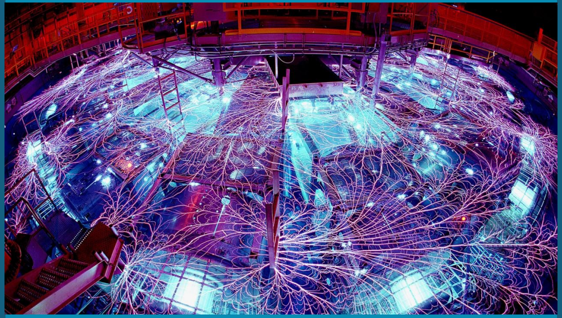
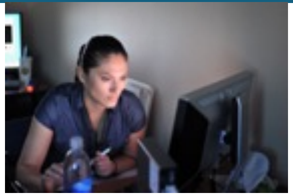
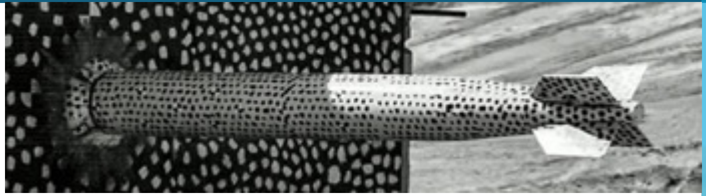
SAND2024-10203C

Mining magnetized liner inertial fusion data: trends in stagnation morphology







PRESENTED BY

W. Lewis, D. Yager-Elorriaga, C. Jennings, J. Fein, G. Shipley, A. Porwitzky, T. Awe, M. Gomez, E. Harding, A. Harvey-Thompson, P. Knapp, O. Mannion, D. Ruiz, M. Schaeuble, S. Slutz, M. Weis, J. Woolstrum, D. Ampleford, L. Shulenburger

ZFSW
August 2024

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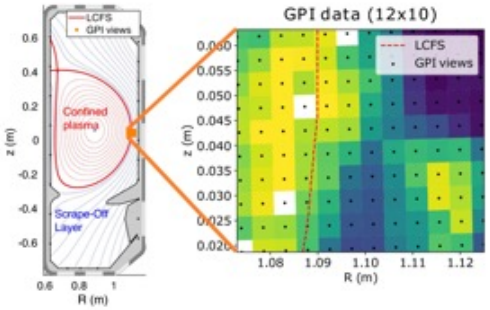
Identifying patterns in unstructured data is critical for a wide range of plasma and high energy density physics applications: the area is ripe for data-driven approaches.

"**<u>Unstructured data</u>** is information that either does not have a pre-defined data model or is not organized in a predefined manner."

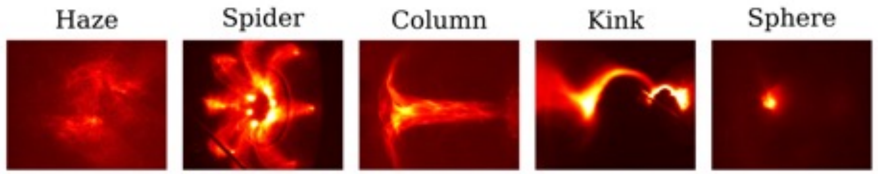
Examples include text documents, **images**, CAD files/drawings, audio, *etc*.

Tracking blobs in fusion plasmas at the Tokamak à Configuration Variable



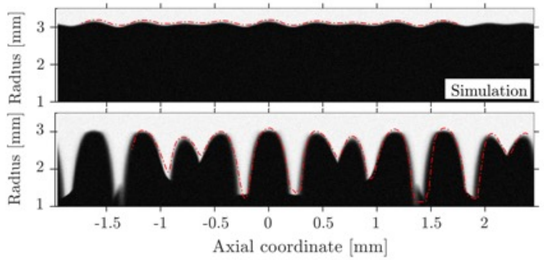
W. Han *et al.* Scientific Reports **12**, (2022).

Classification of Caltech Spheromak image data



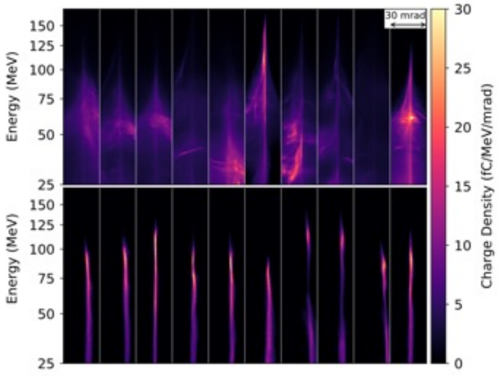
M.J. Falato *et al.* J. Plasma Phys. **88**, 895880603 (2022).

Characterizing instability growth in magneto-inertial fusion



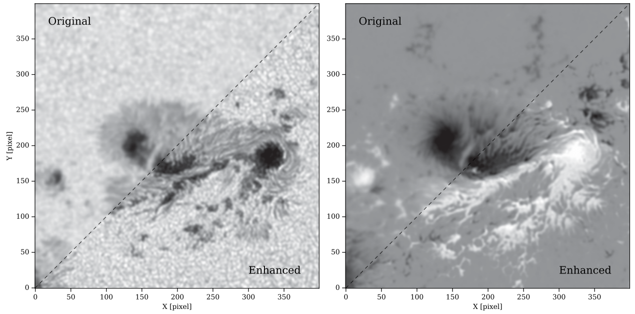
D.E Ruiz *et al.* Phys. Rev. Lett. **128**, 255001 (2022).

Automation and control of laser wakefield accelerators



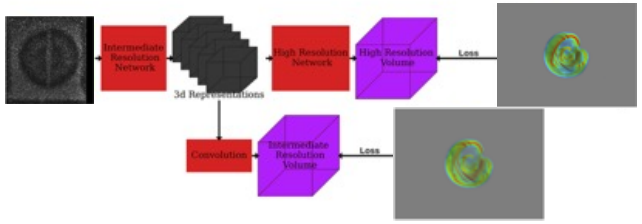
R.J. Shalloo *et al.* Nat. Comm. **11**, 6355 (2020).

Image enhancement of helioseismic and magnetic imager data



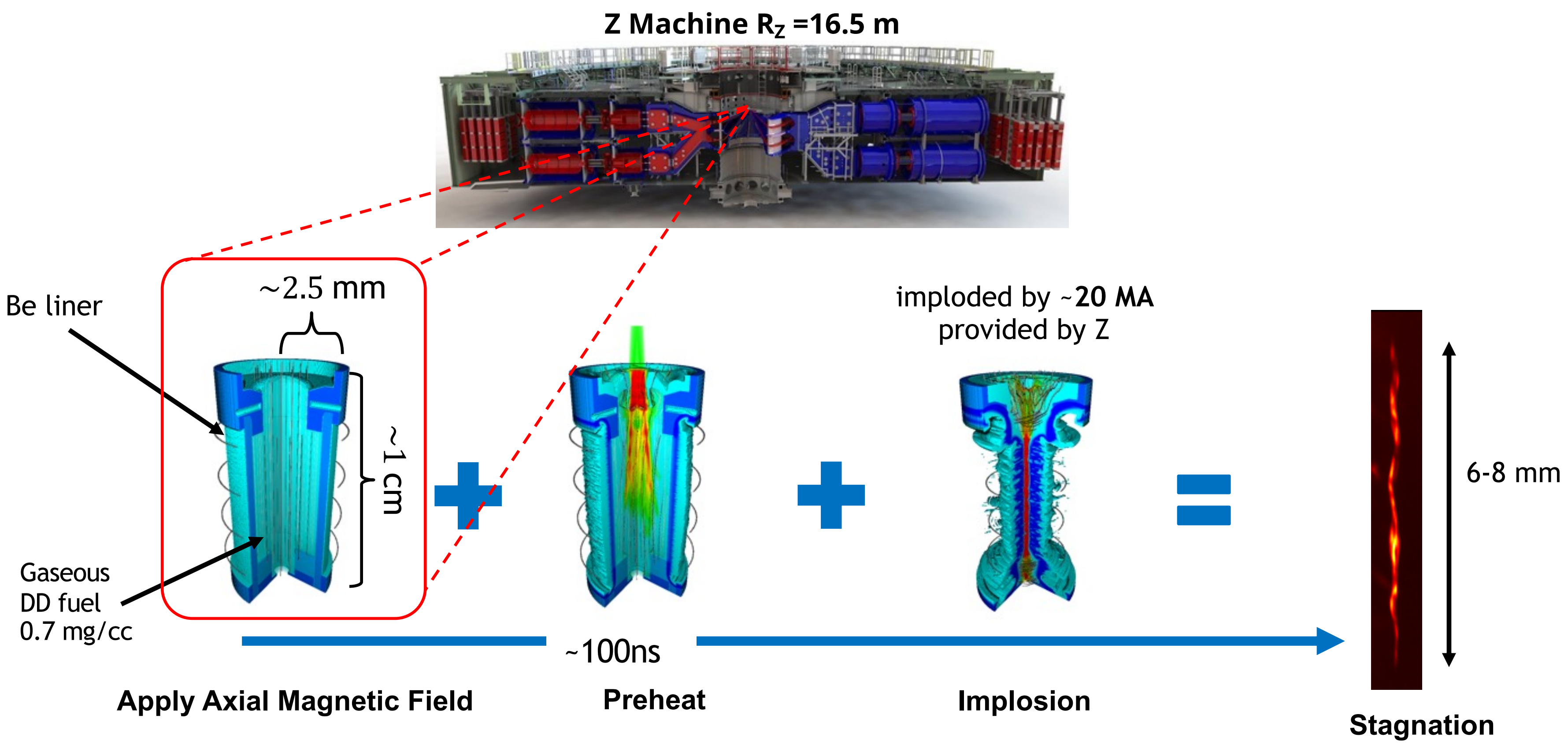
C.J. Díaz Baso and A. Aensio Ramos A &A. **614**, A5 (2018).

Sparse view tomographic reconstruction



B.T. Wolfe *et al.* Rev. Sci. Instrum. **94**, 023504 (2023).

The Magnetized Liner Inertial Fusion (MagLIF) concept fielded on Z relies on three key stages to achieve thermonuclear fusion.

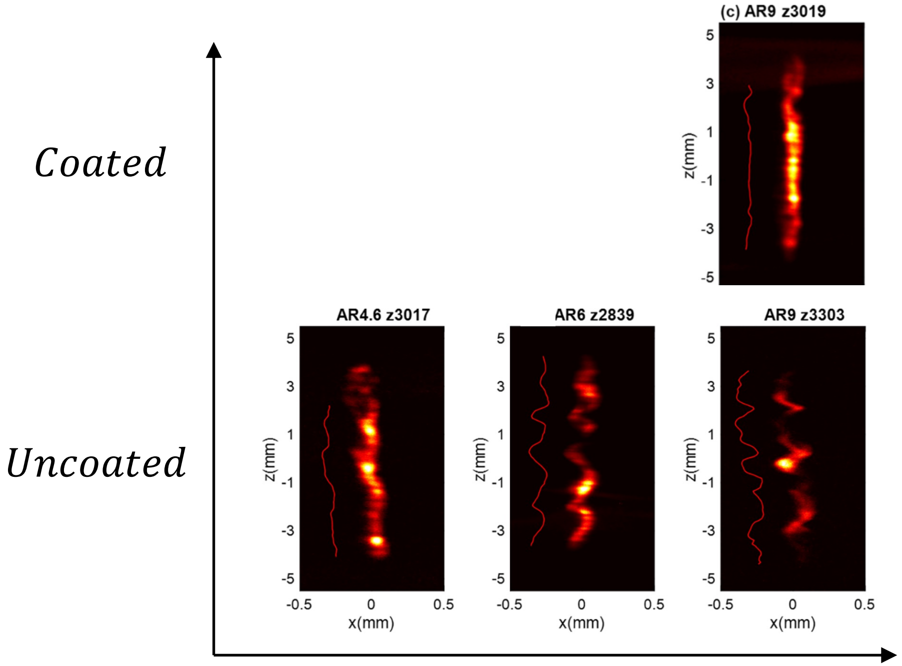


Self-emission x-ray images constitute one of several sources of unstructured data whose structure we may wish to characterize

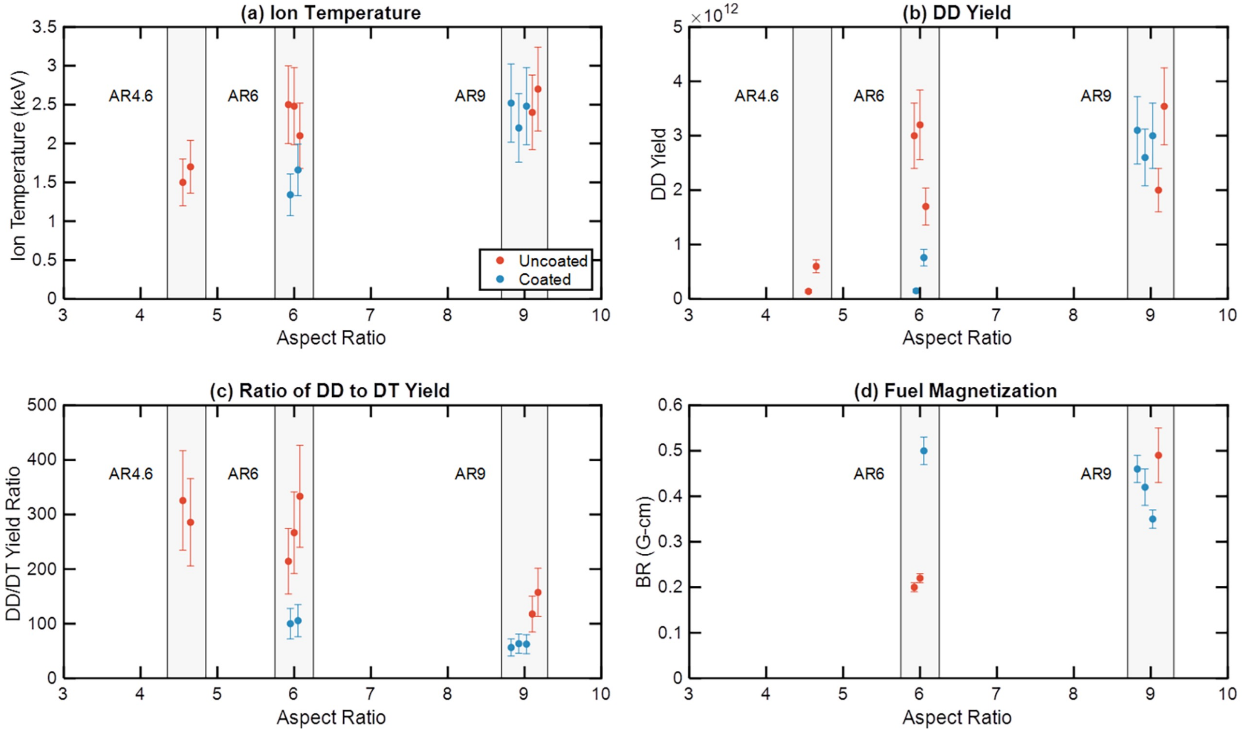
S.A. Slutz *et. al.*, Phys. Plasmas **17**, 056303 (2010).
M.R. Gomez *et al*. Phys. Rev. Lett. **113**, 155003 (2014).

Understanding patterns in stagnation image data from Magnetized Liner Inertial Fusion can contribute to understanding performance and reproducibility.

- Small scale studies have demonstrated the efficacy of mitigating instability growth and feedthrough via
  - liner aspect ratio
    - pro: thicker liner more robust to feedthrough
    - con: reduces implosion velocity
  - dielectric coatings
    - pro: mitigates electro-thermal instability growth thought to seed the magneto Rayleigh Taylor instability
    - con: challenging to model accurately

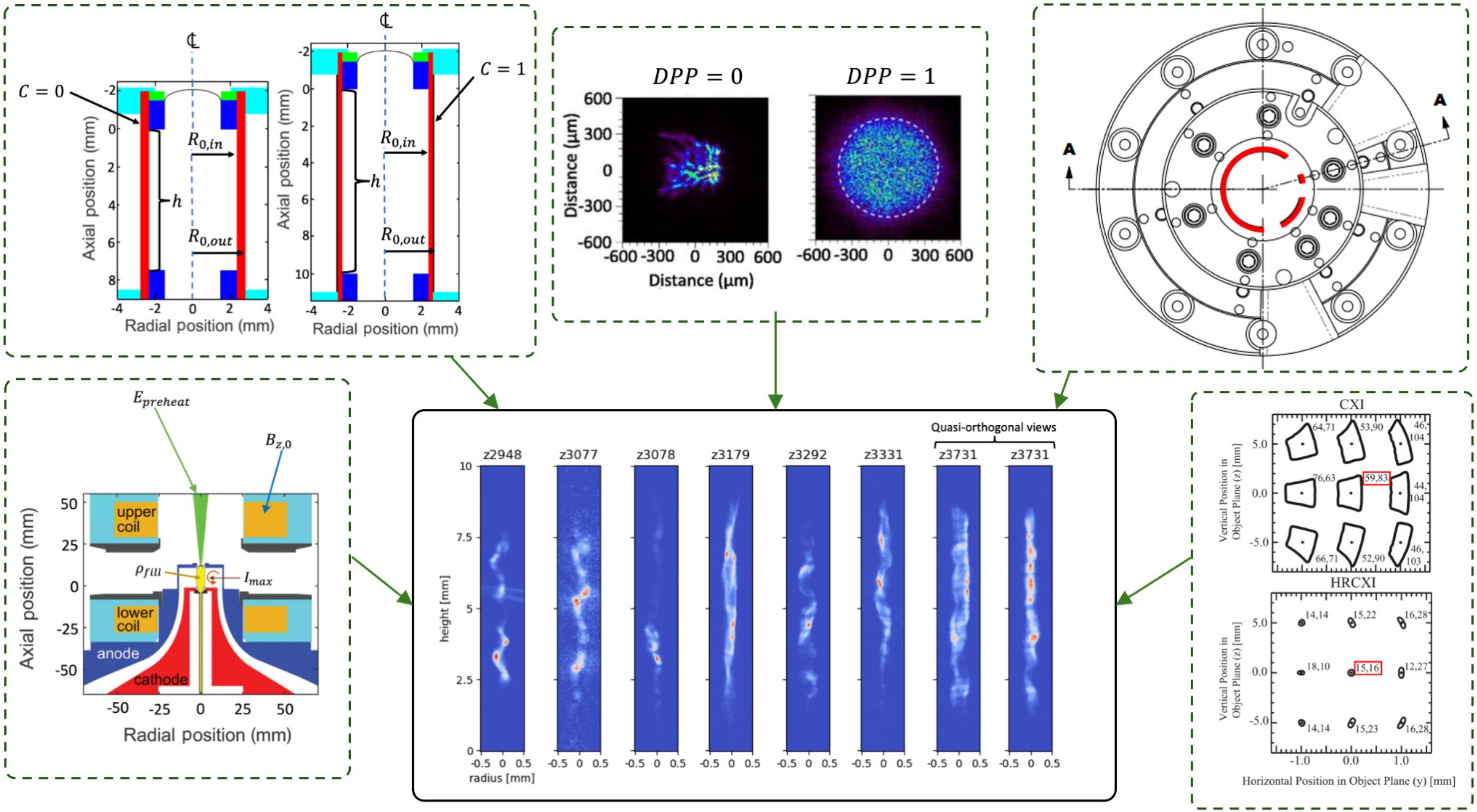


$$AR = \frac{R_{0,in}}{R_{0,out} - R_{0,in}}$$



D.J. Ampleford *et al.*, Phys. Plasmas **31**, 022703 (2024).

However, the design space of MagLIF is large and evolving with many opportunities to introduce/modify three-dimensional effects that could impact stagnation.



W.E. Lewis *et al.*, Phys. Plasmas (Accepted).

Experiments are rare and costly. Detailed exploration of existing data for new insights is of high value for guiding targeted future explorations.

To achieve this goal (aka my talk outline):

- Need ***reasonable*** down select and ***meaningful*** characterization of experimental inputs
  - should characterize unstructured data simply while preserving relevant information
    - note there is a trade-off of dimensionality with retained information

- Need ***meaningful*** metrics characterizing our images that build understanding
  - sensitivities to realities of experiment
    - (e.g. signal-to-noise, registration, imager configuration)
  - physics basis *i.e.* interpretable and/or statistically insightful

- Need ***statistical methods*** to explore data
  - investigate consistency between data and hypotheses
  - posit new hypotheses for further investigation

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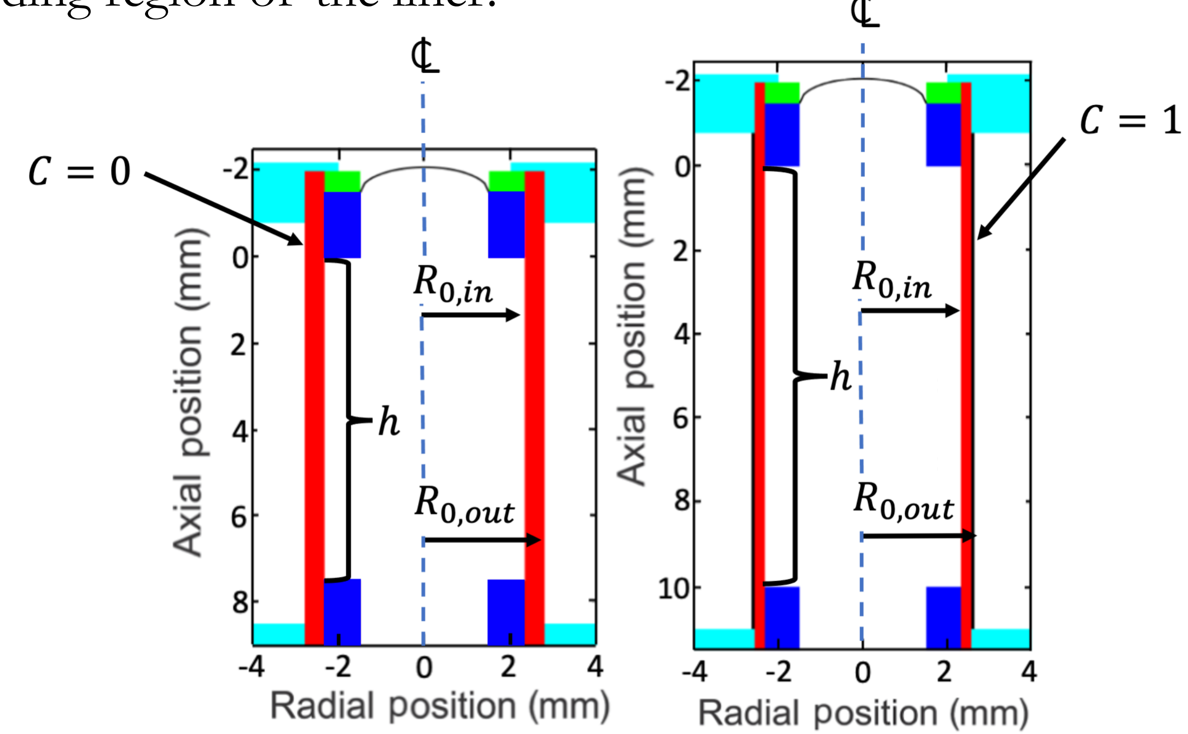
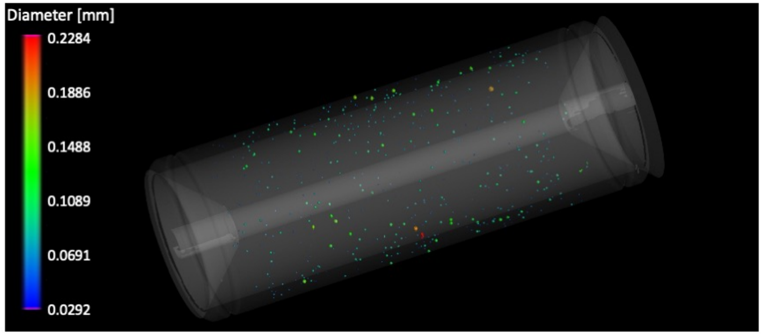
Some design parameters, such as geometric and material based **liner parameters** are relatively straightforward to capture via simple scalars.

- Liner parameters capture information about imploding region of the liner:
  - initial inner radius ($R_{0,in}$)
  - initial outer radius ($R_{0,out}$)
  - height (h)
  - presence of dielectric coating (C)



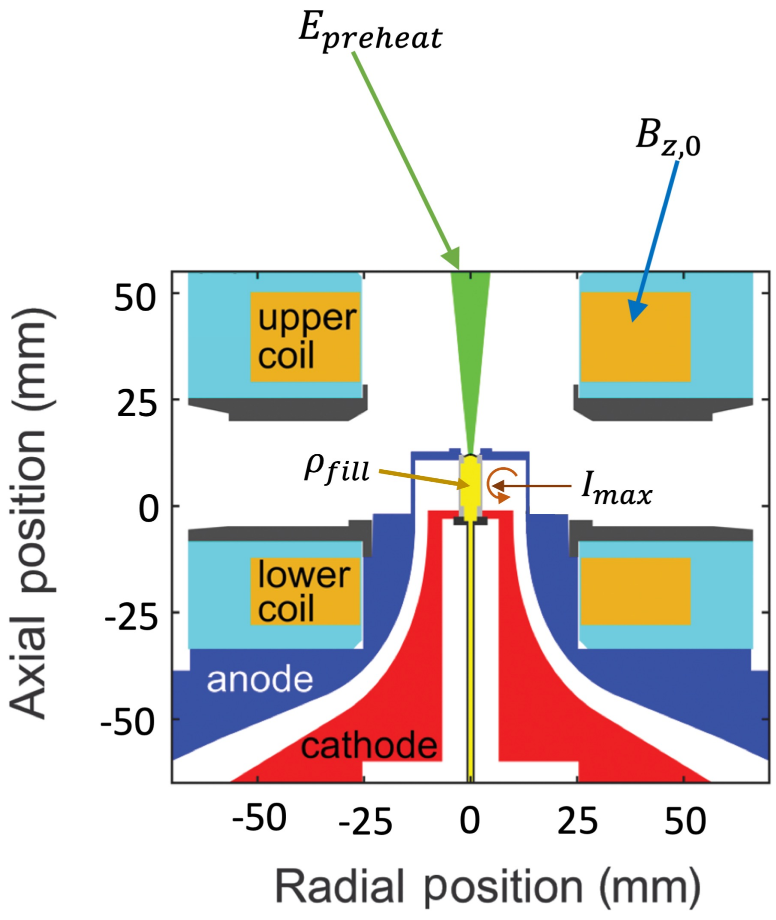
- May eventually include *quality* information
  - Limited by availability of data
    - e.g. target tomography is *becoming* standard



Some key physics parameters required for thermonuclear neutron production termed **integration parameters** are straightforward to capture via simple scalars.

- Integration parameters are associated with the three key phases needed to achieve thermonuclear conditions:
  - gas fill density (ρ_{fill})
  - laser energy deposited ($E_{preheat}$)
  - applied magnetic field strength (B_0)
  - peak current (I_{max})

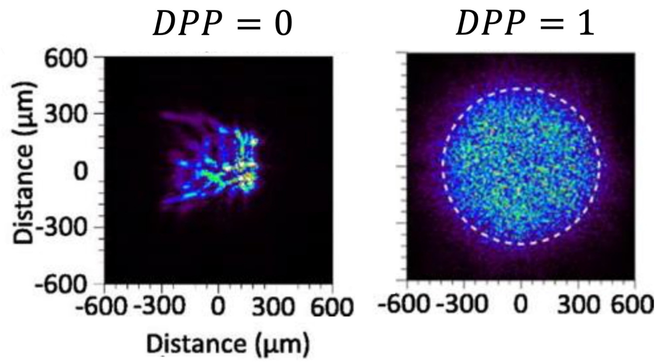
- Again we make certain choices/limitations:
  - e.g. field coil and feed geometry ignored
  - peak current inferred from velocimetry
    - not always available → imputation is required
    - current time history ignored
  - Choices may be considered as part of the processing
    - unstructured → structured data

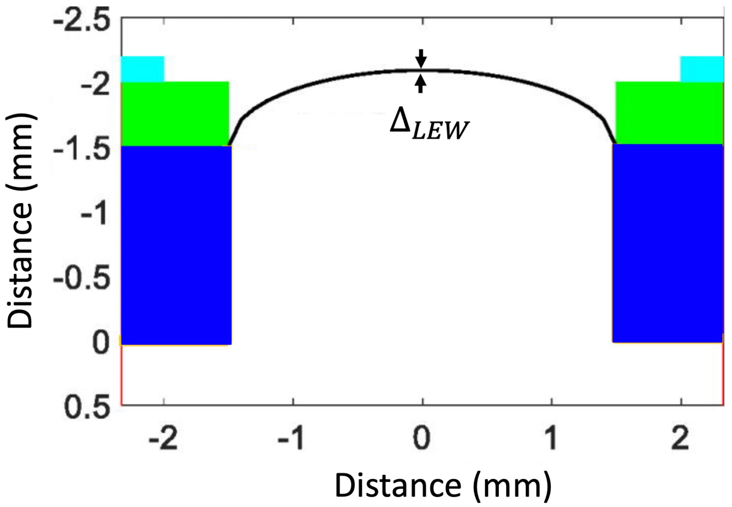


Some preheat **protocol parameters** characterizing *how* laser energy is delivered to the fuel may also be simply characterized.

- preheat protocol parameters are associated with how laser energy is deposited:
  - phase plate smoothing of the laser profile (DPP)
  - thickness of the laser entrance window (Δ_{LEW})

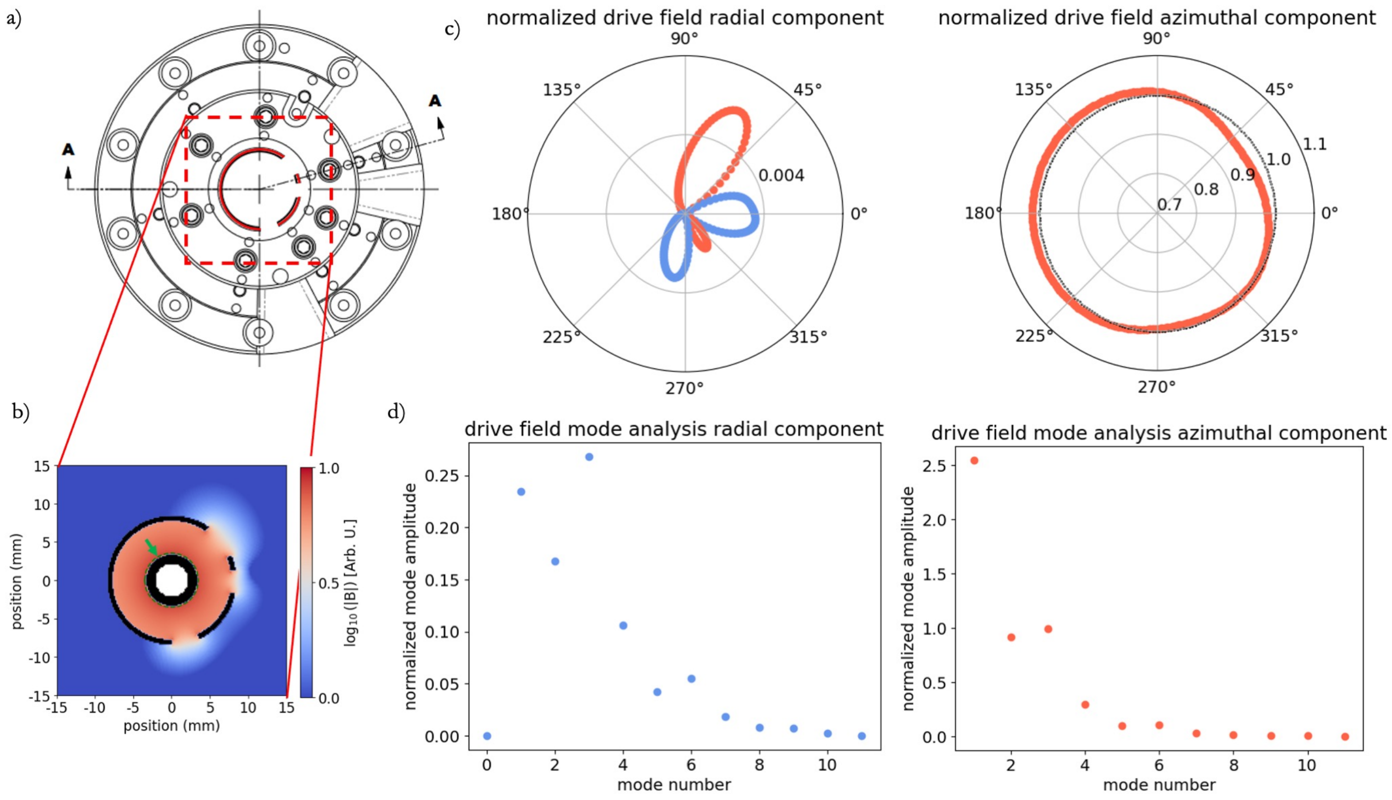
- Again we make certain choices/limitations:
  - detailed spatial profile ignored
  - temporal aspects ignored





Some magnetic drive **protocol parameters** characterizing *how* electrical energy is delivered to the target require more careful consideration.

- magnetic drive protocol parameters are associated with how electrical energy is delivered:
  - Wished to characterize potential for azimuthal asymmetry in drive with few parameters
    - radial component ignored in analysis due to small magnitude



Fourier modes of field at liner surface

$$B_{a(r)}(\phi) = \sum_{m=0}^{\infty} a_{m,a(r)} \cos(m\phi) + b_{m,a(r)} \sin(m\phi).$$

Strength of asymmetry by mode

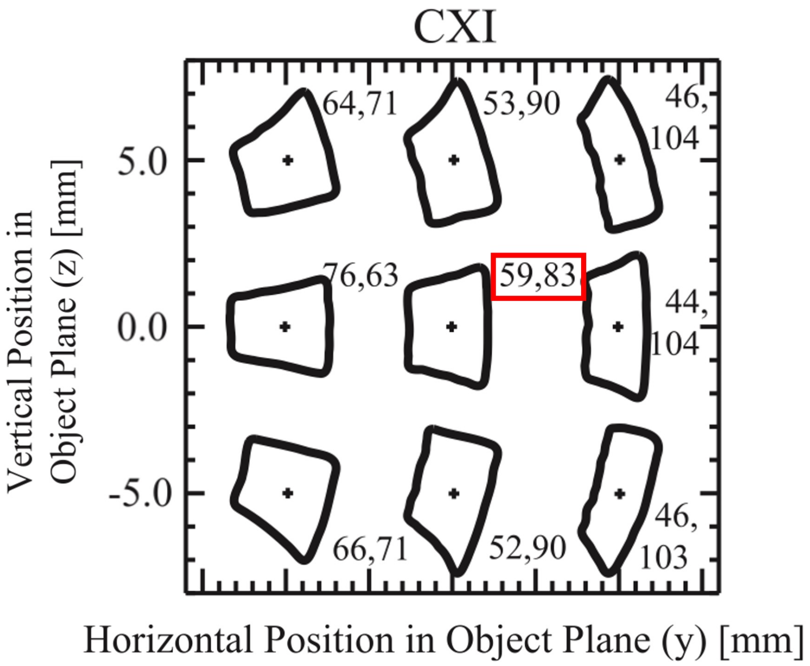
$$C_{m,a(r)} = \sqrt{a^2_{m,a(r)} + b^2_{m,a(r)}}$$

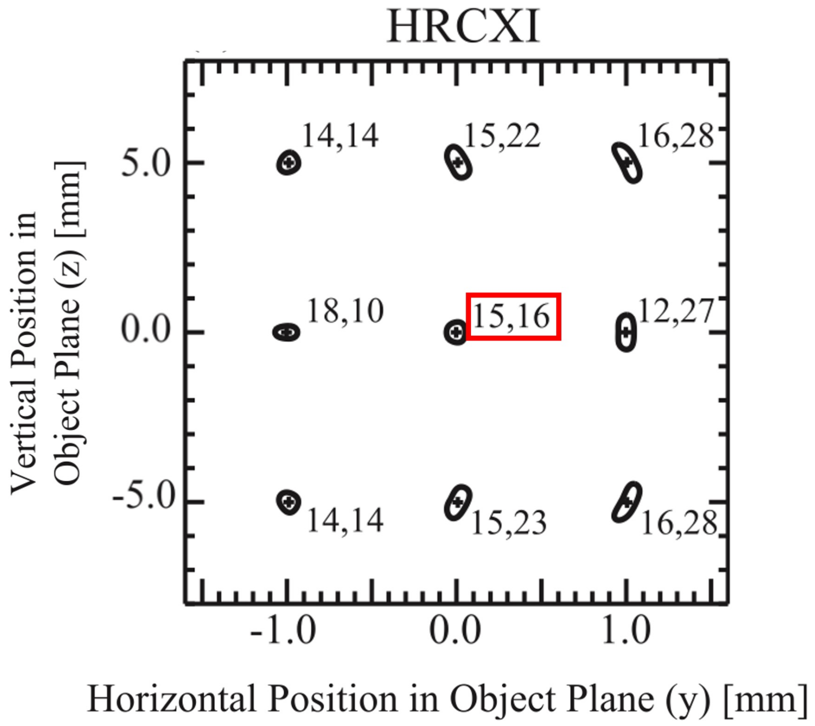
Amplitude of asymmetry along line of sight by mode

$$c_{m,a(r)}(\phi) = \frac{a_{m,a(r)} \cos(m\phi) + b_{m,a(r)} \sin(m\phi)}{C_{m,a(r)}}$$

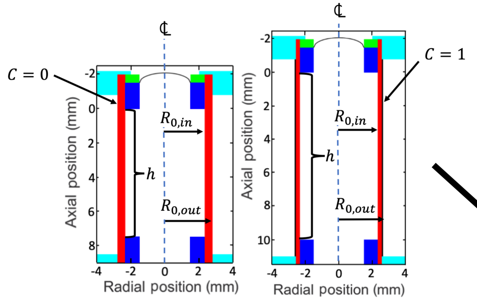
The means by which we collect self-emission from the fuel may also impact *apparent structure* and is captured via **diagnostic parameters.**

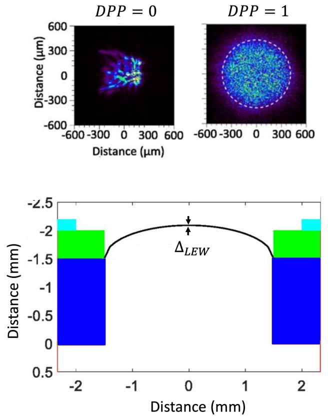
- Spherical crystal x-ray imagers have multiple configurations that change the spatial and spectral response
  - to first order, we expect spatial response can be characterized by a single resolution value
  - spectral response is challenging
    - focus on imagers that consider a spectrally narrow portion of continuum



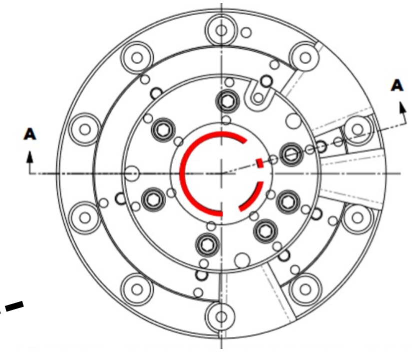


In summary, a variety of structured and unstructured data have been processed into lower dimensional reasonably interpretable form amenable to exploration.





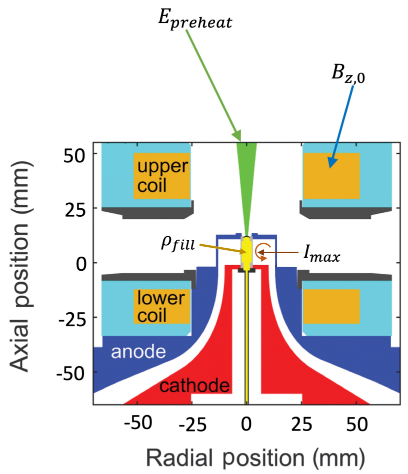
current return can structure



drive asymmetry modes

$C_{m,a(r)}$

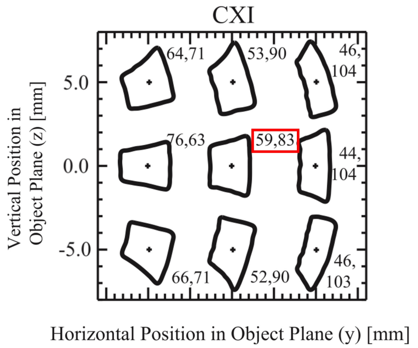
$c_{m,a(r)}(\phi)$



point spread function

resolution at center of object plane

59,83



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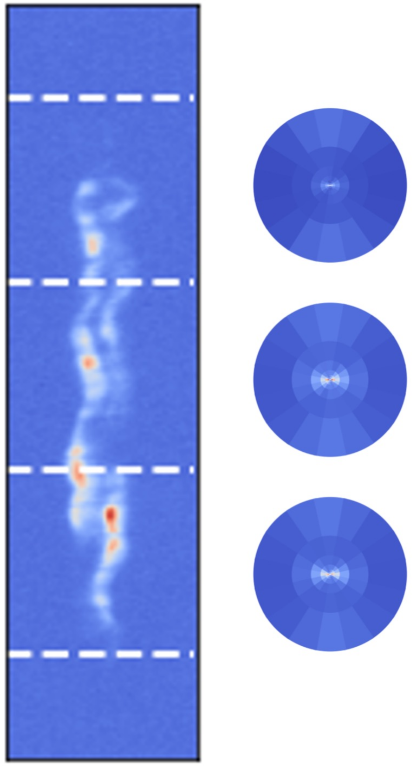
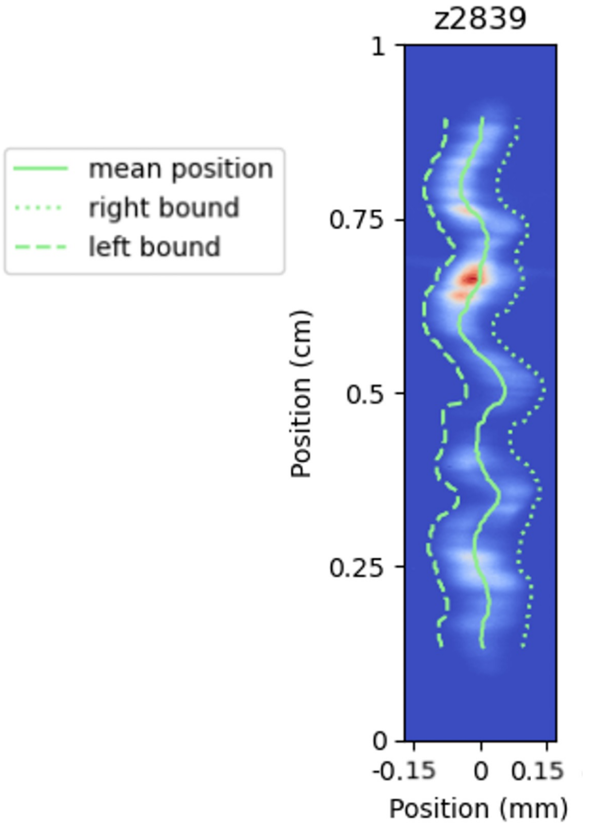
Characterizing the rich *morphology* of the stagnation column produced in MagLIF implosions requires a task dependent balance of interpretability and detail.

Wavelet based image metrics are great for whole-image comparison or classification tasks



Like Fourier transforms, they may not be highly sparse, and can challenge interpretability.

Metrics such as average strand width are interpretable and easier to connect with physics.



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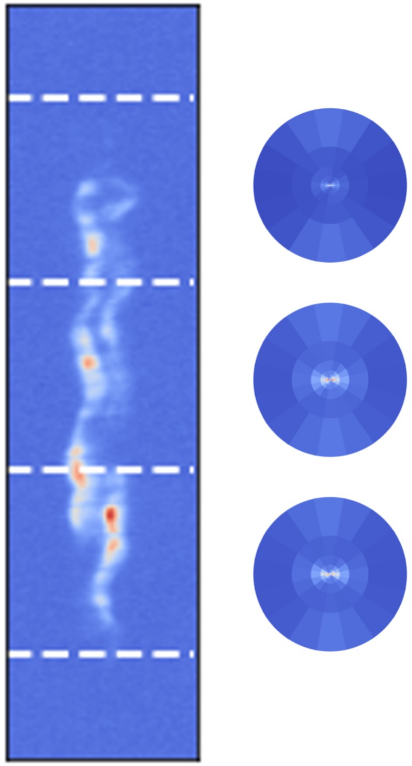

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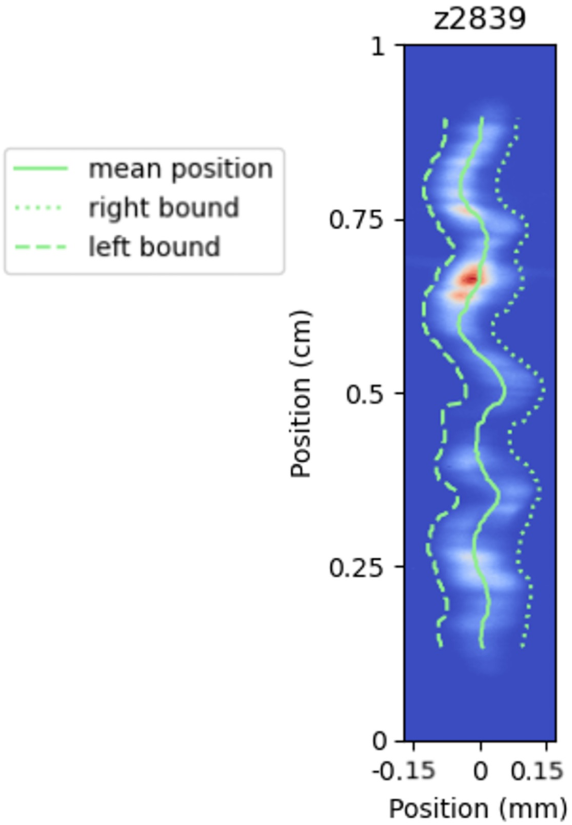
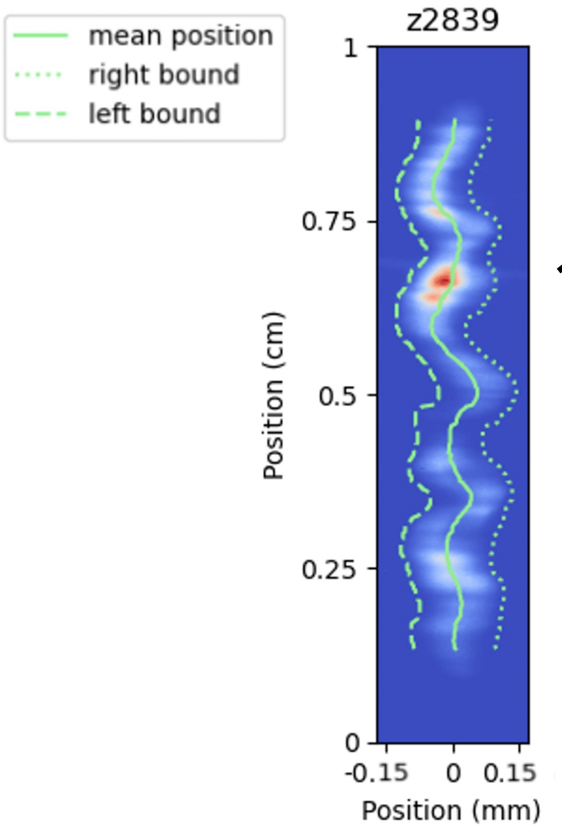


The drastic reduction of information may result in missing important or interesting relationships.

In opting for simpler representations, will seek to better understand how experiment inputs correlate with certain types of instability structure independent of brightness.

mean position

$$s(z) = (s_r(z) + s_\ell(z))/2.$$



Kink-like structure

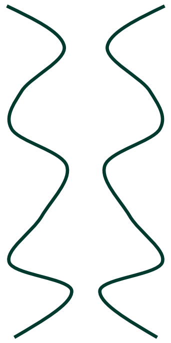
$$E_s = \frac{1}{\mathcal{S}} \int_0^\infty |f(k)|^2 dk$$

$$f(k) = \int_{\mathcal{S}} s(z) e^{-ikz} dz,$$

Sausage-like structure

$$CR(z) = \frac{R_{0,\text{in}}}{(s_r(z) - s_\ell(z))/2}$$

$$\sigma CR = \sqrt{\frac{1}{\mathcal{S}} \int_{\mathcal{S}} (CR(z) - \overline{CR})^2 dz},$$



Average compression

$$CR(z) = \frac{R_{0,\text{in}}}{(s_r(z) - s_\ell(z))/2}$$

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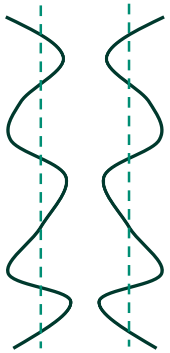

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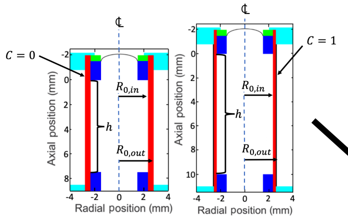

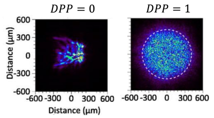

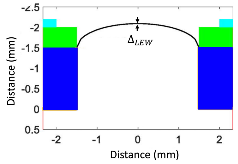

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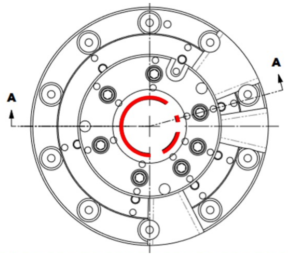

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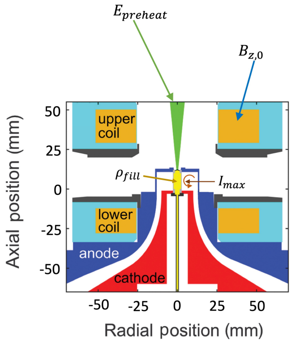

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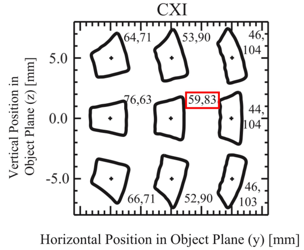

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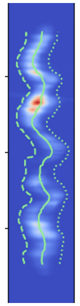

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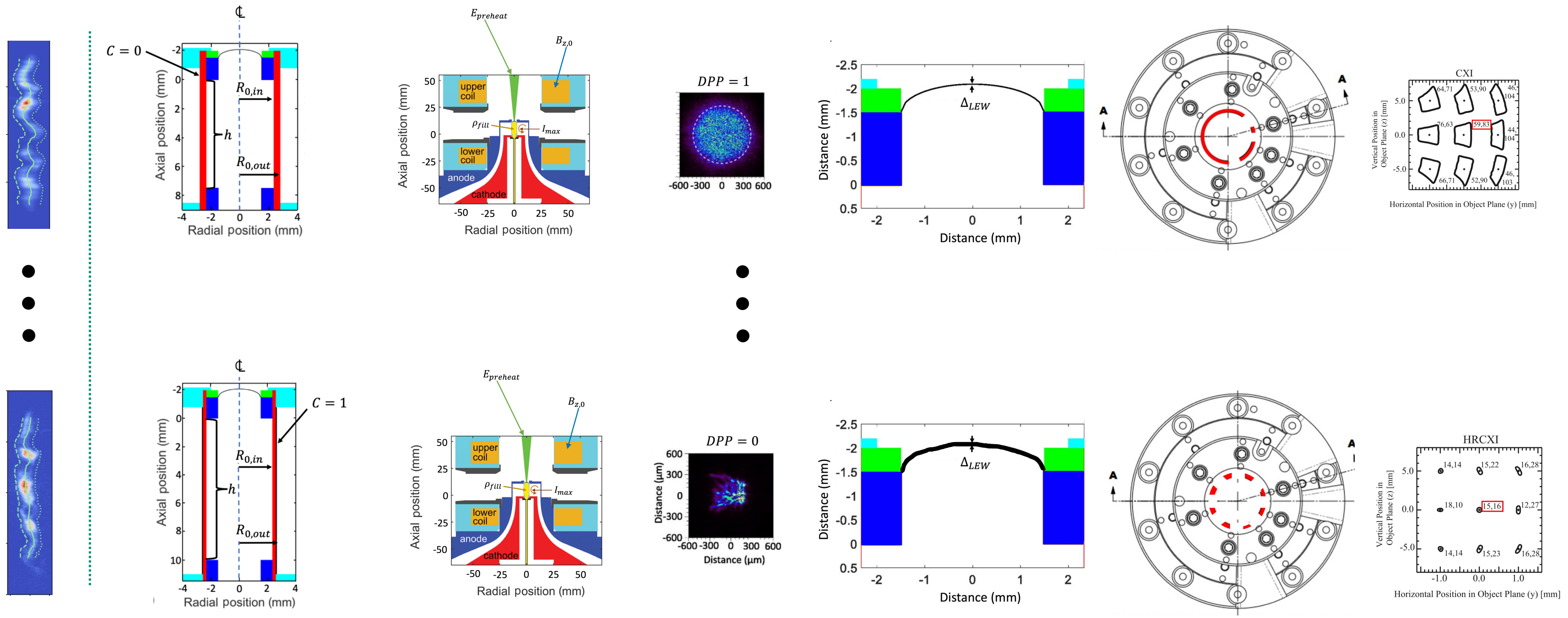
When estimating the association between variables, linear regression analysis is perhaps the most common and basic starting point.



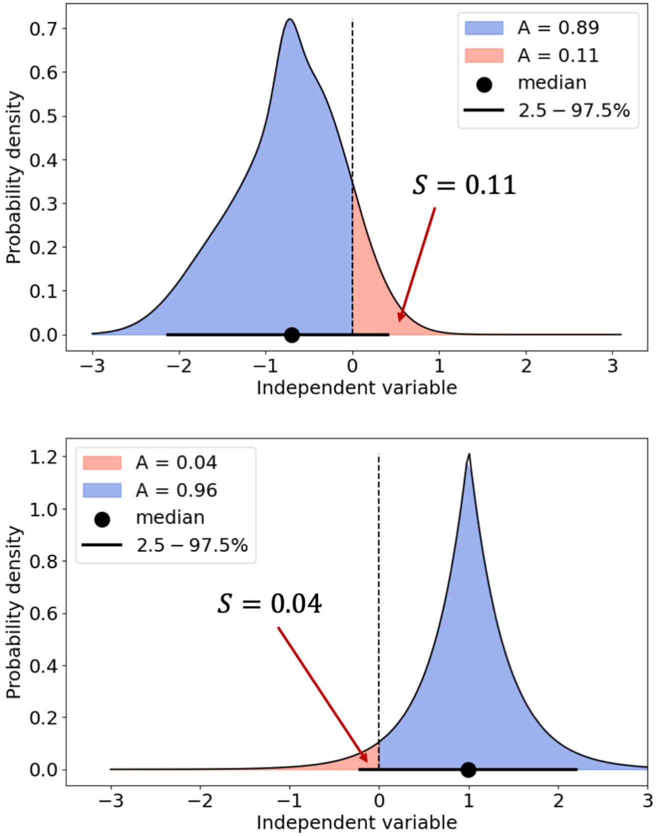
$$Y = AX + b + \epsilon$$

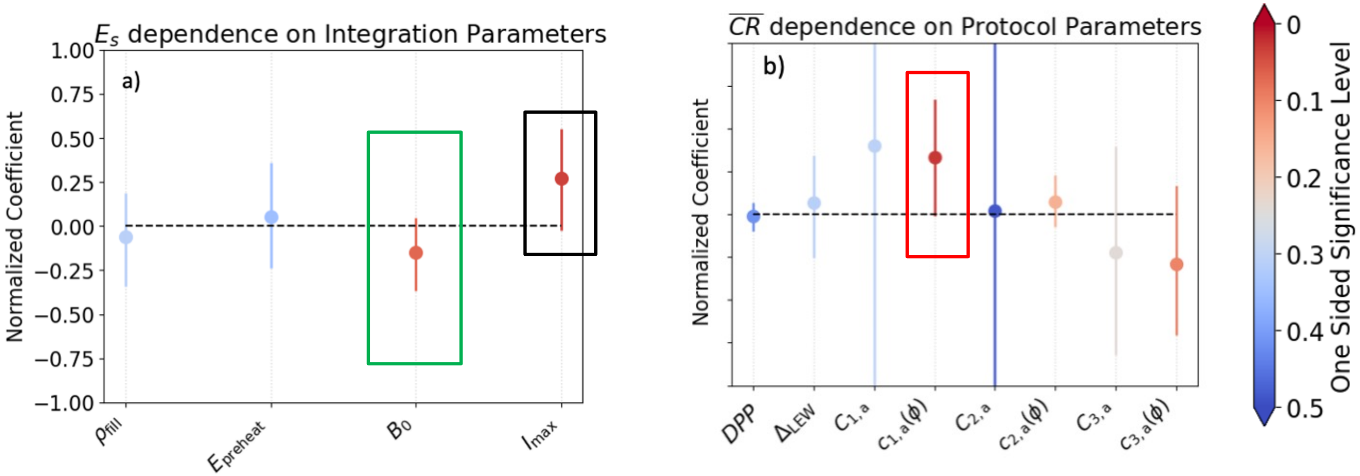
Each coefficient in this vector will measure the linear correlation between an input and the morphology parameter under consideration.

Performing Bayesian regression gives the full posterior distribution for these coefficients allowing for assessment of uncertainty and correlation structure.

- There are 18 input parameters and 3 different image features resulting in 54 different coefficients
  - I won't attempt to cover them all here
  - Note that all inputs and outputs were min-max scaled to [0,1]

Significance level and error bars





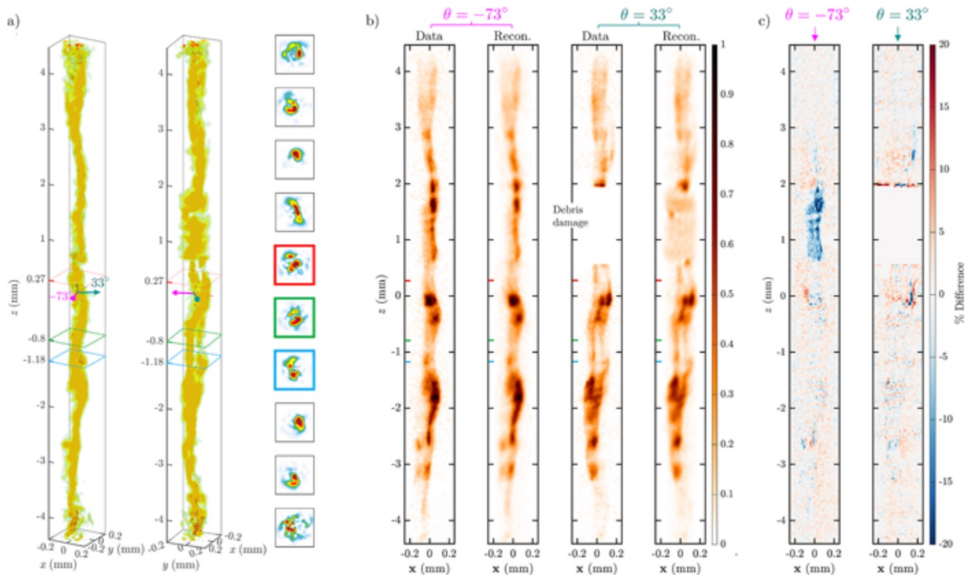
First evidence for (kink) stabilizing effect of magnetic field in integrated MagLIF experiments

Expected behavior of kink structure with peak current

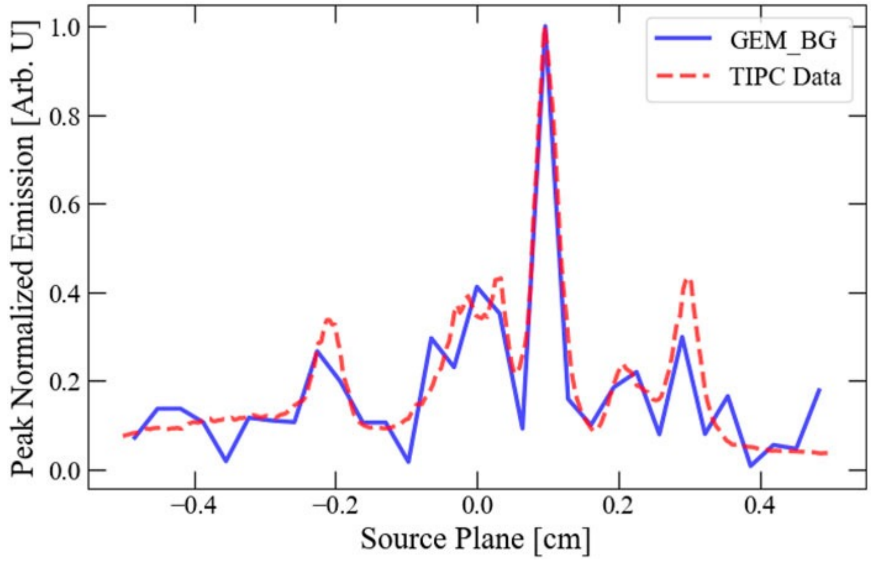
Evidence for robust effect of asymmetric current return can on convergence with respect to view angle

By performing simultaneous analysis of all available MagLIF data, we can search for correlations for which no experiments were explicitly designed to test.

- Get the benefit of utilizing all available data which may resolve previously unexpected effects
  - Largest morphology study to date
    - uncovers a number of surprising null results (e.g. inner and outer radii don't show expected correlation with CR)
- Linear regression analysis is quite general and may now be carried out across a variety of MagLIF observables
  - Looking to apply to a variety of other morphology metrics and diagnostics and platforms as data become available
    - 3D reconstruction metrics, one-dimensional neutron images, x-ray spectra, etc.



J.R. Fein *et al.*, J. Appl. Phys. **135**, 133301 (2024).



S. Ricketts *et al.*, Rev. Sci. Instrum. **95**, 033501 (2024).

Questions/Comments?