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Multilayer coating design methods for a high-energy x-ray imaging optic

Complex Design Requirements

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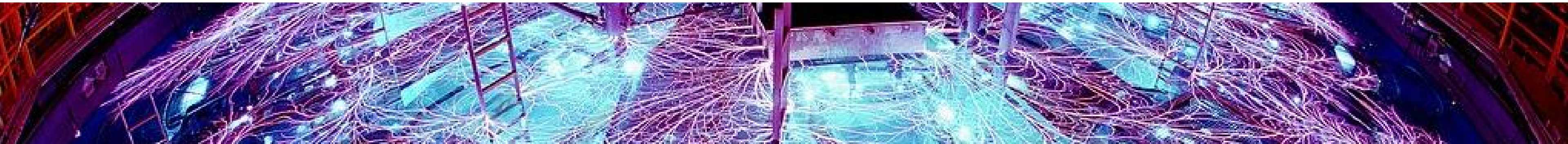
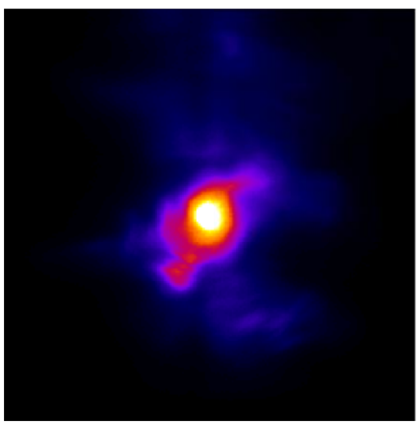
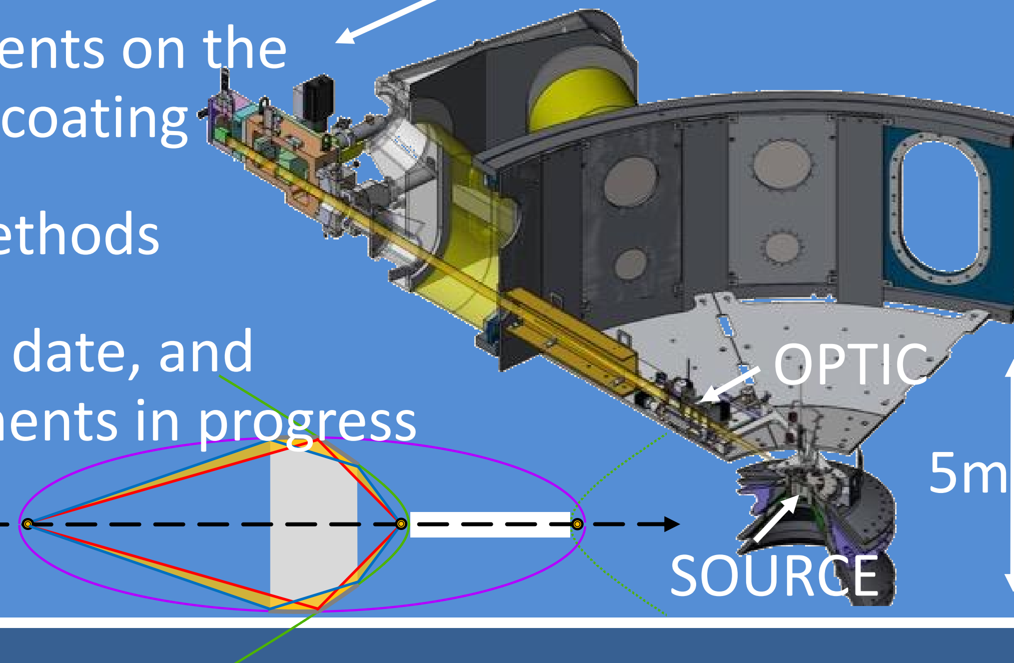
Outline





- Introduction – imaging a hot plasma
- Requirements on the reflective coating
- Search methods
- Results to date, and improvements in progress
- Wrap-up

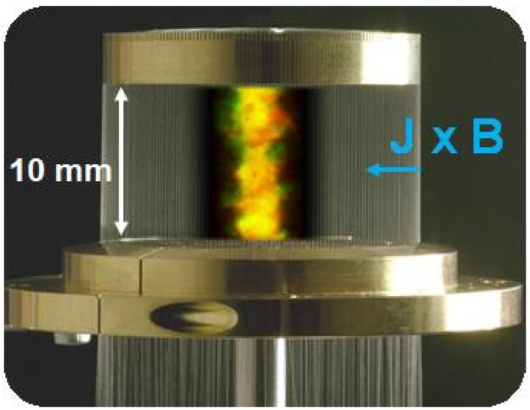


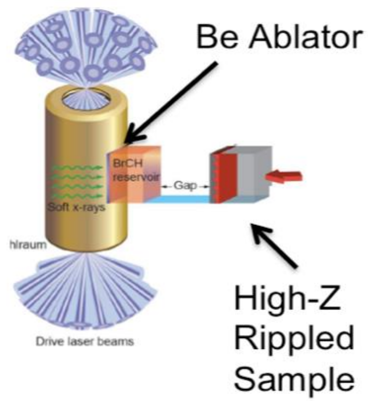
Hi-resolution, narrowband imaging with >15 keV x-rays is desirable in many high-energy-density physics applications

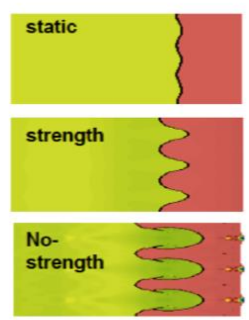
K-shell x-ray sources on Z[1,2]

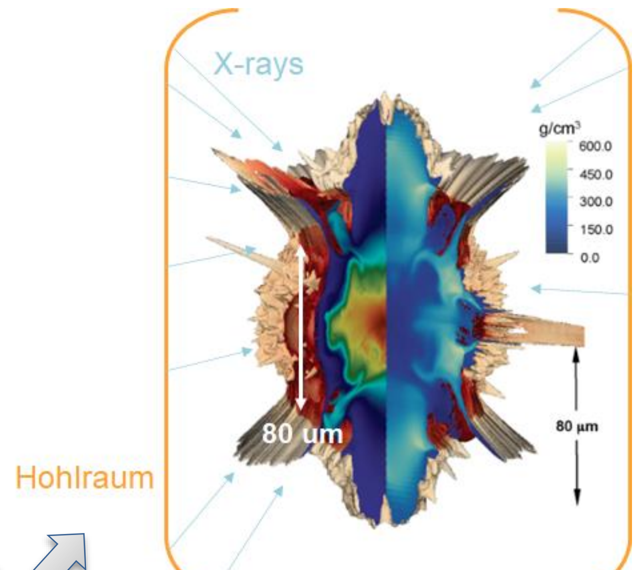
Strength of hi-Z materials[4]

ICF capsule hot spot[3] imaging









Z-machine
(Sandia National Laboratories)

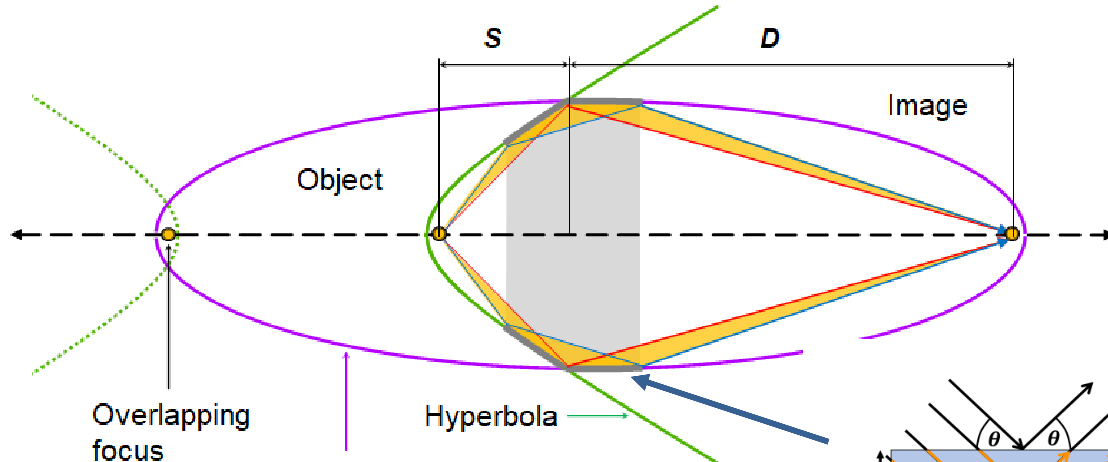
National Ignition Facility
(Lawrence Livermore National Laboratory)

1. Jones, B., et al. RSI (2008), 2. Ampleford, D. J. POP (2014),
3. Clark, D. S., et al. (2016). Physics of Plasmas, 23(5), 4. Park, H. -S., et al. PRL (2015)

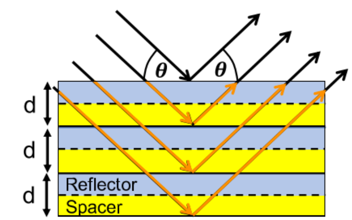
A Wolter optic offers the greatest light collection of alternatives available for these x-ray energies

Wolter type-I microscope:

Imagers w/equiv. res., mag., FOV	
Optic	**Throughput (Sr)**
Wolter	$4 - 60 \times 10^{-7}$
Crystal Imager	4×10^{-8} **
Pinhole Imager	2×10^{-9}

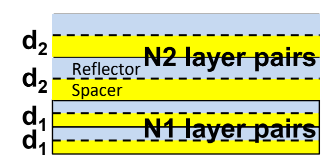


Constant-d:



Reflective coatings are needed to work at higher glancing angles

2-block-d:

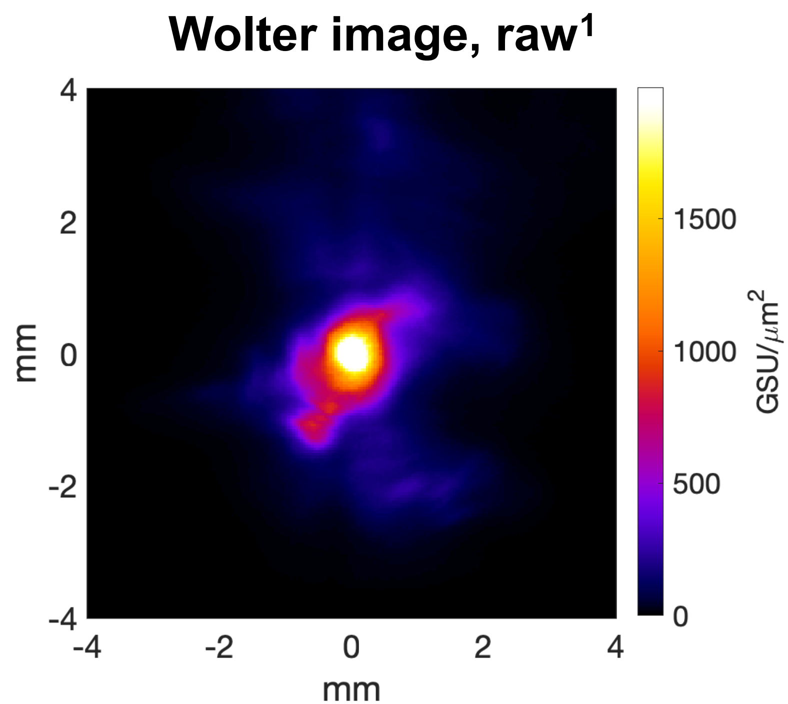


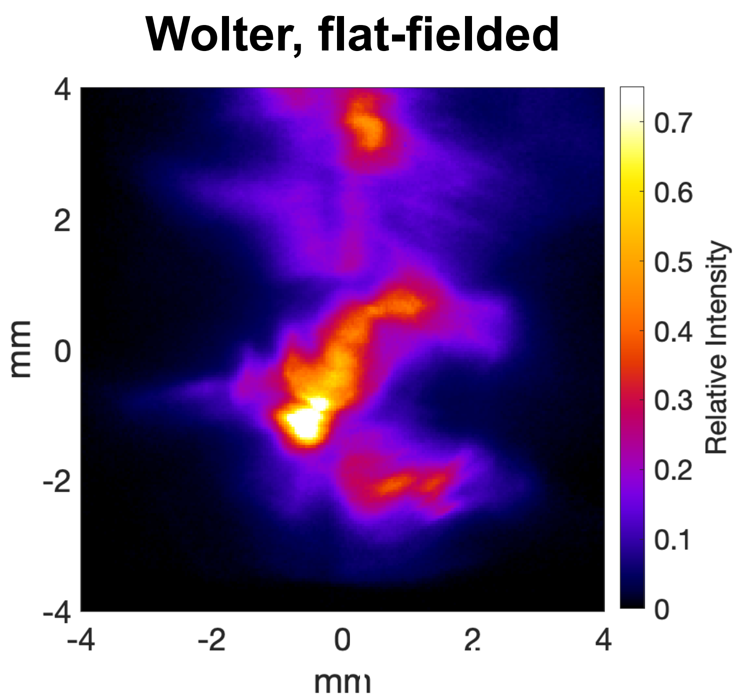
<u>Advantages:</u>

- **Can image over large FOV while maintaining <150-µm resolution**
- **High collection efficiency from geometry and multilayer ($\Omega_{optic} = 10^{-4}$ Sr, $R^2 > 1\%$)**
- **Customizable energy bandpass – <u>we can tune with multilayer coating design</u>**

1. H. Wolter, Ann. Phys. (1952), 2. J. K. Vogel et al., Rev. Sci Instrum (2018), **Schollmeier, et al., RSI (2016)

Results with an earlier Wolter demonstrate resolution and light-gathering

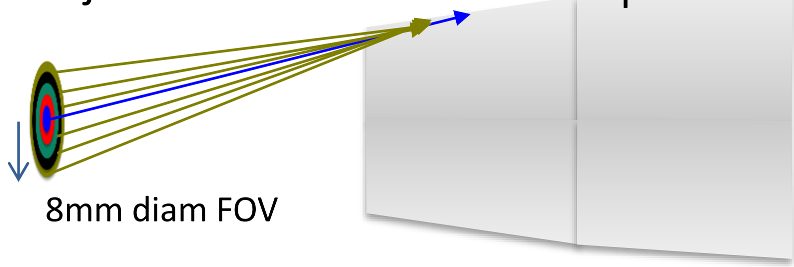




- Wolter optic has about 4X finer spatial resolution, and >100X more photons gathered.

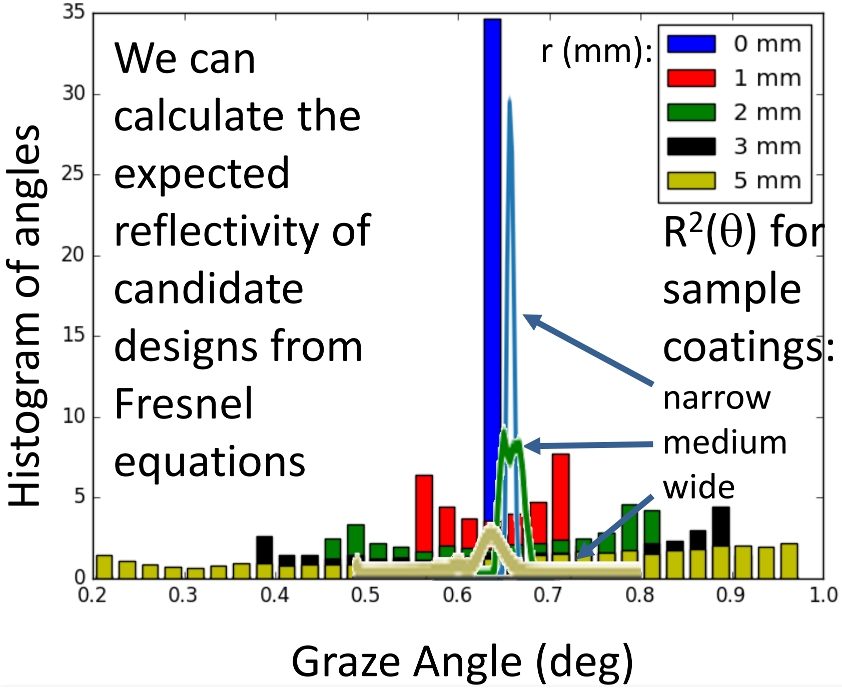
1. J.R. Fein, RSI (2018)

A coating covering the full angle range is possible but has drawbacks

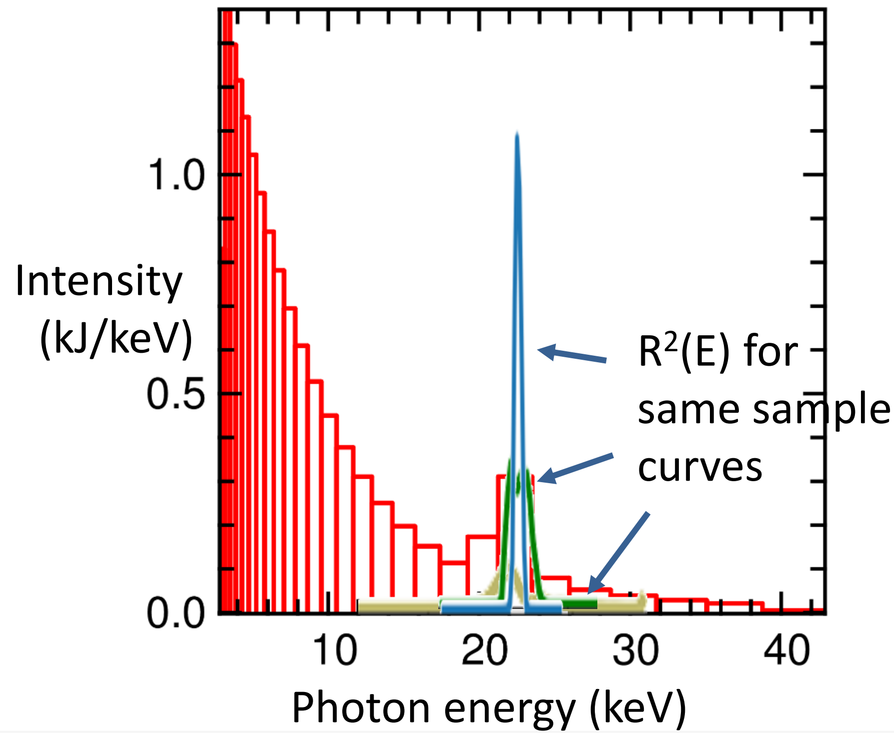


Accepting all angles would accept too wide a range of energies.

Histogram of incidence angles vs r across FOV:



Plasma spectrum from a typical target:



Compromise coating bandwidth must include multiple tradeoffs

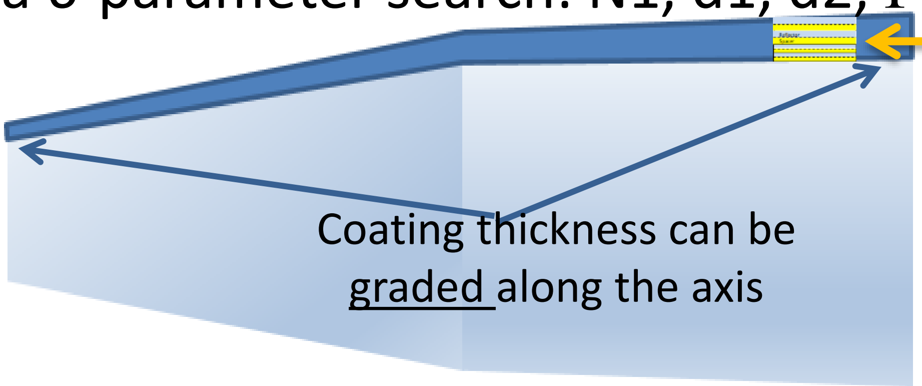
Specifications for coating with compromise bandwidth:

- BW = <= 1 keV (or signal:background >= ~4)
- Signal:noise >= 5
- Throughput uniformity < 5x variation from r = 1 to r = 4 mm

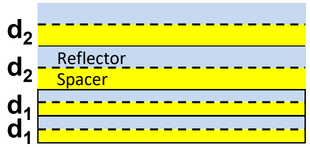
For a coating design we must consider:

- Wider bandwidth means lower optic throughput
- Tails of reflectivity curve still affect off-axis photons ($\Rightarrow$ non-uniform response over FOV)
- Bandwidth above peak of interest means more background

It is a 6-parameter search: N1, d1, d2, Γ1, Γ2, grade-%



Γ = fractional reflector thickness:
Γ_2 = reflector$_2$/d$_2$

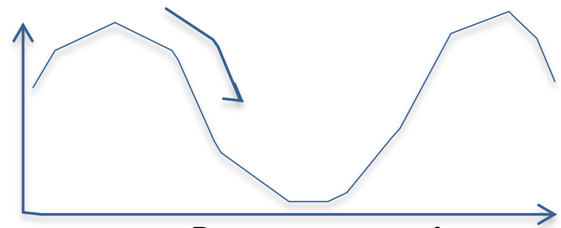


Various approaches to searching a parameter space

- Exhaustive
- Gradient descent
- Gradient descent from multiple starts (e.g. Latin Hypercube Sampling or Sobol sampling)
- Markov Chain Monte Carlo…
- And many others …

Sidebar: Do start points matter in gradient descent?

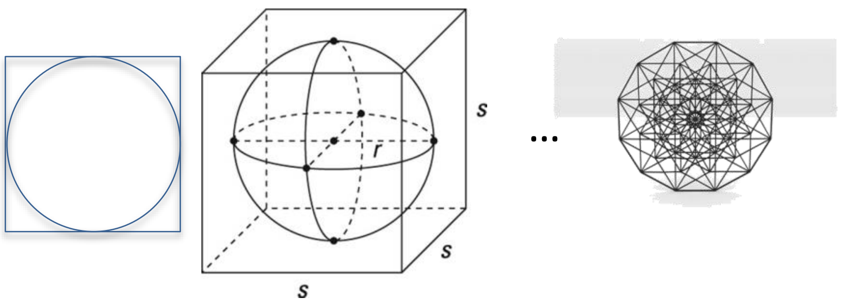
Cost



Parameter x1

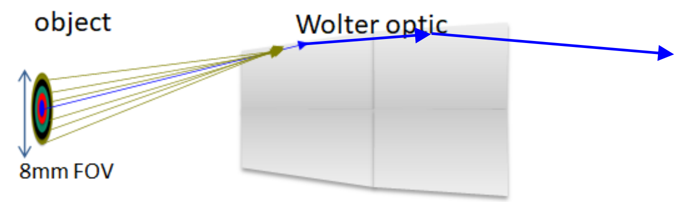
Odds of landing in "circle":

2D 3D … 6D

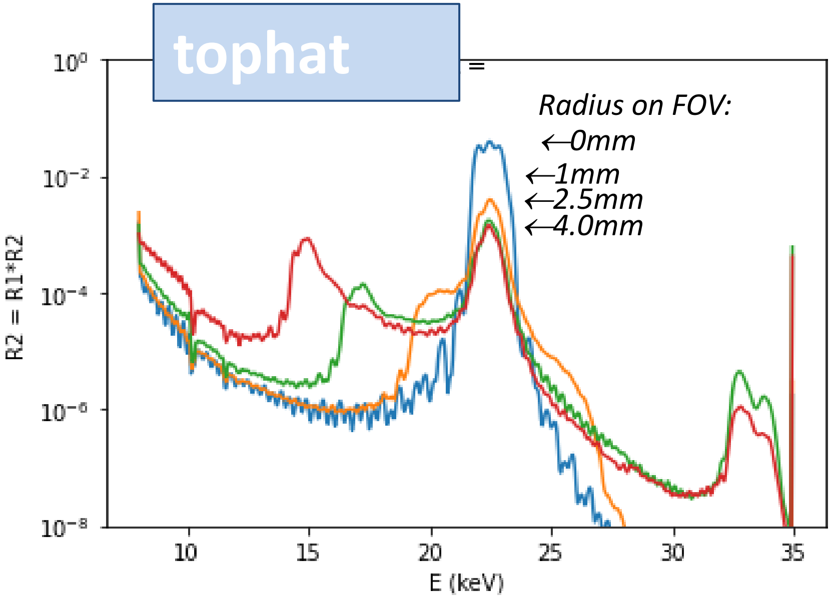


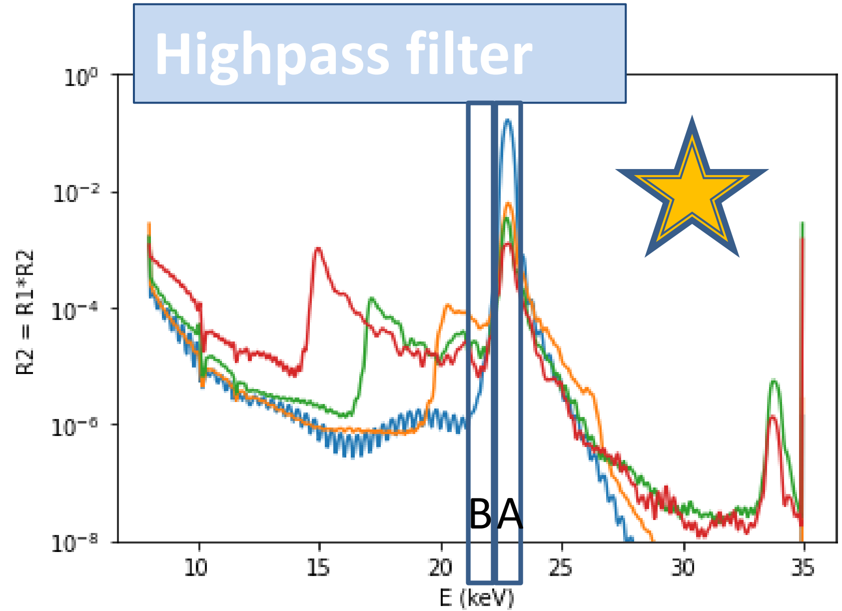
0.79 0.52 0.081

Approach 1 gave candidate designs for most recent optic



- With large-parallel gradient descent we made candidate designs for two criteria





Criteria were still under discussion, so two designs were made: tophat for broad flat passband, or filter for background rejection. Searched 3-parameter subspace.

Highpass seeks to maximize $\int_A R^2(E) / \int_B R^2(E)$

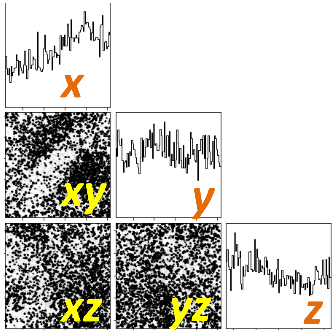
Final choice was a coating similar to the highpass filter – optic now being tested for use.

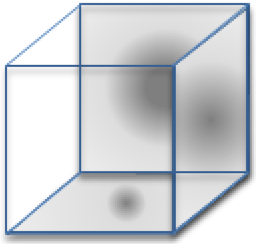
Work on Approach 2, to cover all 6 parameters, is still underway

- Needed: a method to efficiently maximize over a large parameter space
  - Efficiency is key when each call of the “cost” (i.e. figure of merit) function is time-consuming
  - The method must explore both up and down the cost surface, to not miss finding other, neighboring hills
  - A map of the cost surface is better than just finding the maximum
- One well-developed method is Markov-Chain Monte Carlo (MCMC)
  - Calculate a set of “walkers” that explore in parallel
  - Over time more walkers collect in high areas, greater point density at high points

How to plot a high-dimensional distribution:

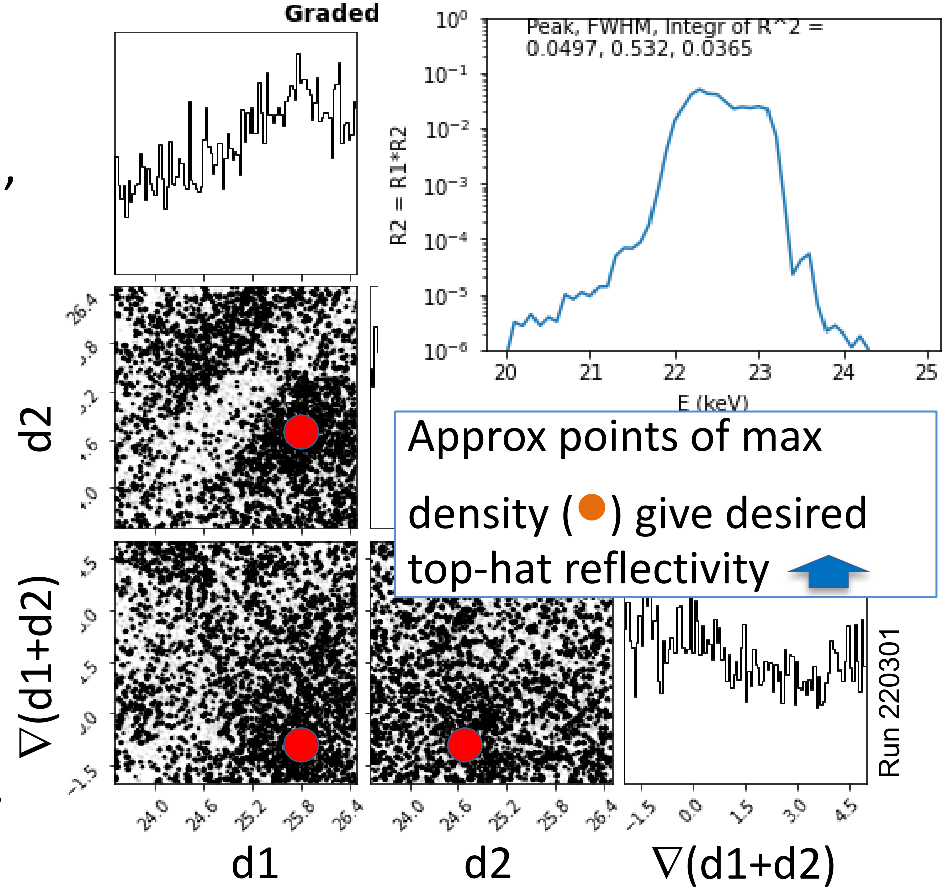
Corner Plot





MCMC is running for 3-parameter searches. Scaling up needs more work

- Example 3-parameter search
  - Package used is “Emcee Hammer”[1]
  - Varying block layer-pair thicknesses d1, d2 and thickness gradient
  - Best solution is where walkers have greatest density of walkers gathers
  - Ready-to-use Python code with documentation and examples – just a single *import* statement to start
  - Parallelization to scale up has been a challenge (this is about 9 hours single-cpu)
  - We are evaluating related methods for more efficiency



1. D. Foreman-Mackey *et al*. 10.1086/670067

Summary

- Wolter-type x-ray optics are in use as plasma diagnostics
- An important advantage is their customizable energy-selectivity, through design of the reflective coating
- Coating design methods are under active improvement
  - As goals evolve
  - As design abilities improve
- Many powerful optimization methods are “easily” available.

BACKUP SLIDES