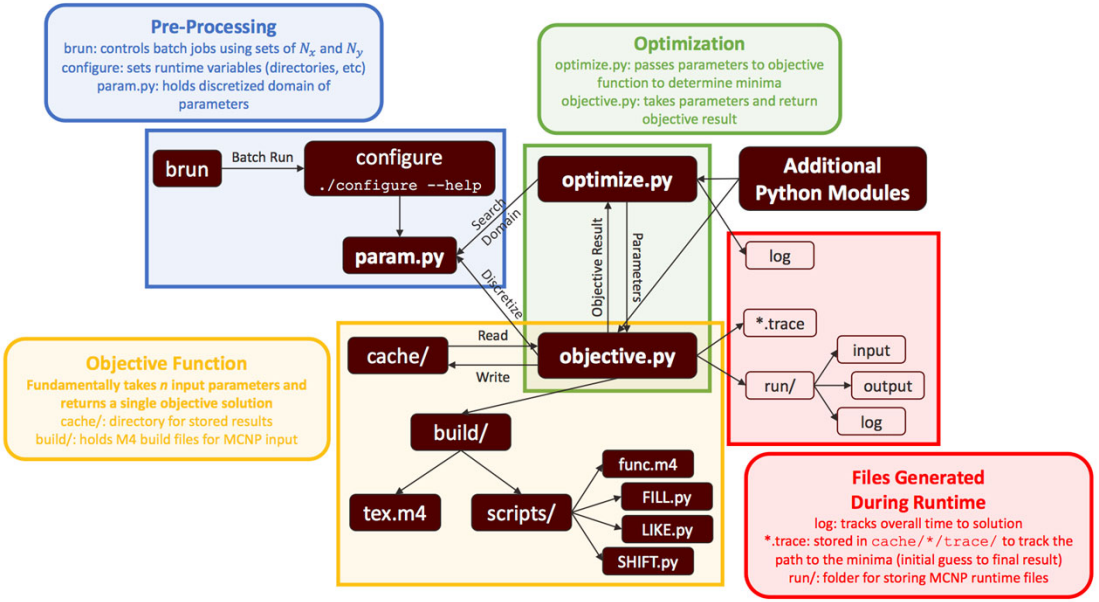
^{239}Pu (PANN) ZPPR Plates

- Plutonium Aluminum No Nickel (PANN) plates
- Stainless steel (SS304) packets
- 105g of fuel per plate
  - 99g of Pu (95 wt% ^{239}Pu)
- Density of 15.1 g/cm^3

^{233}U ZPPR Plates

- Uranium oxide power
- Stainless steel (SS304) packets
- 33g of fuel per plate
  - 28g of ^{233}U
- Density of 1.62 g/cm^3

Optimus

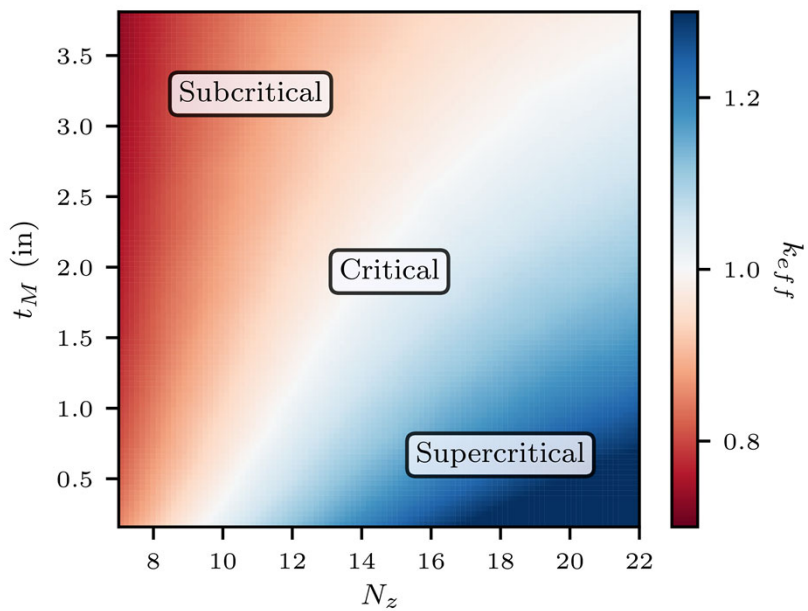


- Optimization and machine learning software package tailored specifically for designing critical experiments
- Developed by the Nuclear Criticality Safety Division at Lawrence Livermore and written in Python
- Being extended to support general criticality safety analysis

Objective Function

- Create local minima where the configuration is critical

$$f(k_{eff}) = \left|k_{eff} - 1\right|^{0.5}$$



Objective Function

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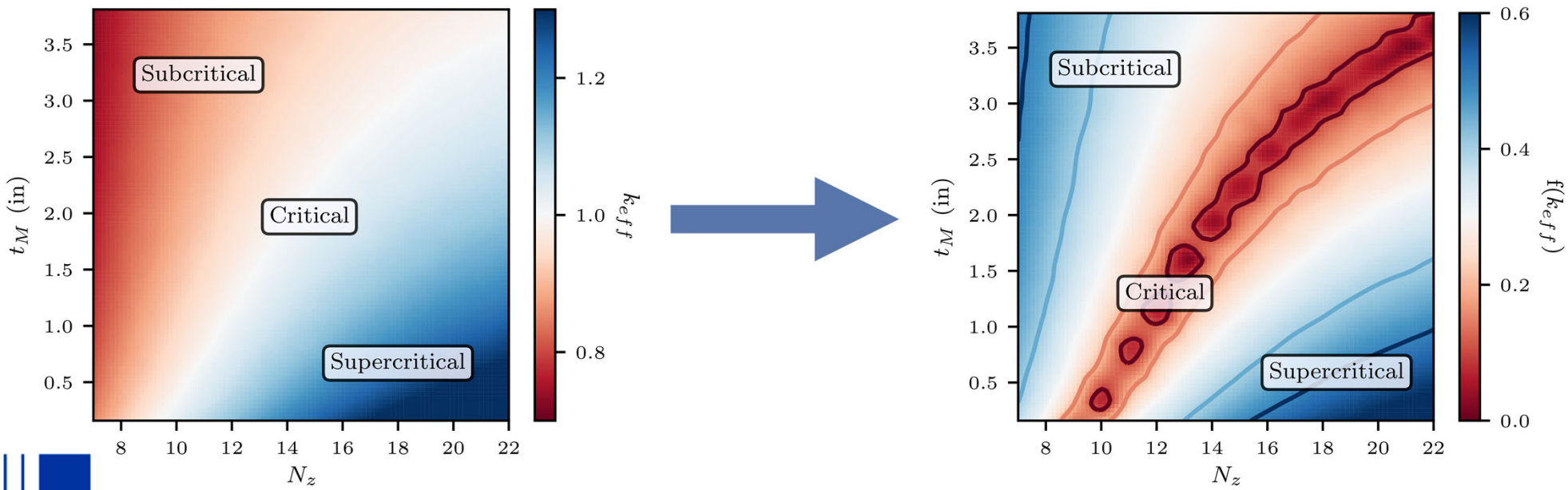
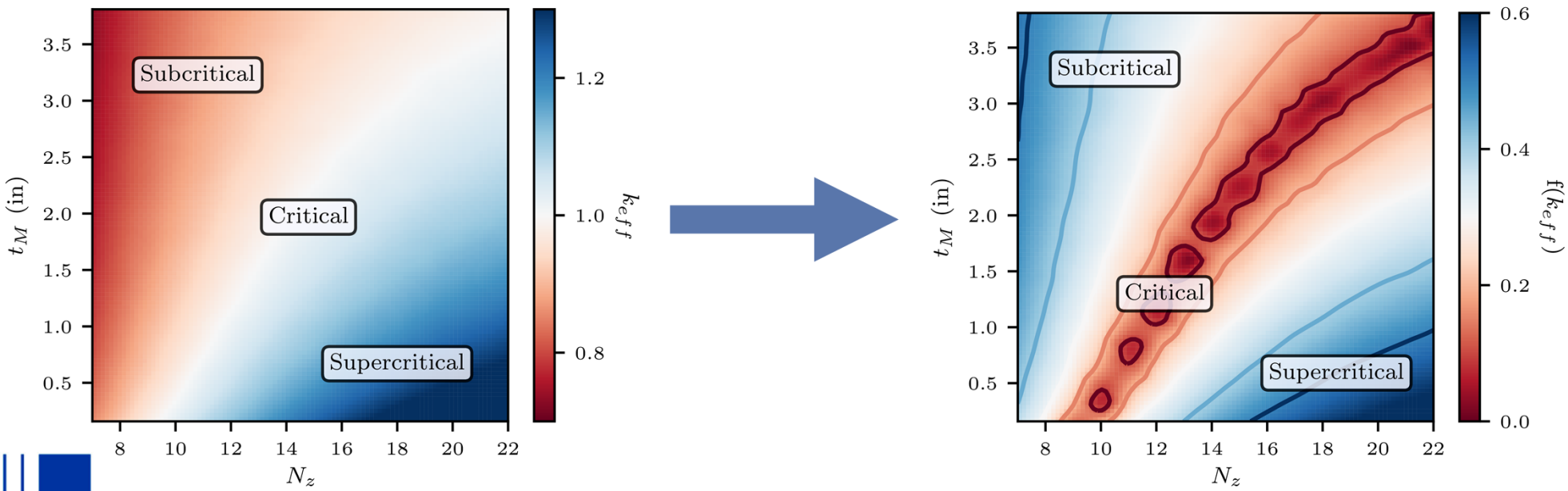


Objective Function

Multiplication factor of the configuration based on the input parameters

- Create local minima where the configuration is critical

$$f(k_{eff}) = |k_{eff} - 1|^{0.5}$$

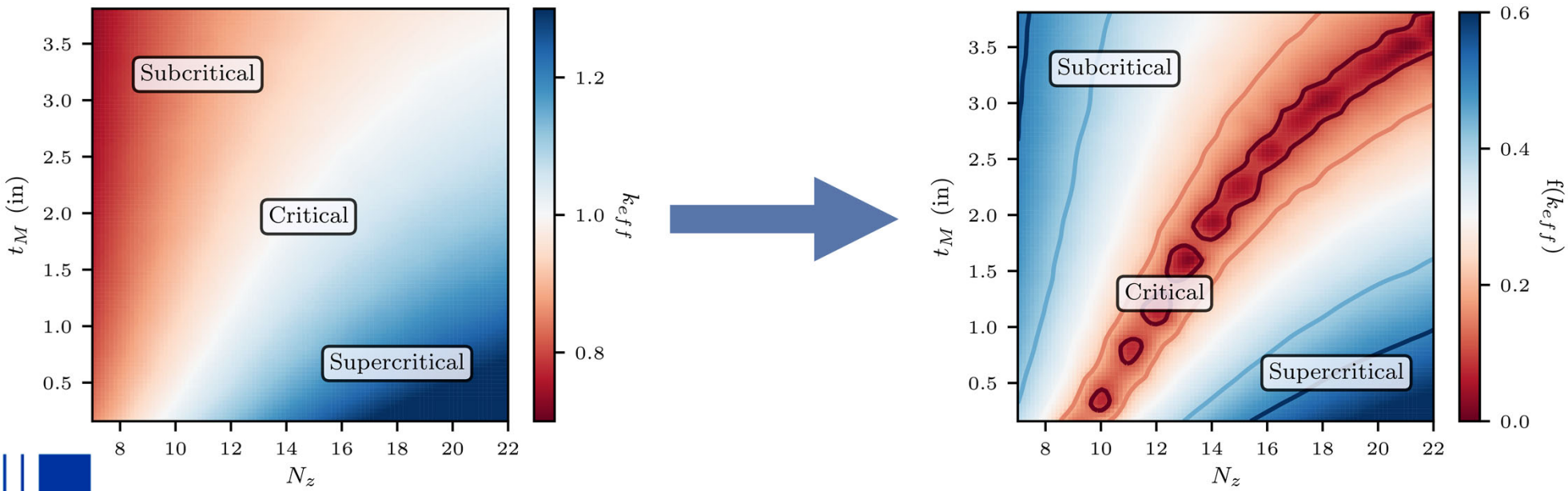


Objective Function

Desired multiplication factor

- Create local minima where the configuration is critical

$$f(k_{eff}) = |k_{eff} - \boxed{1}^{0.5}$$

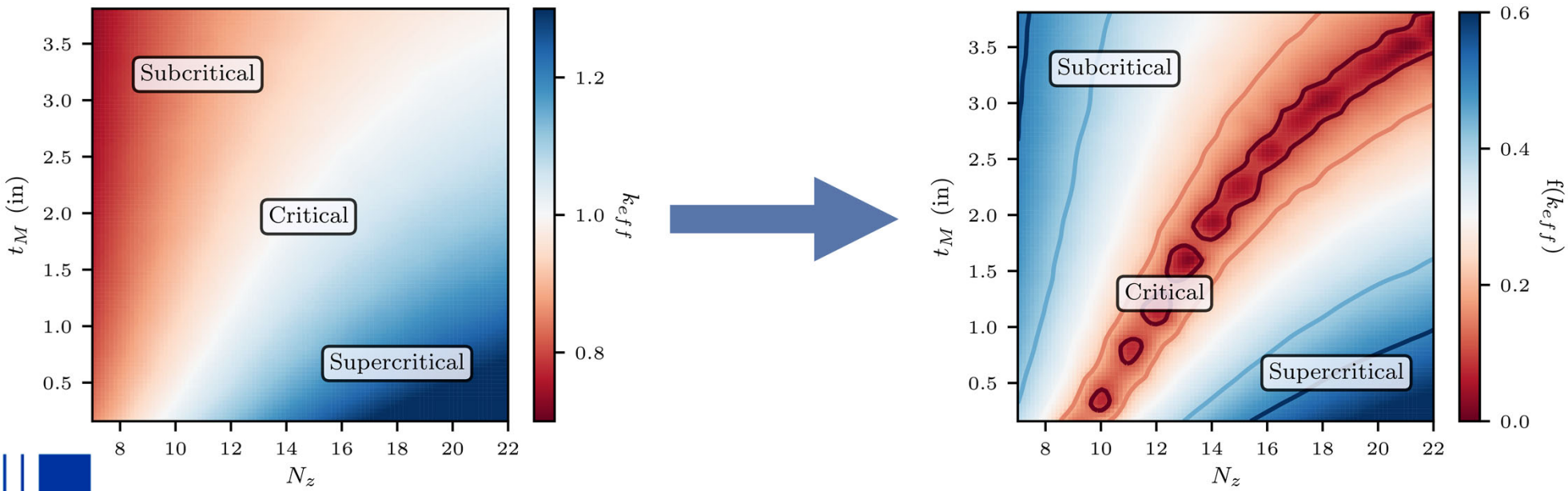


Objective Function

Gradient penalty

- Create local minima where the configuration is critical

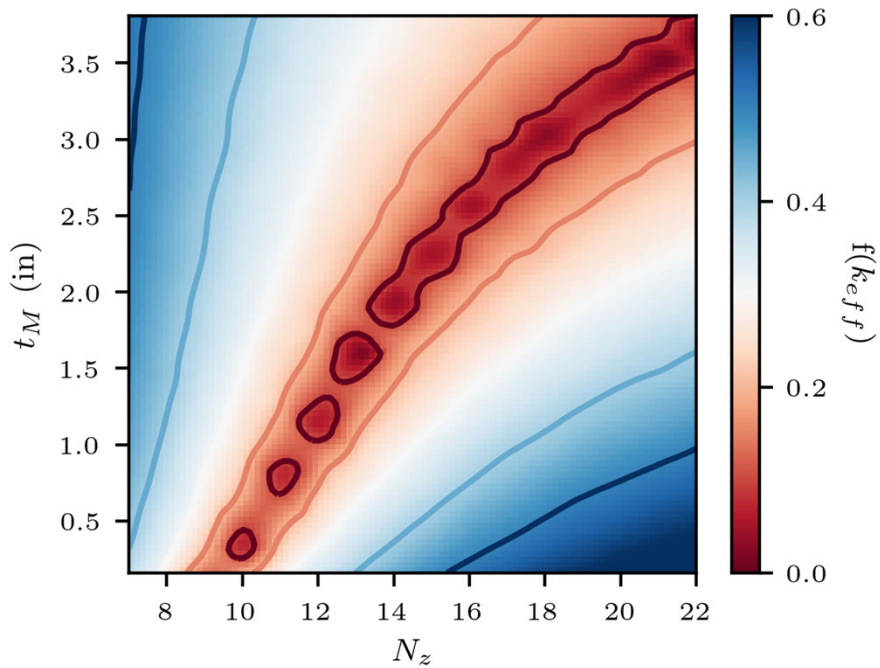
$$f(k_{eff}) = |k_{eff} - 1|^{0.5}$$



Optimizing the Objective Function

$$f(k_{eff}) = \left|k_{eff} - 1\right|^{0.5}$$

- Discretize the domain
- Apply an optimization method to determine the local minima (critical configurations)
  - Gradient descent
  - Linear search
- Powell's Method



Optimizing the Objective Function

$$f(k_{eff}) = \left|k_{eff} - 1\right|^{0.5}$$

- *Discretize the domain*
- Apply an optimization method to determine the local minima (critical configurations)
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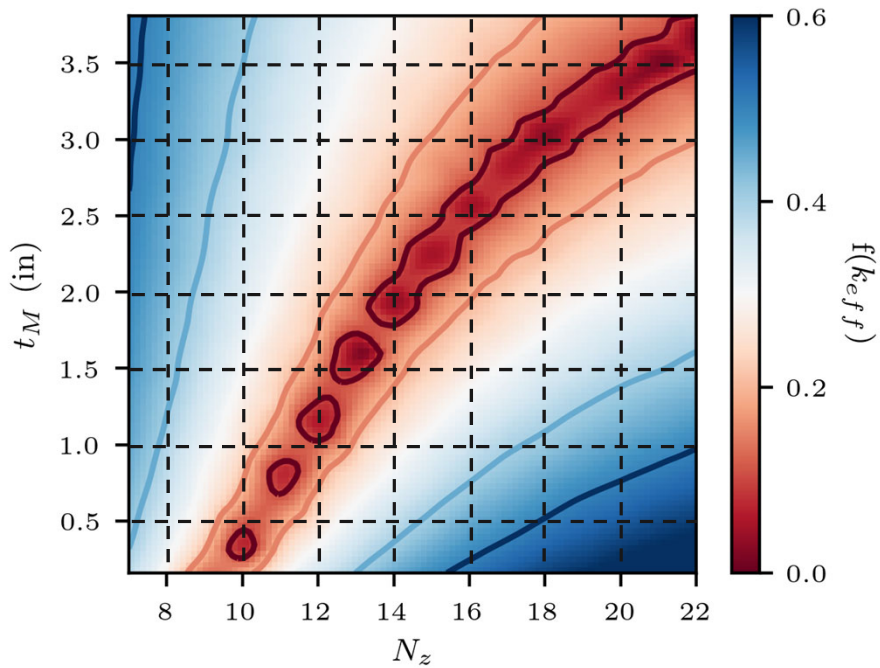
  - Linear search
- Powell's Method



Optimizing the Objective Function

$$f(k_{eff}) = \left|k_{eff} - 1\right|^{0.5}$$

- Discretize the domain
- Apply an optimization method to determine the local minima (critical configurations)
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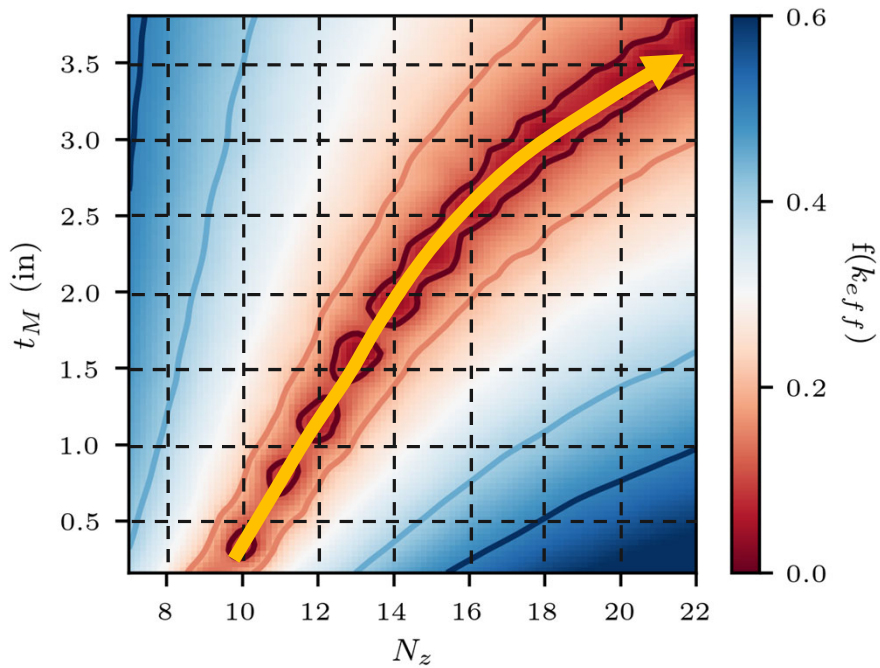
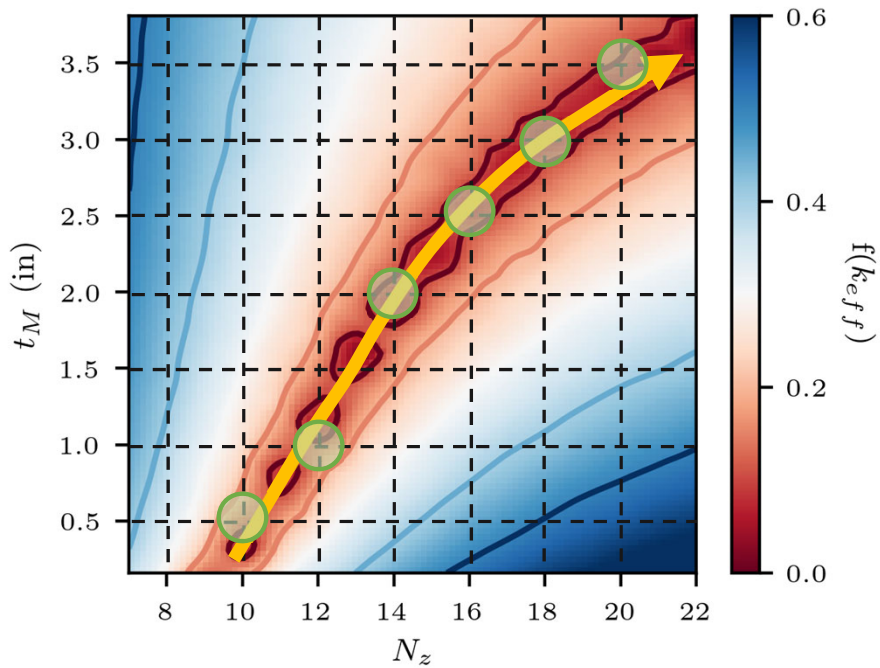


Optimizing the Objective Function

$$f(k_{eff}) = \left|k_{eff} - 1\right|^{0.5}$$

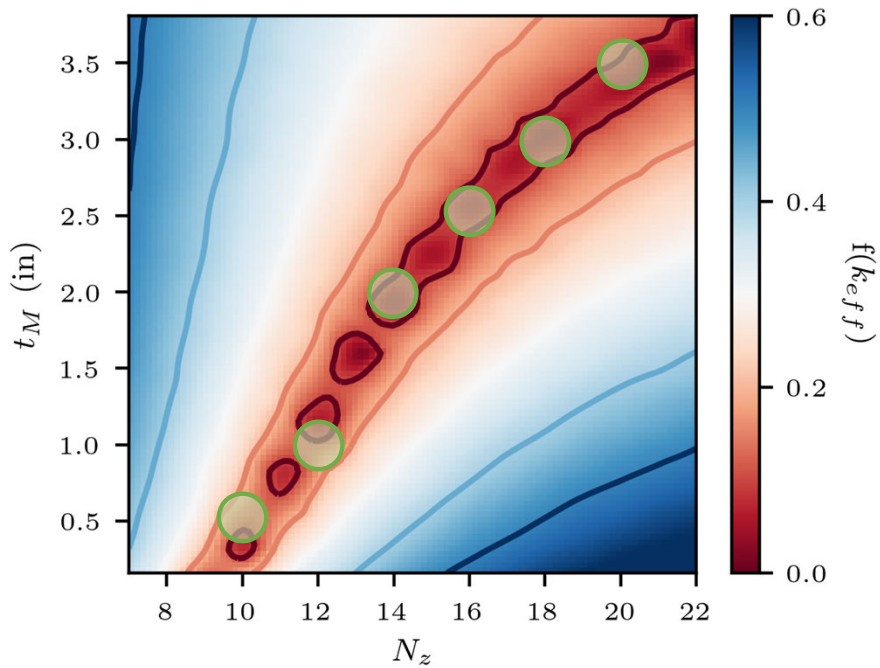
- Discretize the domain
- Apply an optimization method to *determine the local minima* (critical configurations)
  - Gradient descent
  - Linear search
- Powell's Method



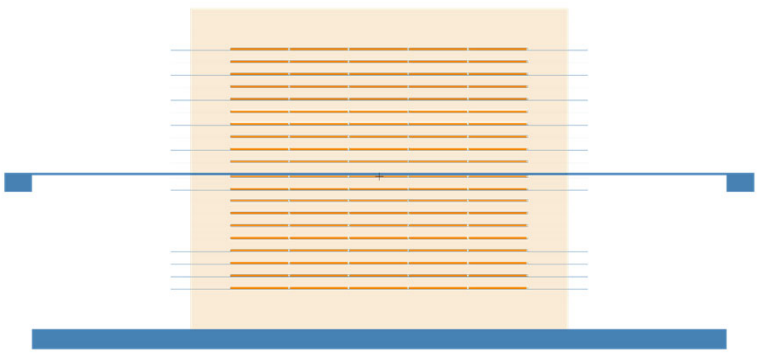
Optimizing the Objective Function

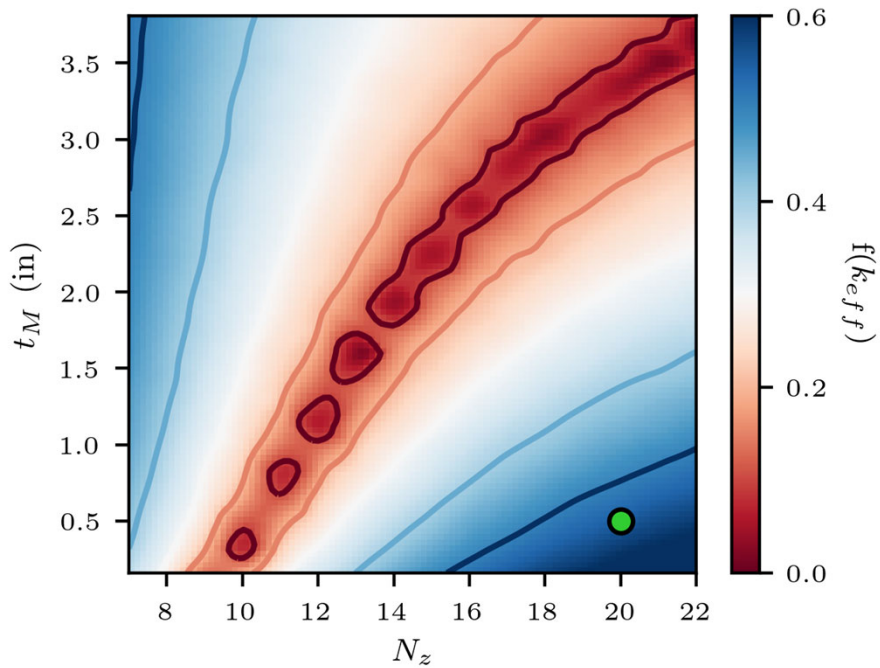
$$f(k_{eff}) = \left|k_{eff} - 1\right|^{0.5}$$

- Discretize the domain
- Apply an optimization method to determine the local minima (critical configurations)
  - Gradient descent
  - Linear search
- *Powell's Method*

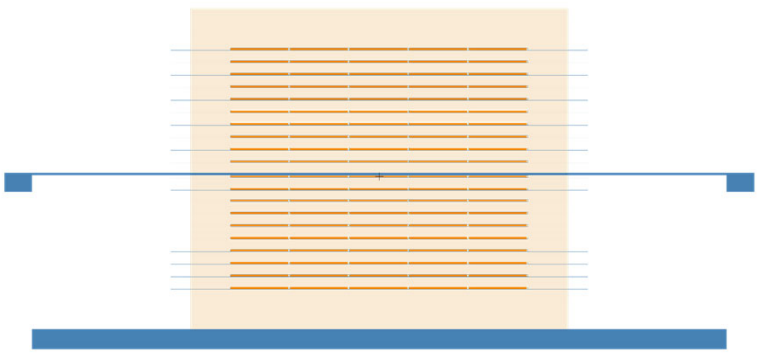


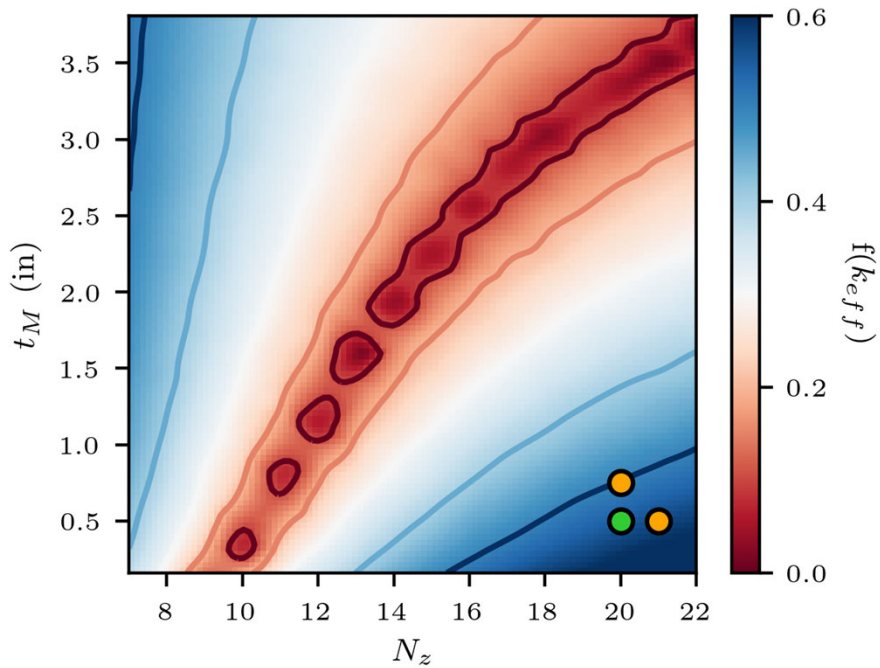
Randomly selected starting point
Supercritical Configuration (k > 1)



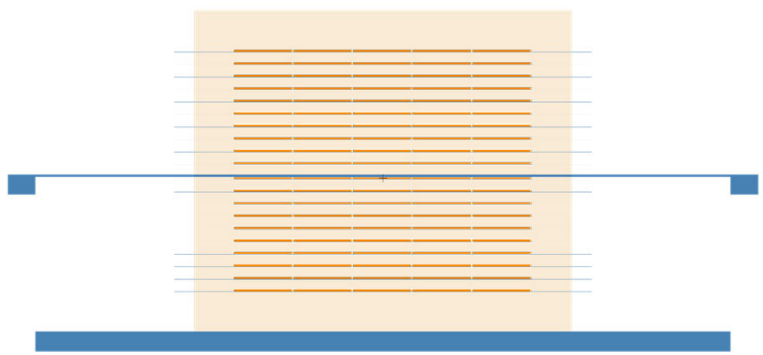


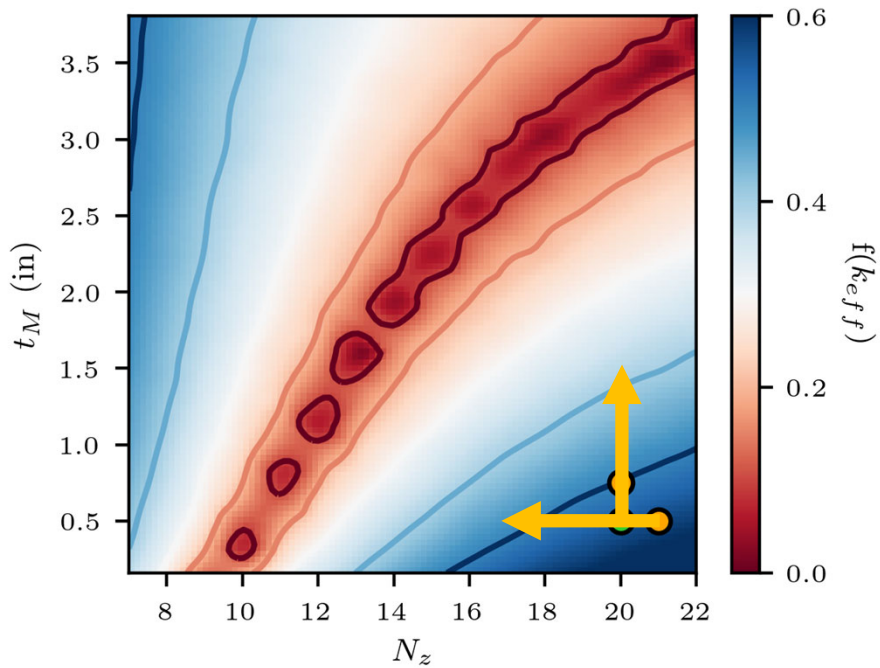
Evaluate the gradients



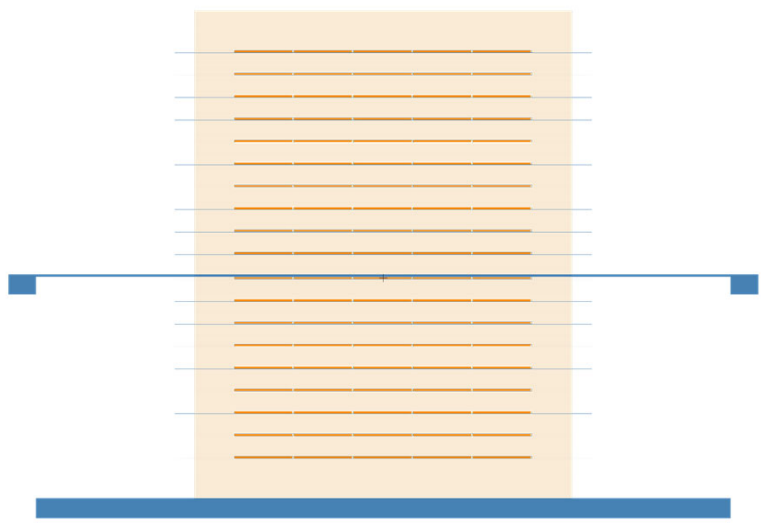


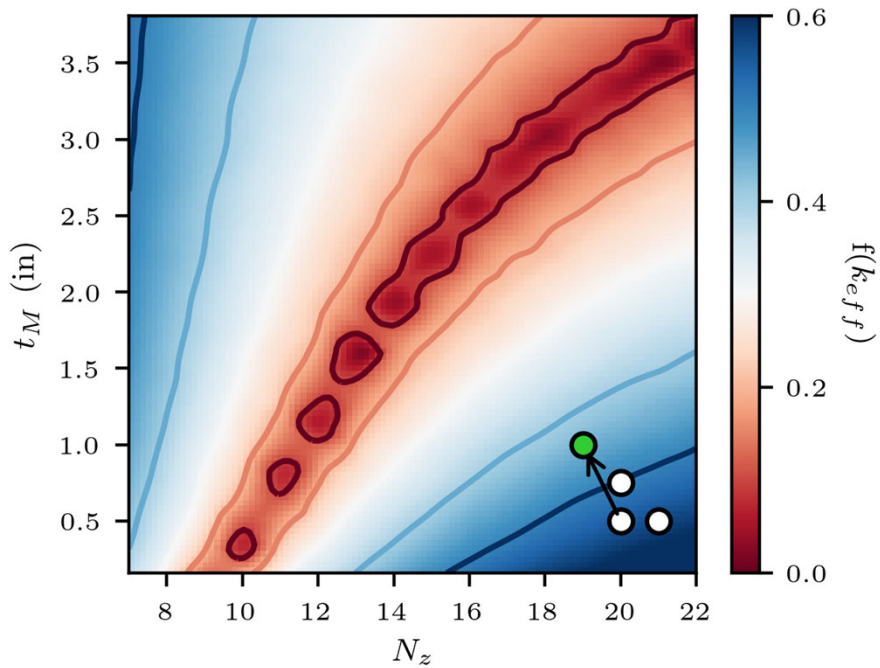
Evaluate the gradients
Point towards less fuel and more moderation



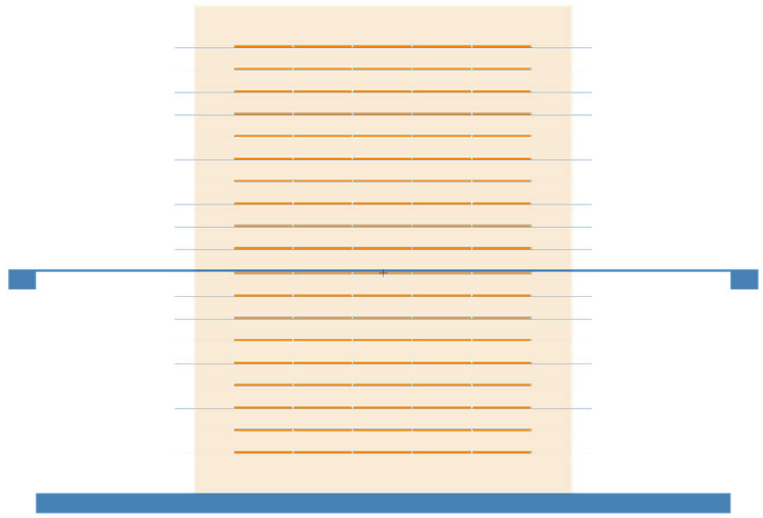


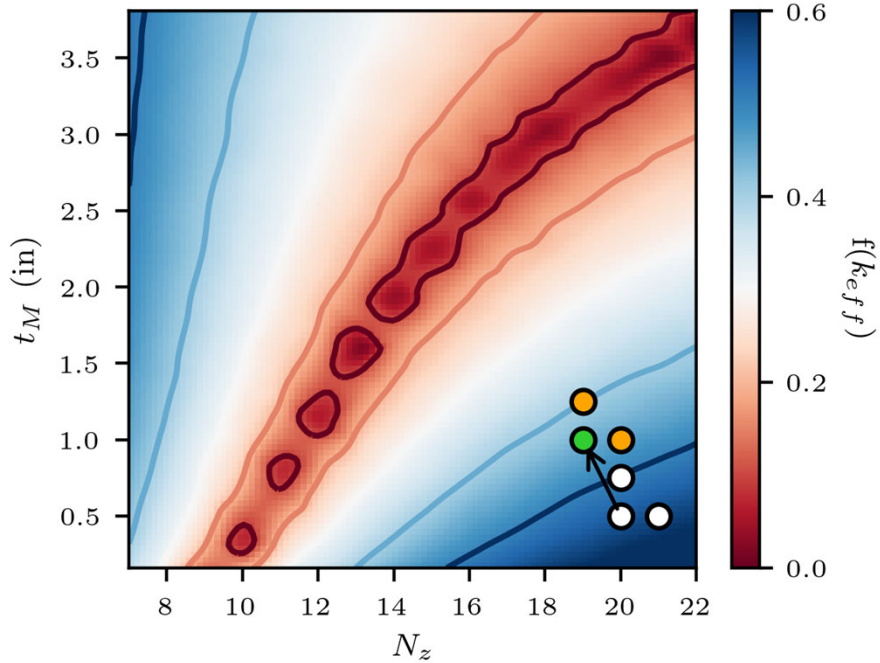
Create a new configuration
Again, supercritical (k > 1)



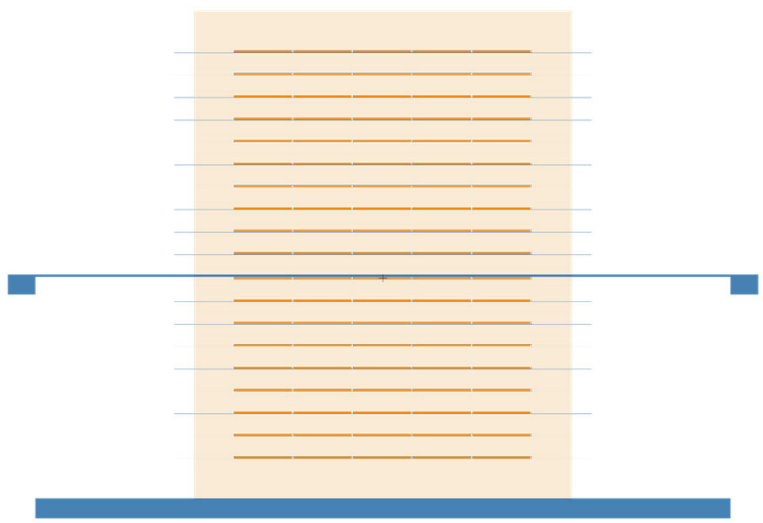


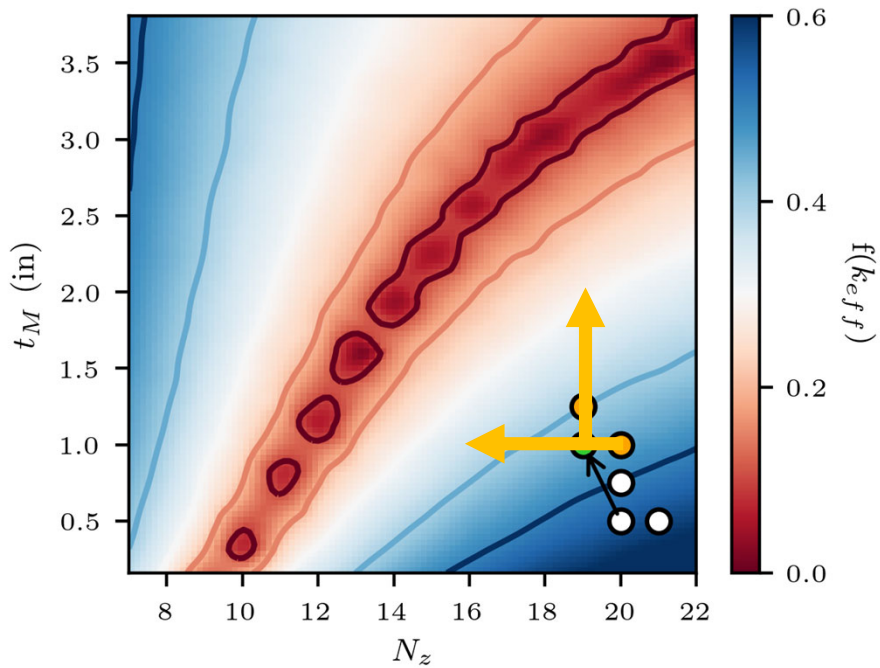
Evaluate the gradients



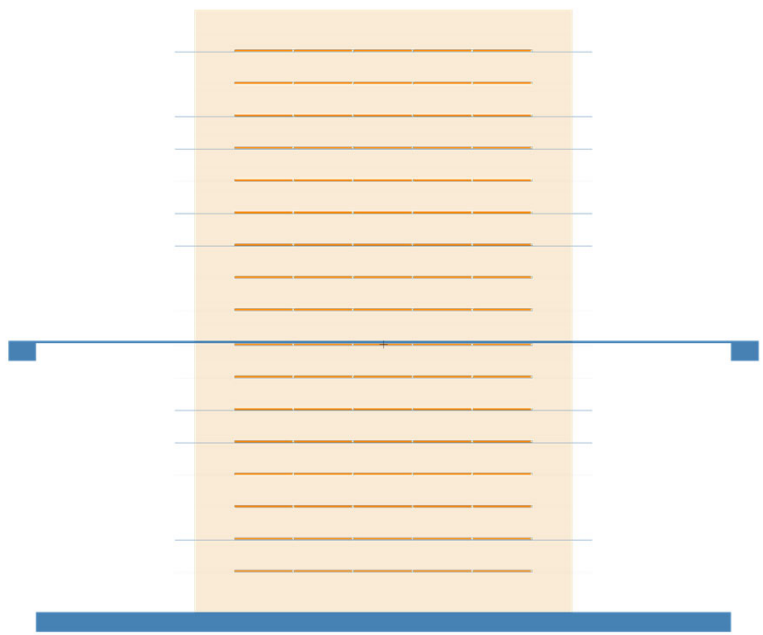


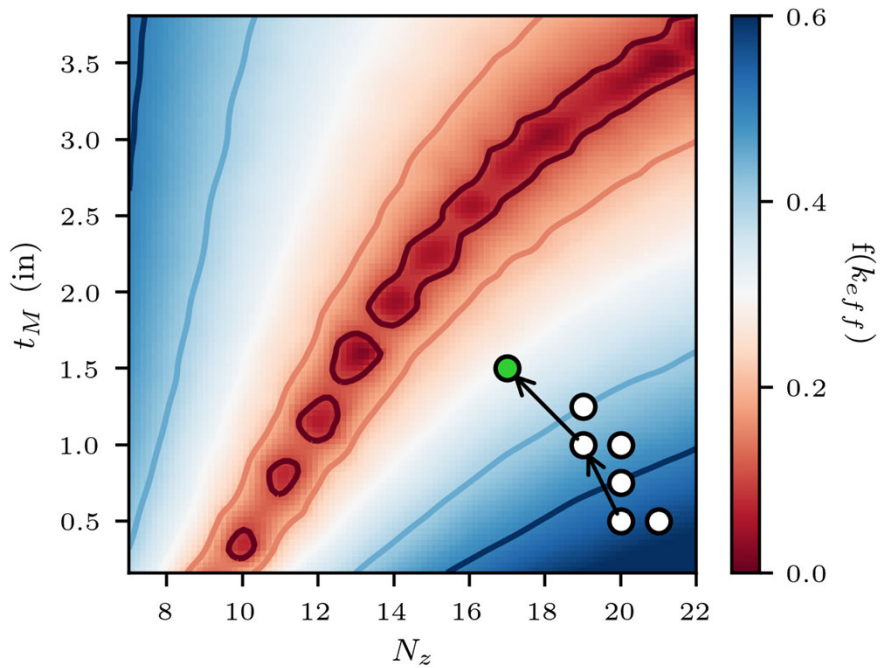
Evaluate the gradients
Again, point towards less fuel and more moderation



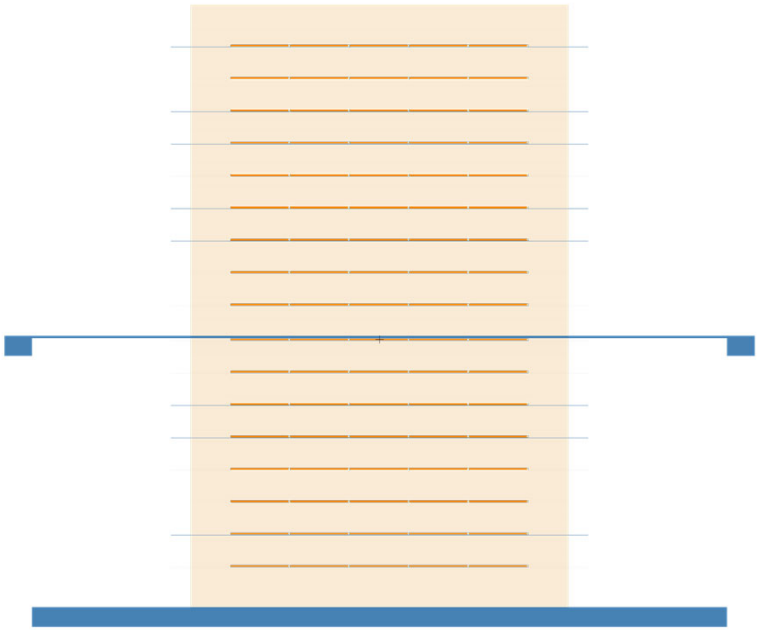


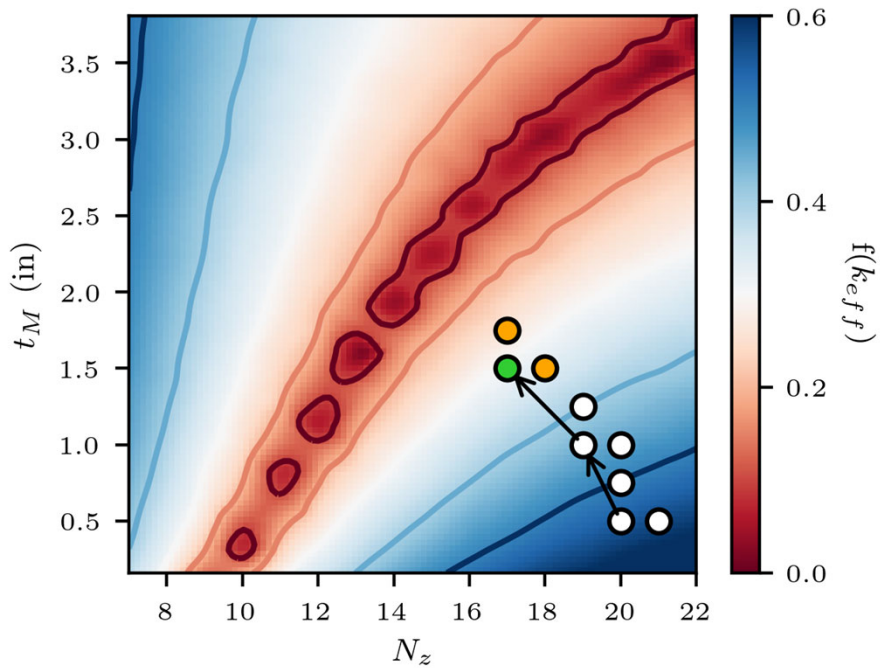
Create a new configuration



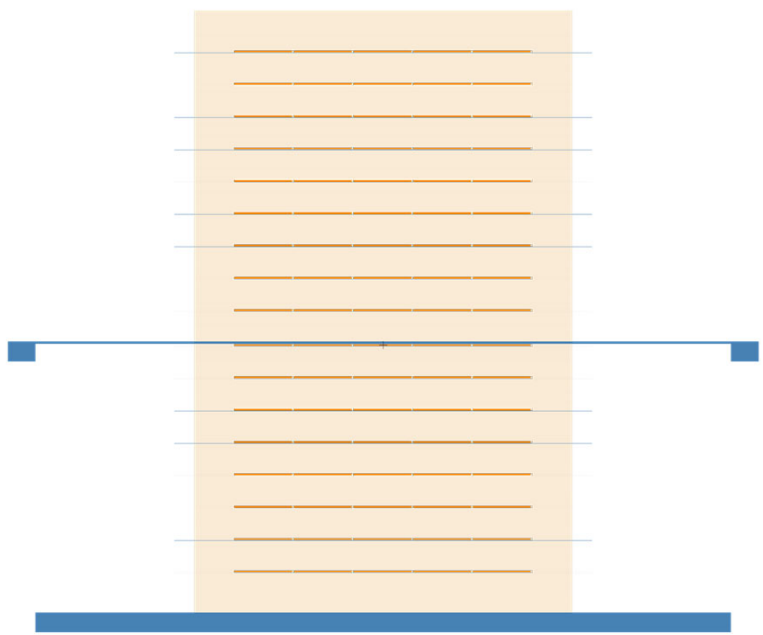


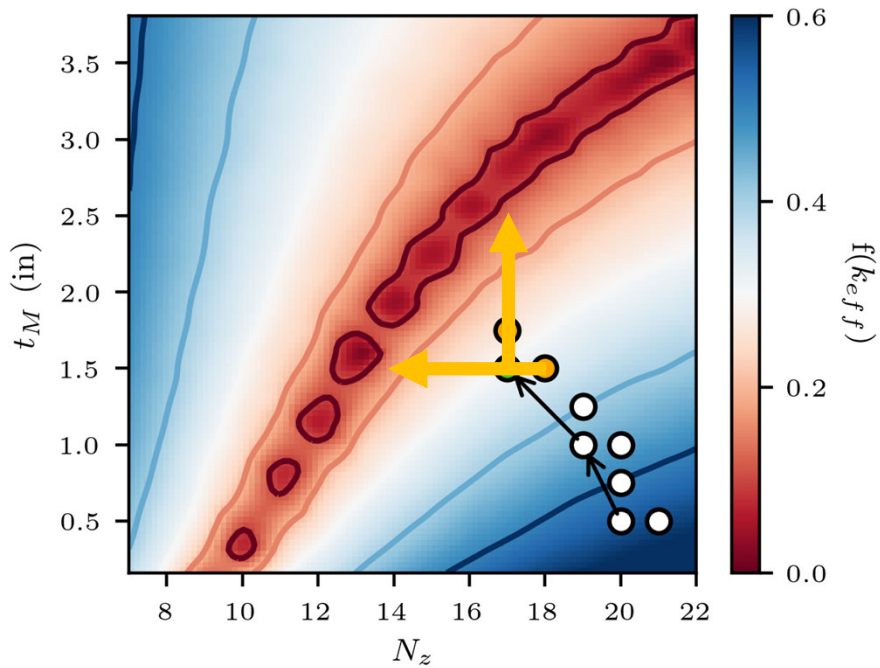
Evaluate the gradients



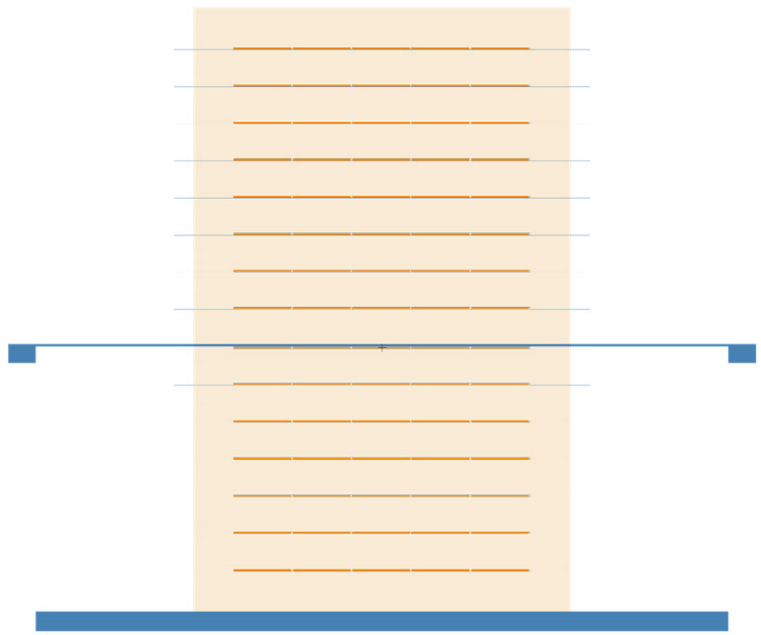


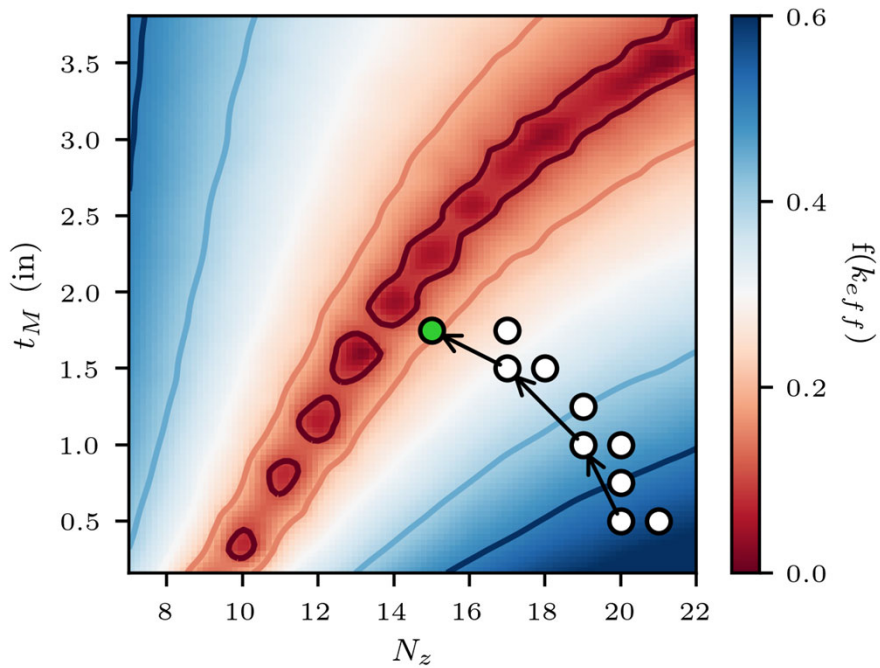
Evaluate the gradients
Still, point towards less fuel and more moderation



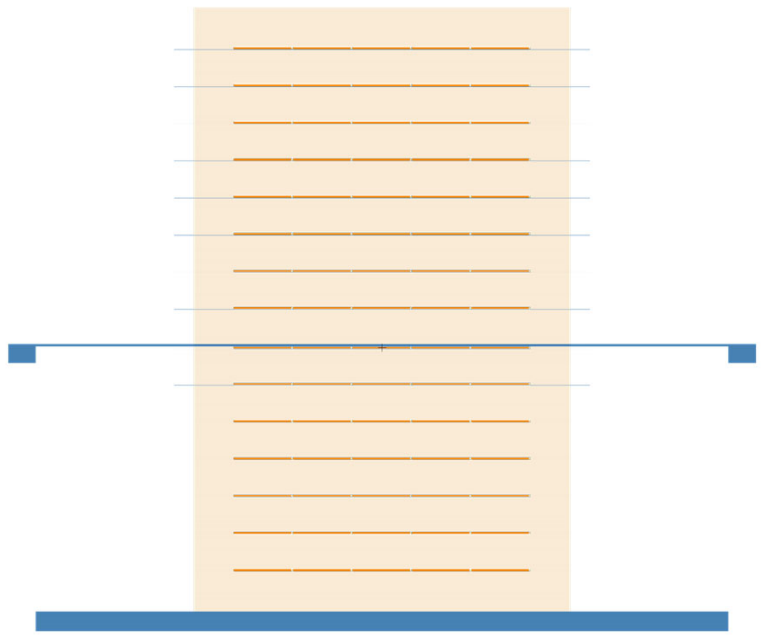


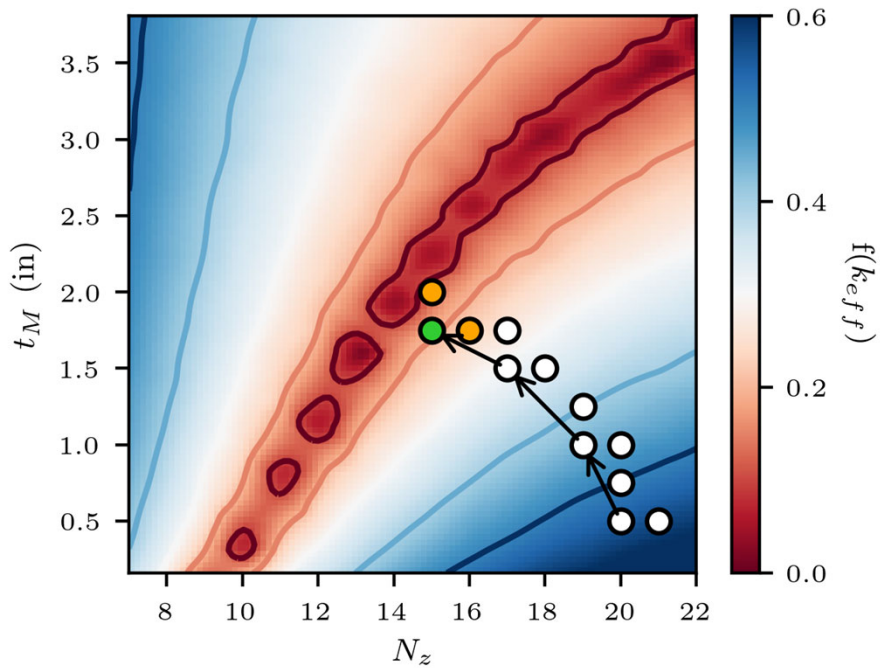
Create a new configuration



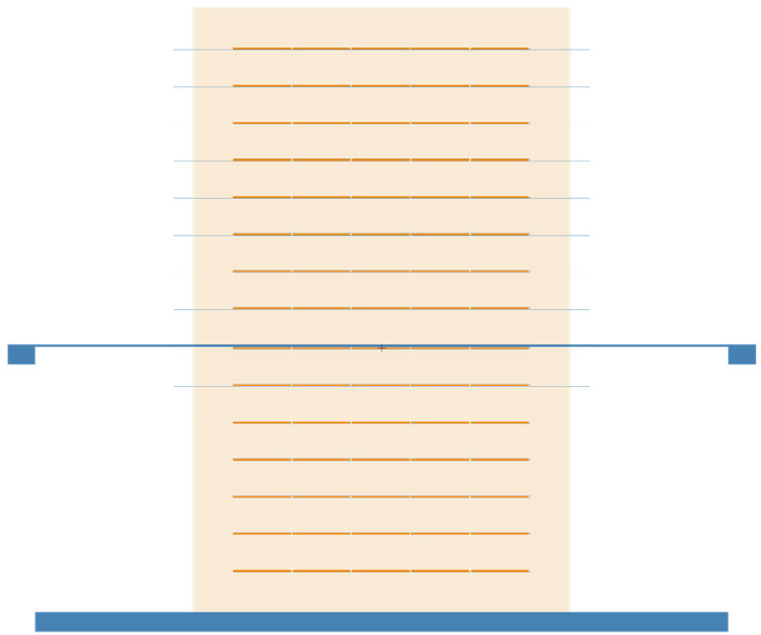


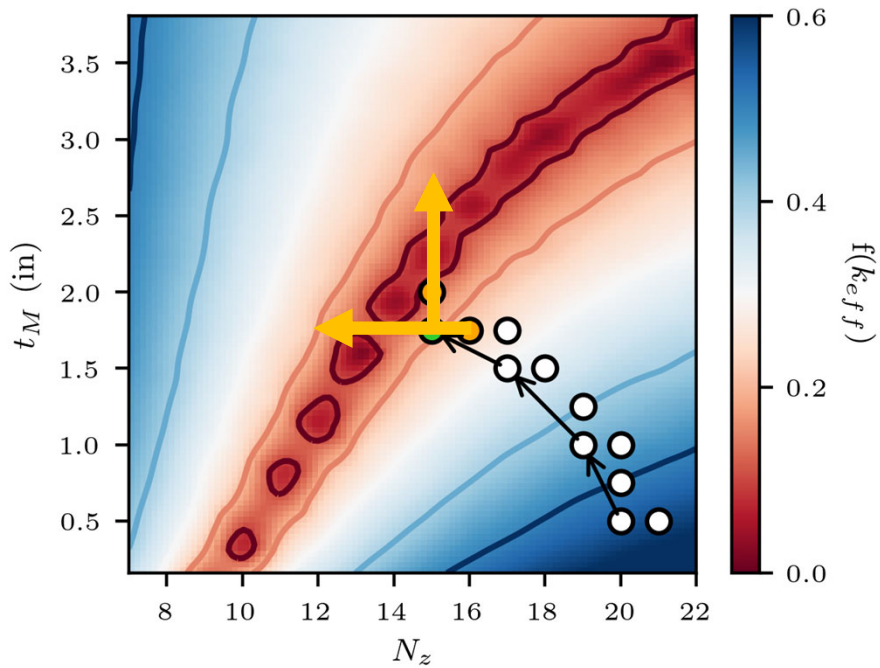
Evaluate the gradients



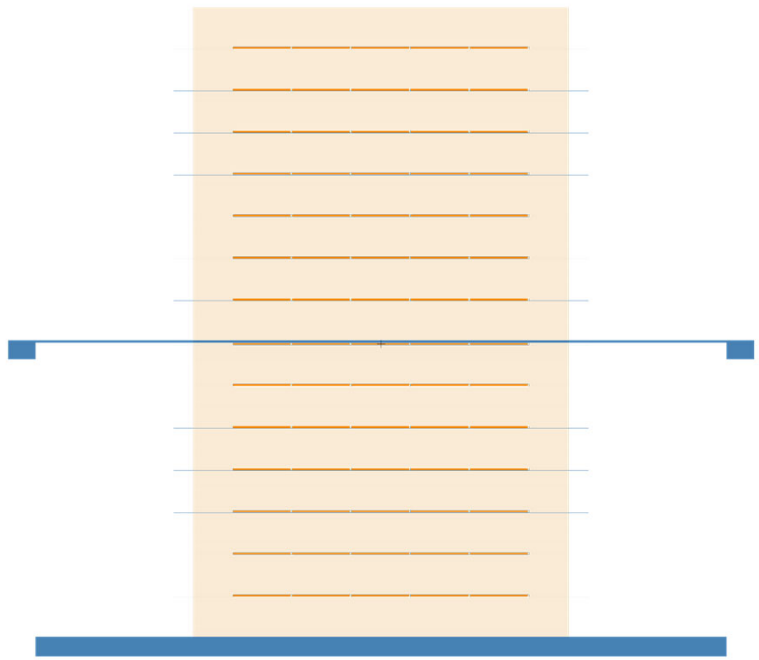


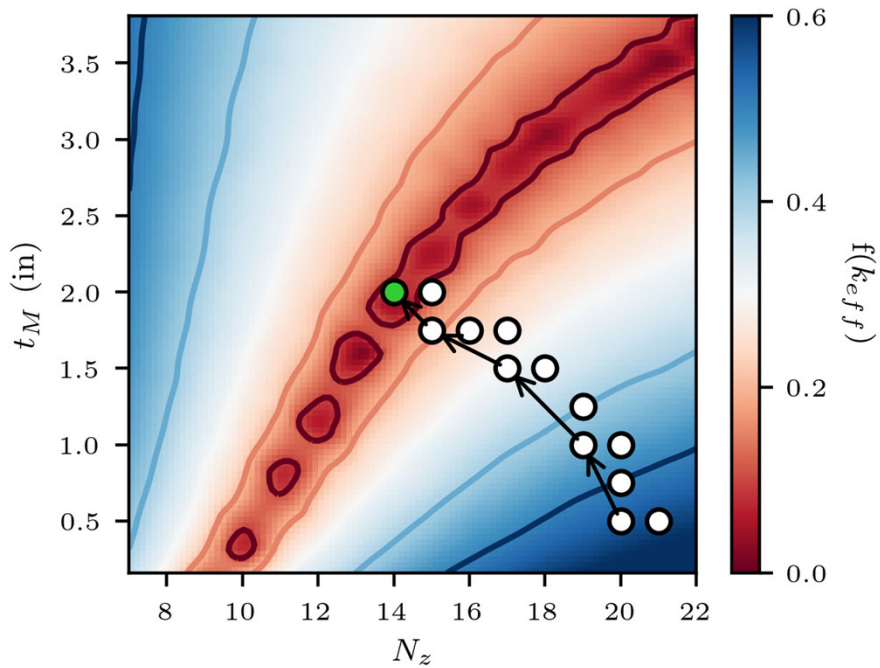
Evaluate the gradients
Less fuel and more moderation



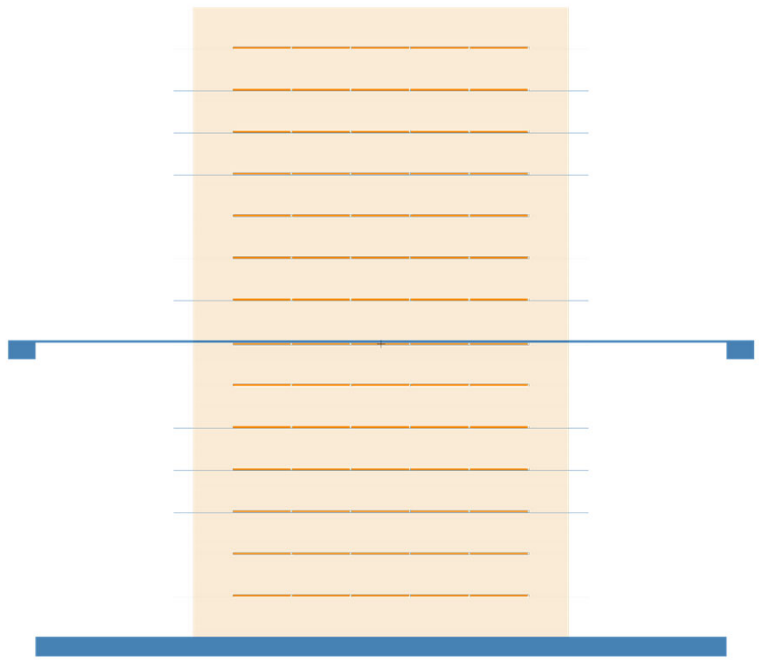


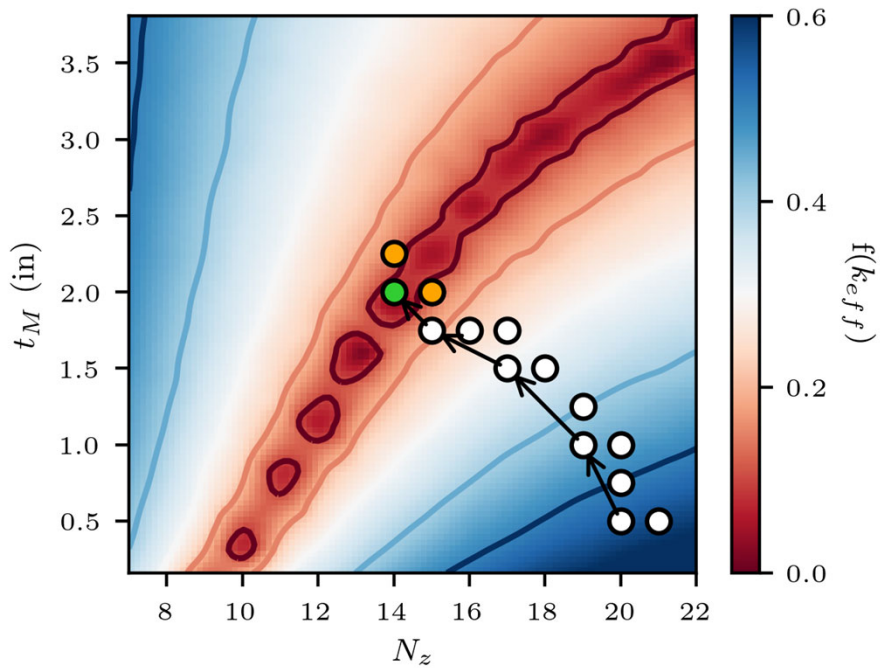
Create a new configuration
This one is roughly critical (k ~ 1)



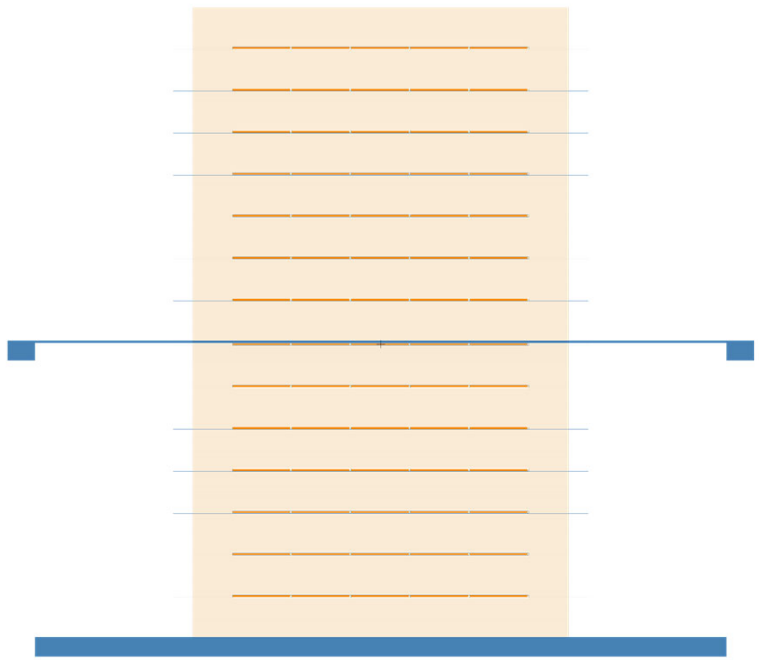


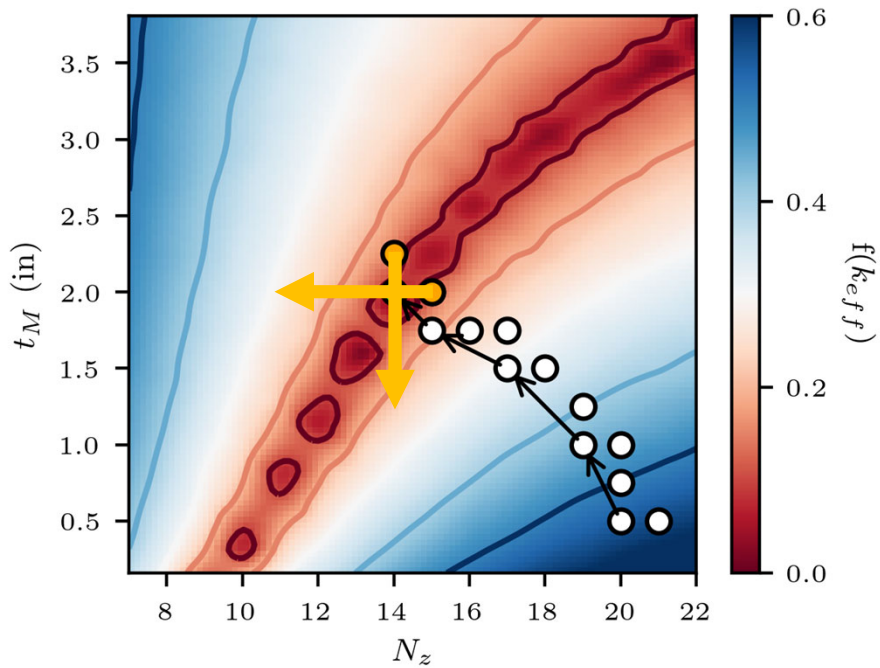
Evaluate the gradients



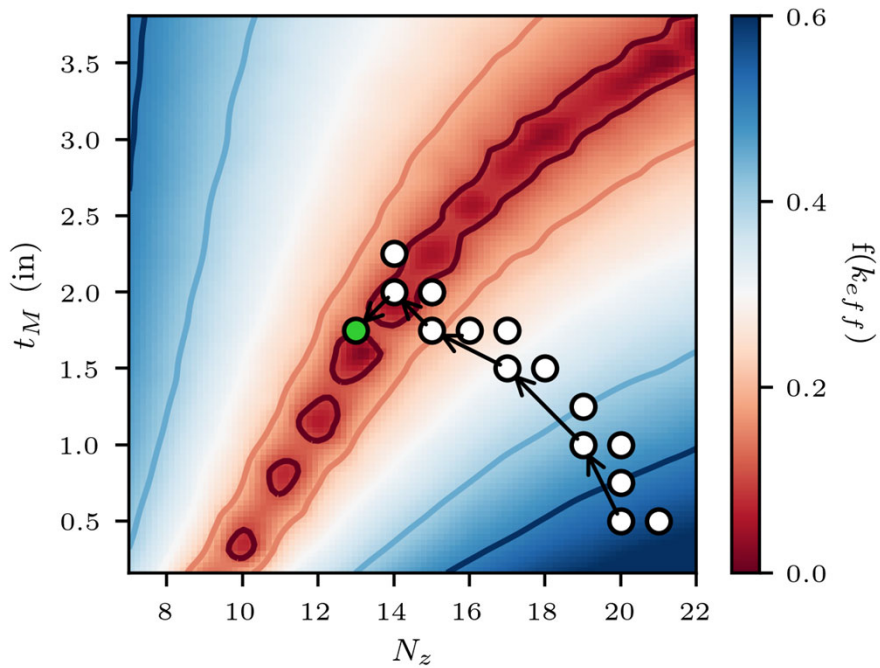


Evaluate the gradients
Now, points towards less fuel and *less* moderation

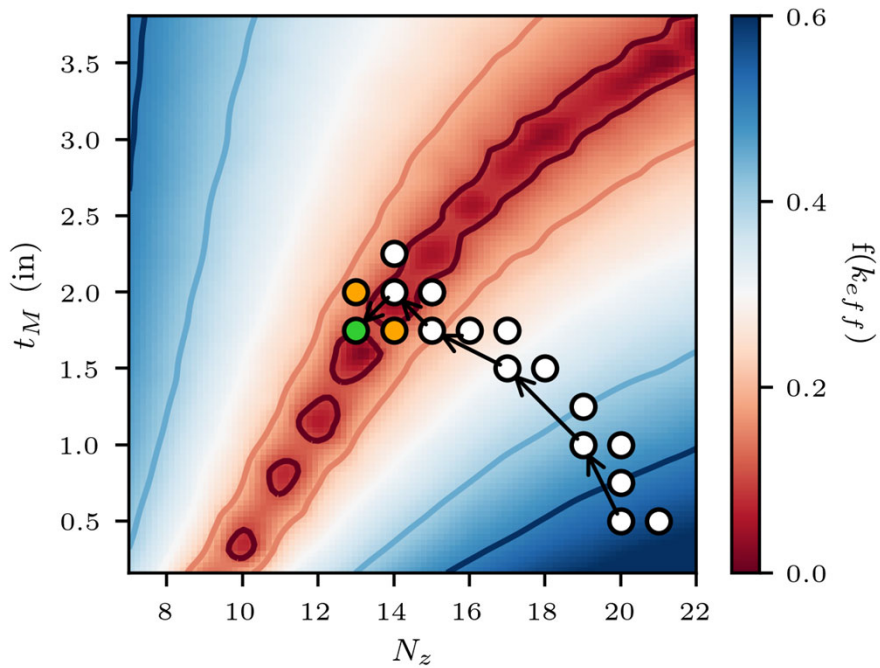




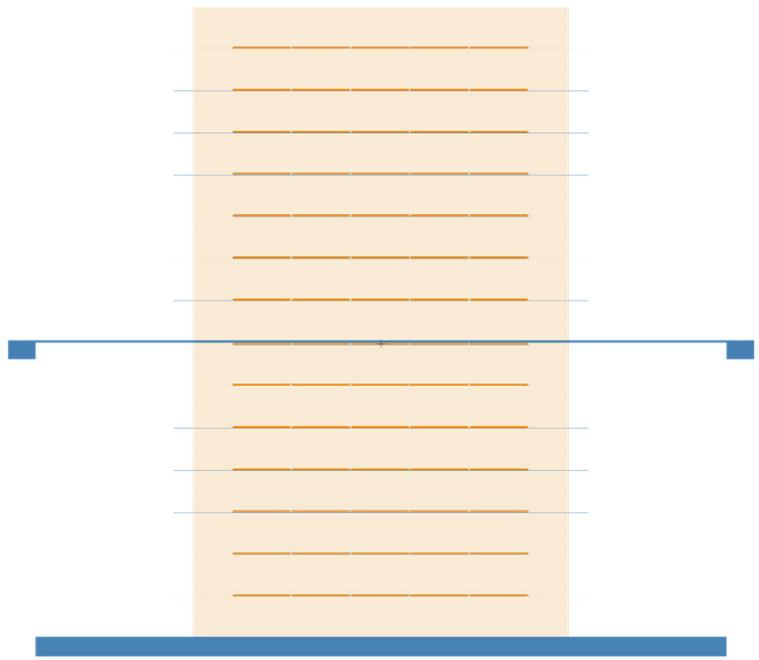
Create a new configuration
Now, subcritical (k < 1)

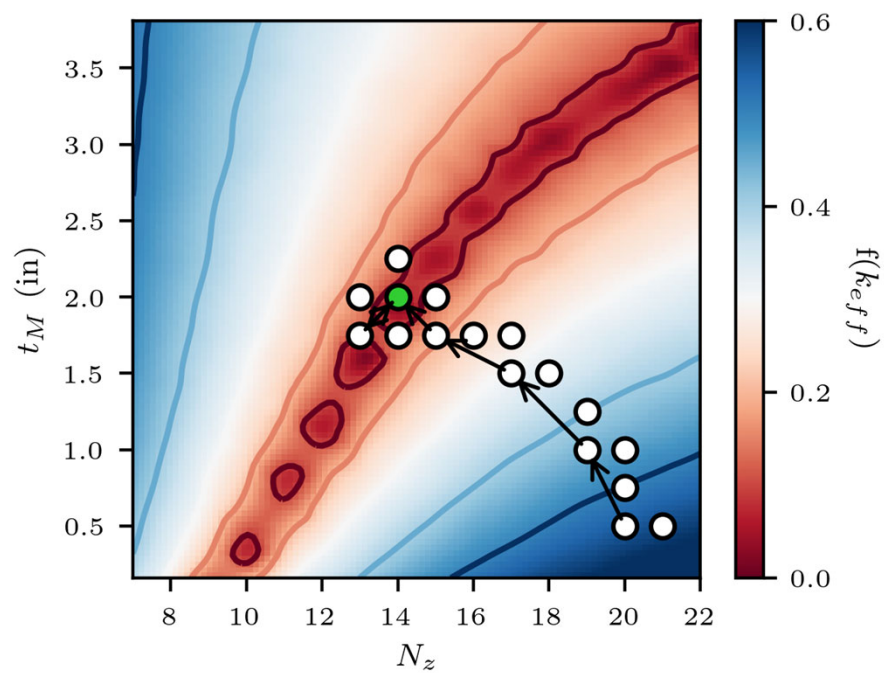


Final gradient evaluations



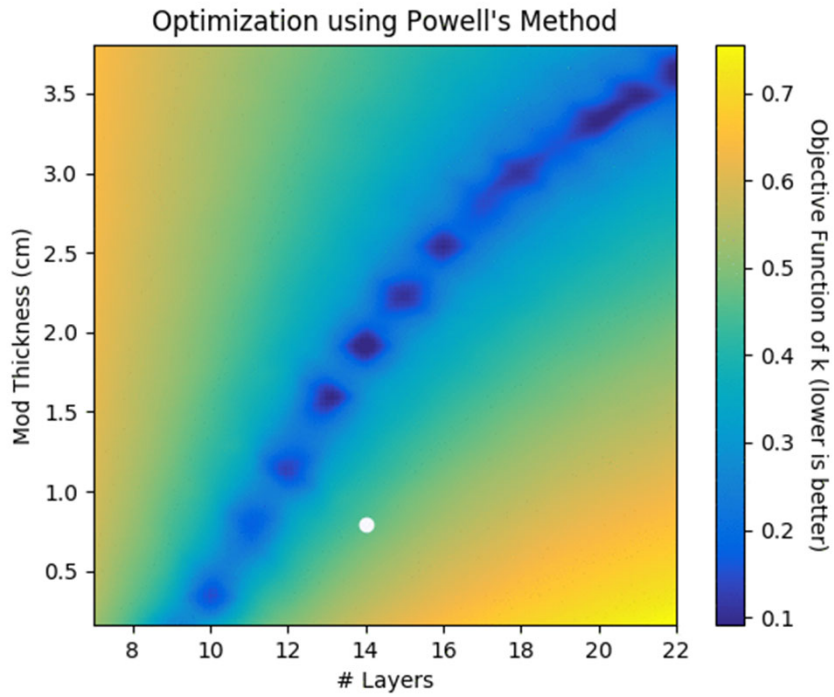
Select the minimum as the configuration closest to critical





Optimizing the Objective Function

- Example of a linear search using Powell's Method
- These are the actual steps that were taken to determine some of the reported critical configurations



Results

^{239}Pu/Alumina TEX

- 8 critical assemblies selected
  - Intermediate fraction: 0.68
  - No thermal fission (<1%)
- Alumina moderator can be used to fine tune the neutron energy spectrum

^{233}U/Polyethylene TEX

- 14 critical assemblies selected for CED-2
  - Thermal fraction: 0.81
  - Intermediate fraction: 0.57
- No critical assemblies with a majority fast fission were found

^{233}U/Polyethylene Critical Configurations

Nx	Ny	Nz	Moderator Thickness t_M (cm)	Reflector Thickness t_R (cm)	Fission Fractions		
					Thermal	Inter	Fast
6	4	11	0.794	2.54	0.53	0.41	0.06
6	4	18	0.476	2.54	0.41	0.51	0.08
6	4	11	0.635	3.81	0.52	0.42	0.06
6	4	15	0.476	3.81	0.46	0.47	0.08
8	6	13	0.476	2.54	0.41	0.51	0.08
8	6	19	0.318	2.54	0.32	0.57	0.11
9	6	13	0.476	2.54	0.41	0.51	0.08
9	6	18	0.318	2.54	0.32	0.57	0.11
7	5	6	4.76	2.54	0.81	0.16	0.03

^{233}U/Polyethylene Critical Configurations

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9	6	18	0.318	2.54	0.32	0.57	0.11
7	5	6	4.76	2.54	0.81	0.16	0.03

^{239}Pu/Alumina Critical Configurations

Nx	Ny	Nz	Moderator Thickness t_M (cm)	Reflector Thickness t_R (cm)	Fission Fractions	
					Inter	Fast
9	6	19	2.54	7.60	0.51	0.49
9	6	20	4.45	12.7	0.66	0.34
10	6	17	2.38	7.60	0.50	0.50
10	6	17	4.60	12.7	0.66	0.33
11	7	12	2.22	10.2	0.50	0.50
11	7	15	4.76	10.2	0.67	0.33
12	8	11	2.86	10.2	0.56	0.44
12	8	12	5.56	10.2	0.68	0.31

^{239}Pu/Alumina Critical Configurations

Nx	Ny	Nz	Moderator Thickness t_M (cm)	Reflector Thickness t_R (cm)	Fission Fractions	
					Inter	Fast
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10	6	17	2.38	7.60	0.50	0.50
10	6	17	4.60	12.7	0.66	0.33
11	7	12	2.22	10.2	0.50	0.50
11	7	15	4.76	10.2	0.67	0.33
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12	8	11	2.86	10.2	0.56	0.44
12	8	12	5.56	10.2	0.68	0.31

Conclusions and Future Work

- These critical configurations will help to verify and validate nuclear data for neutron-induced fission with ^{239}Pu and ^{233}U by maximizing the relative fission fraction in the intermediate energy range
- Optimus offers a significant time savings during the design and search process for critical configurations
- IER-329 (^{233}U/Polyethylene) will further study these 14 configurations in the CED-2 report

Acknowledgments

- Thanks to the DOE Nuclear Criticality Safety Program for funding this Integral Experiment work and for further funding IER-329
- Thanks to our colleagues at the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) for their technical expertise and the collaboration that inspired the test cases and development of the Optimus software package
  - IRSN maintains a similar and much more mature code called Promethée: http://promethee.irsn.fr

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Questions?

Thanks for attending!