Modeling measurement uncertainties for x-ray radiograph analysis

Calculating error bars with a non-parametrized, gradient-descent based forward fit routine

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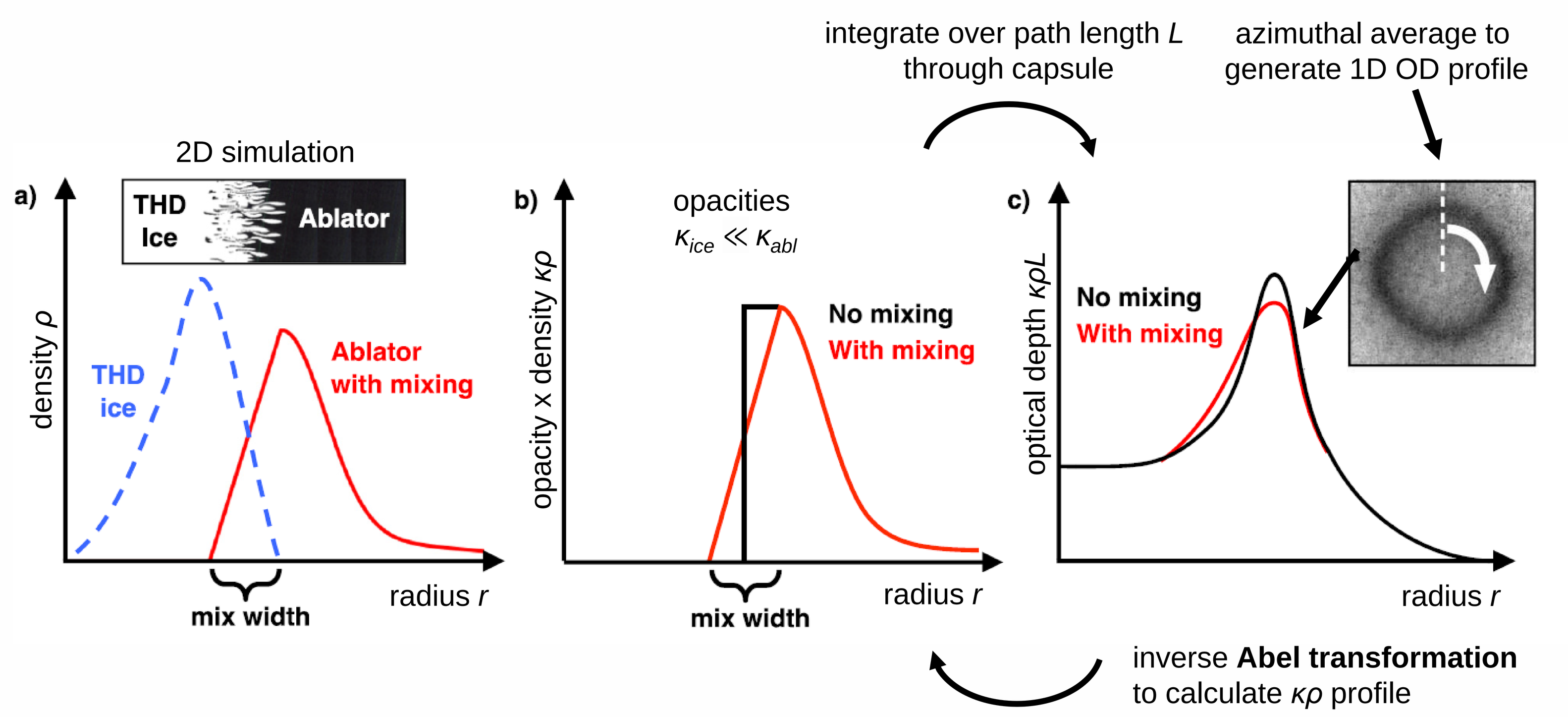
Any experimental measurement involves uncertainties and noise, which propagate through the data analysis routines and result in a confidence interval on the measured value. We present the new PEREGRINE software tool that includes known sources of error as well as experimental uncertainty ranges in the analysis of x-ray radiographs to refine the calculation of error bars. We apply this gradient-descent based routine to the mix width measurements of imploding inertial confinement fusion (ICF) capsules and estimate the impact of the different sources of uncertainty onto the measurement using synthetic radiographs.

ABLATOR-ICE MIX IN ICF IMPLOSIONS CAN BE MEASURED WITH X-RAY RADIOGRAPHY [1]



Mixing between layers in imploding inertial confinement fusion (ICF) capsules degrades the implosion performance. X-ray radiography can investigate mix based on the illustrated principle: (a) Mixing of ice and ablator modifies the radial density profiles at the interface. (b) The $\kappa\rho$ (opacity x density) profile is dominated by the ablator. The width of the profile slope determines the mix width. (c) The x-ray radiograph is created by x-ray photons passing through the capsule, integrating the $\kappa\rho$ profile over the path length L resulting in an optical depth (OD).

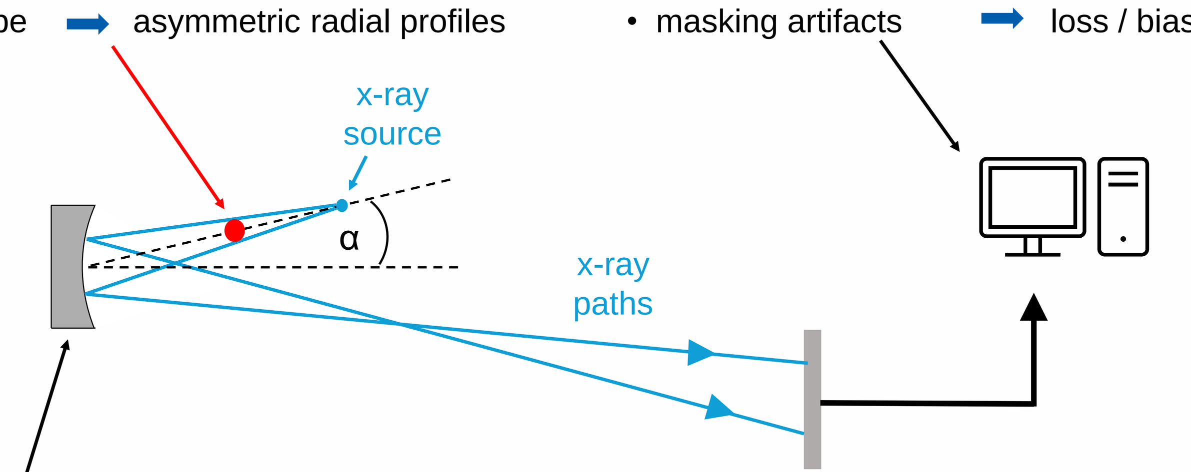
X-RAY CRYSTAL IMAGING RADIOGRAPHS ARE IMPACTED BY THE DIAGNOSTIC AND ANALYSIS METHOD

object: imploding capsule

- velocity ➡ motion blur
- shape ➡ asymmetric radial profiles

analysis

- amount of averaging ➡ noise
- masking artifacts ➡ loss / biasing of information



optic: focusing crystal

- crystal shape ➡ aberrations, e.g., astigmatism
- alignment ➡ asymmetric magnification, blurring

detector

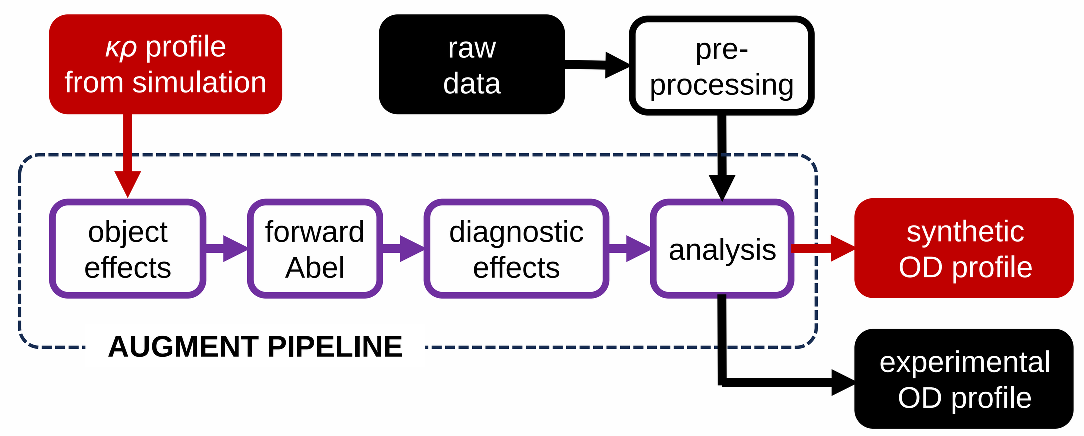
- detection efficiency ➡ noise / SNR
- detector design ➡ obstructed pixels

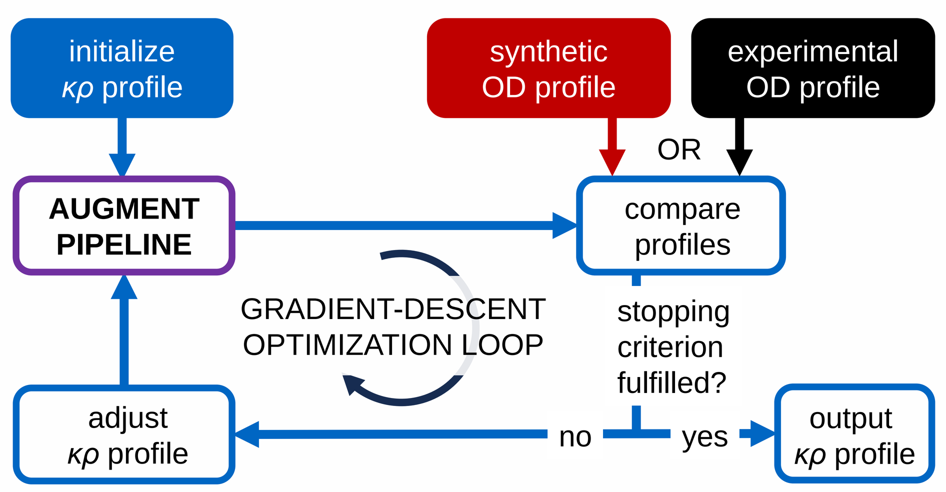
The measurement uncertainties and noise in radiographs recorded with an x-ray imager, e.g., the Crystal Backlighter Imager[2] at the National Ignition Facility (LLNL), are impacted by effects and tolerances from each part of the measurement process. If identified and thoroughly characterized, the contributions of these sources can be used to determine realistic error bars on the measured metric.

PEREGRINE* PROVIDES FRAMEWORK TO CREATE MULTI-USE PIPELINES FOR X-RAY RADIOGRAPH PROCESSING

*Propagation of Errors in Radiograph Evaluation using a Gradient-descent Routine Including Noise and Experimental uncertainties

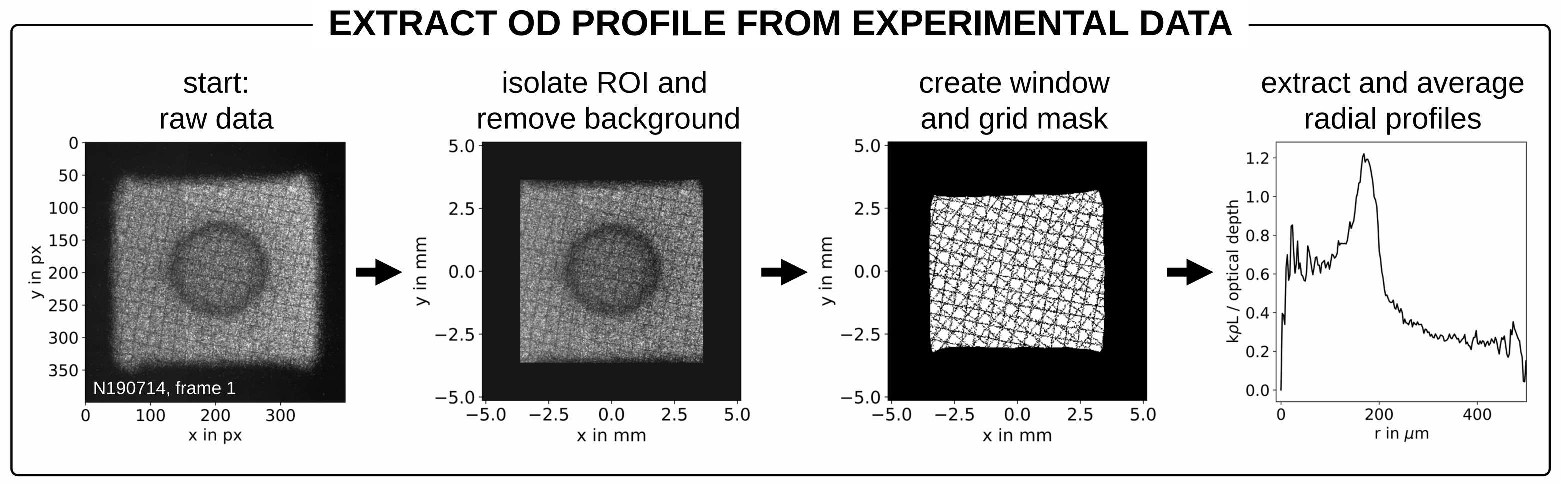
All diagnostic properties and processing steps are implemented as augment functions, which can be chained in a pipeline. The augments provided by PEREGRINE can generate and process synthetic and experimental data.

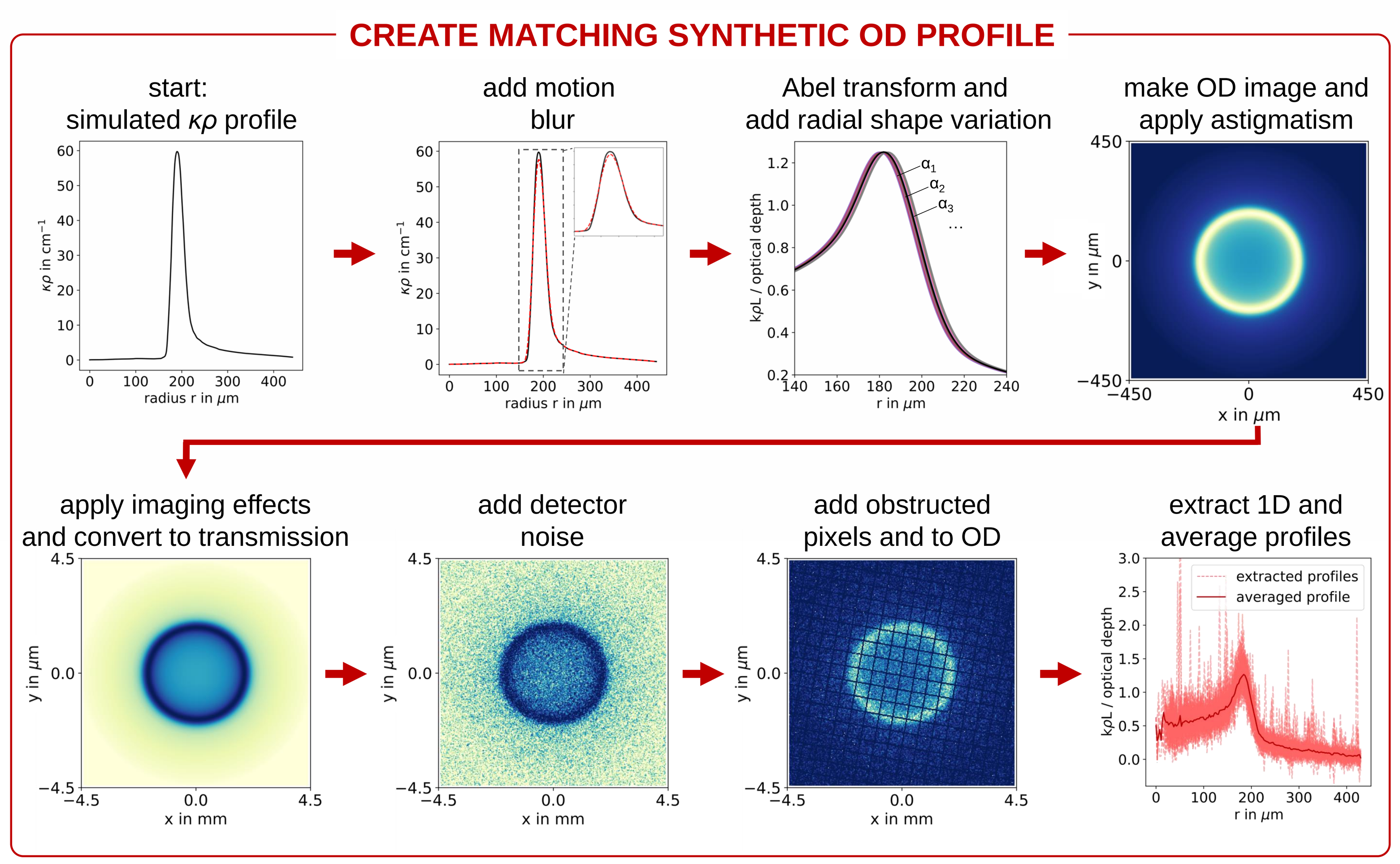




The same pipeline can be used to perform an uncertainty-aware Abel unfold of an input profile using PEREGRINE's gradient descent optimization routine. The initialization profile can be random noise, making this method superior to parametric fit models relying on prior information about the underlying $\kappa\rho$ profile shape.

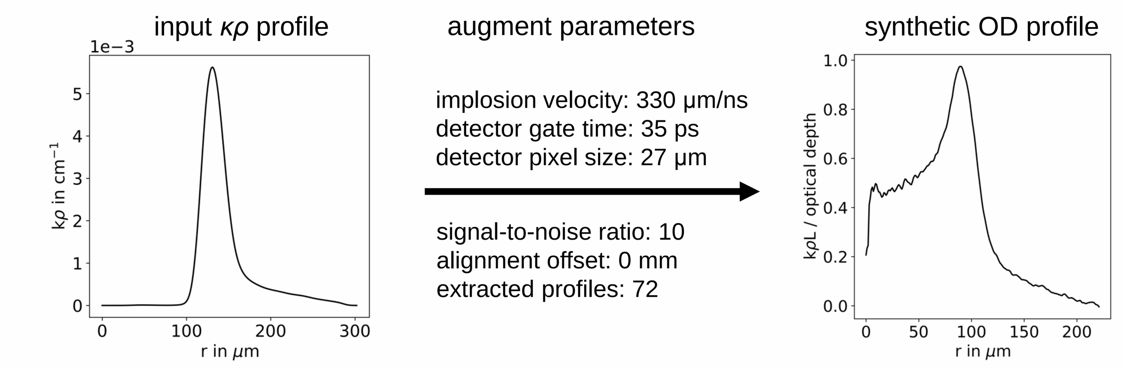
PEREGRINE PROCESSES EXPERIMENTAL AND SYNTHETIC DATA USING AUGMENT PIPELINES





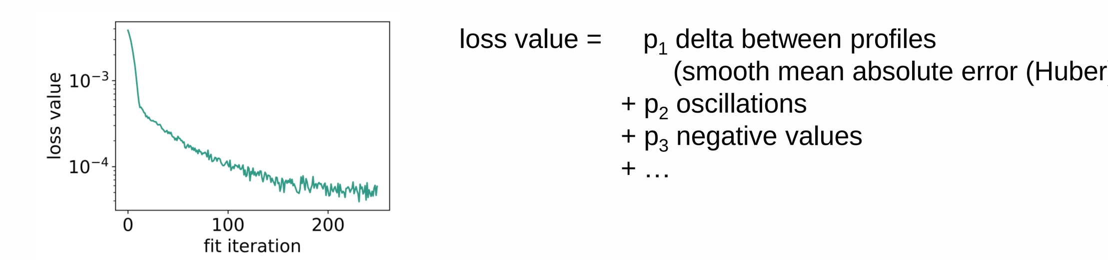
GRADIENT-DESCENT BASED ABEL OPTIMIZATION ROUTINE IS TESTED USING SYNTHETIC PROFILES

1. Generate synthetic OD profile with one set of experimental parameters



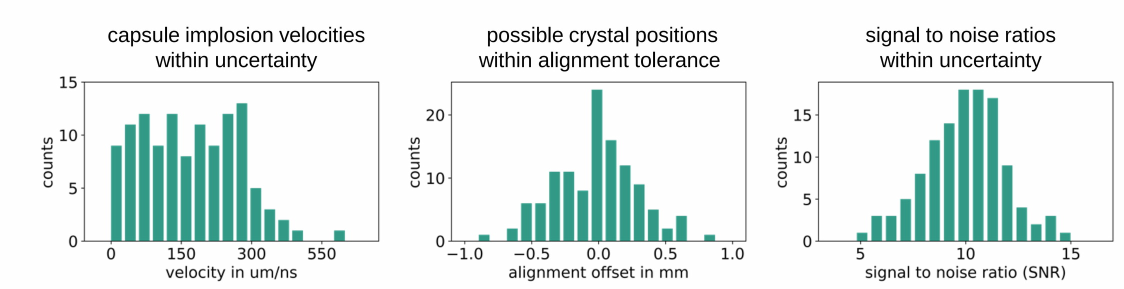
A simulated $\kappa\rho$ profile serving as ground truth is modified with a pipeline of effects with known parameters. The resulting OD profile resembles a realistic experimental profile and is used as input for the unfold routine.

2. Tune hyper-parameters of the gradient-descent fit routine



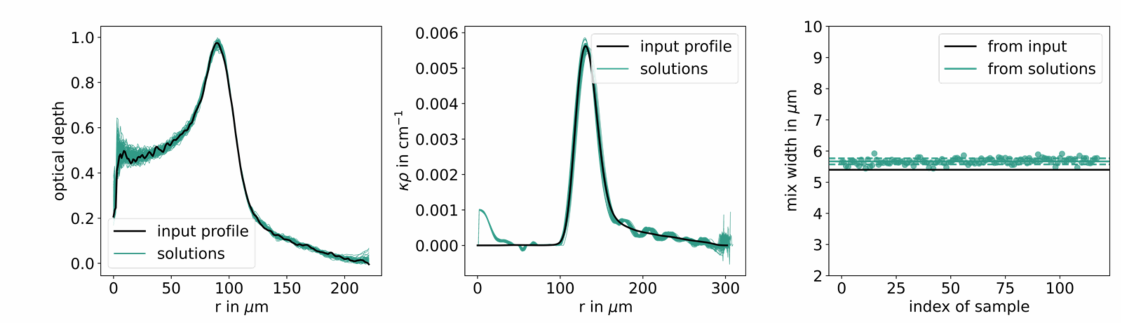
The loss value (LV) curve is influenced by the hyper parameters (e.g. learn rate, iterations, momentum, …) and penalty values p_i of the gradient descent unfold routine. The shape of the LV curve is used to optimize these hyper parameters.

3. Sample parameters from possible value ranges



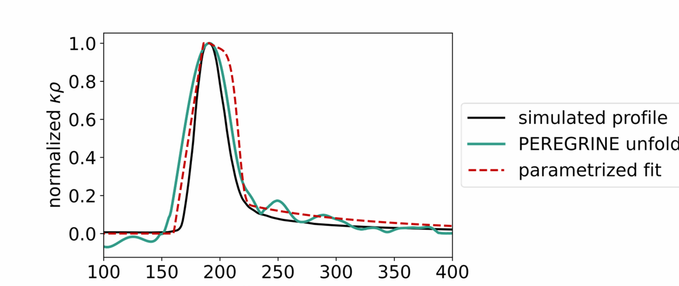
Parameter distributions for generating a set of unfold solutions. The type of distribution is chosen to match the represented tolerances or uncertainties.

4. Create set of possible solutions based on the sampled parameters



Set of solutions for the synthetic OD input profile using different sets of pipeline parameters from the distributions shown above. The inferred mix width[1] is within 0.25 µm of the width determined from the ground truth $\kappa\rho$ profile, which is < 1% of the 10s of µm mix width scales that are of interest.

COMPARISON TO PARAMETRIZED FIT ROUTINE SHOWS ADVANTAGES IN COMPLEXITY AND PERFORMANCE



Unfold results of a mix width measurement experiment (N190417) analyzed with a parametrized fit routine and with PEREGRINE compared to the respective simulated $\kappa\rho$ profile. In contrast to the parametrized fit, PEREGRINE is not limited to return profiles with a pre-determined shape and can calculate more realistic profiles.

NEXT STEPS

PEREGRINE will be applied to experimental data taken during previous campaigns to calculate the underlying mix widths with realistic error bars. Also, it will be used to study the impact of the various diagnostic and methodical effects to determine which parts of the experiment need to be improved most urgently.

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[1] G. N. Hall et al., Phys. Plasmas 31 / 022702 (2024)

[2] G. N. Hall et al., Rev. Sci. Instrum. 90, 013702 (2019)