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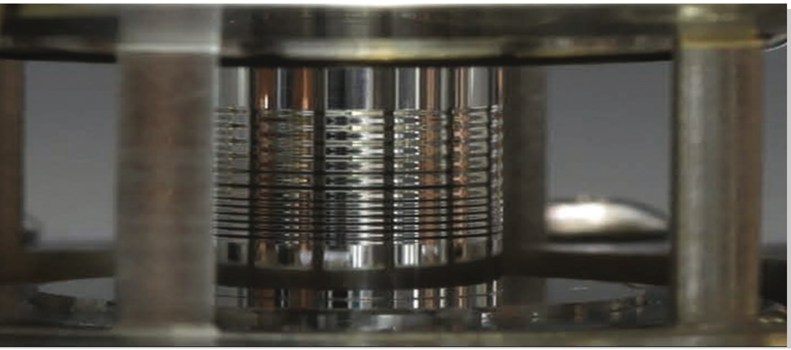

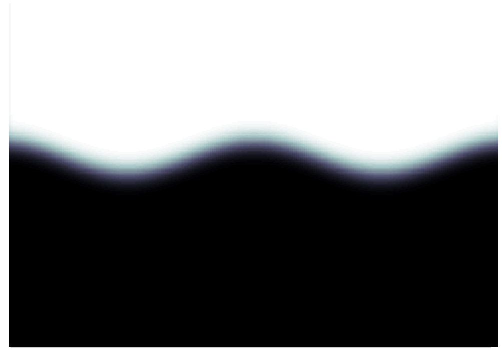

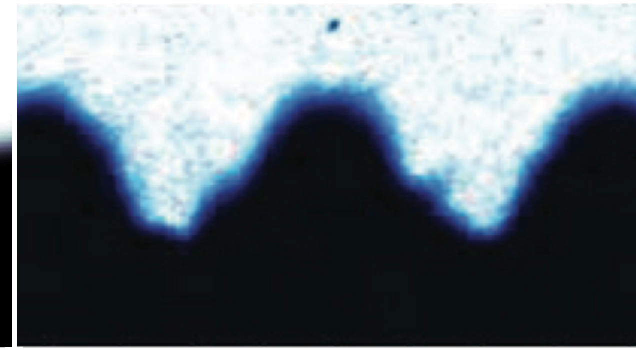

Magneto-Rayleigh-Taylor growth and feedthrough in cylindrical liners

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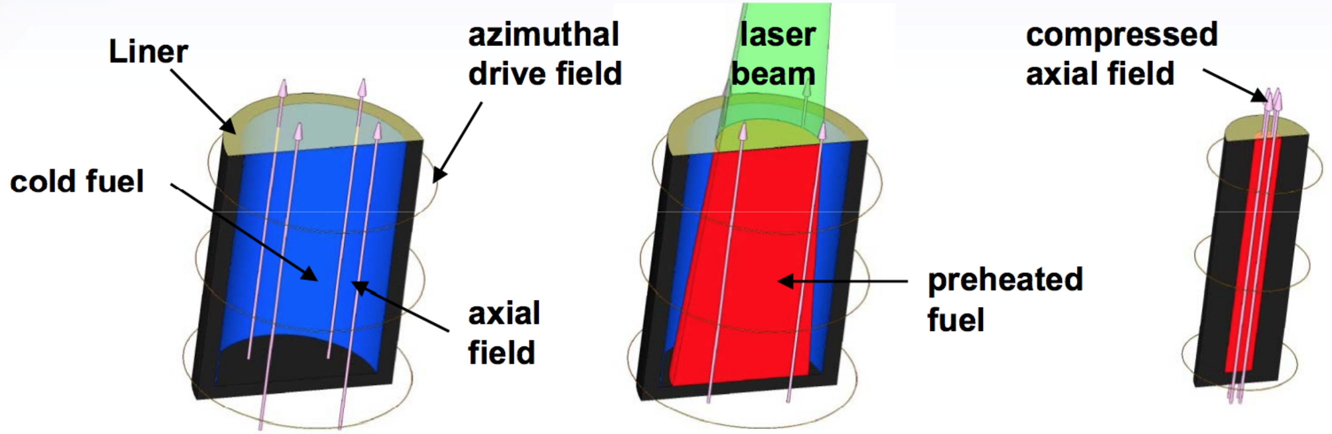
Motivation

- MRT is one of the greatest challenges to success of the Magnetized Liner Inertial Fusion (MagLIF) concept
  - Magnetic fields introduce additional complexity over classical RTI
- Feedthrough has an important role in the stability of the fuel/liner interface in MagLIF concept
  - Also relevant to dynamic materials experiments on Z
- Analytic results provide a fast way to analyze these problems
- Hydra, a rad-hydro-MHD code, provides another tool for modeling experiments on Z and other HEDP platforms
  - Needs benchmarking

Goal: apply these tools to a liner implosion and compare to experimental results

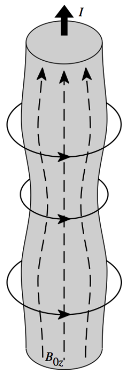
Magnetized Liner Inertial Fusion (MagLIF)*,** may be a promising path to high yields on Z, but liner integrity is critical

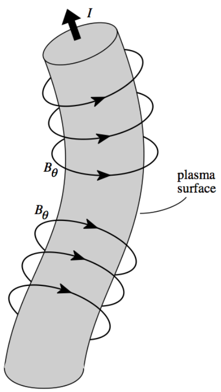


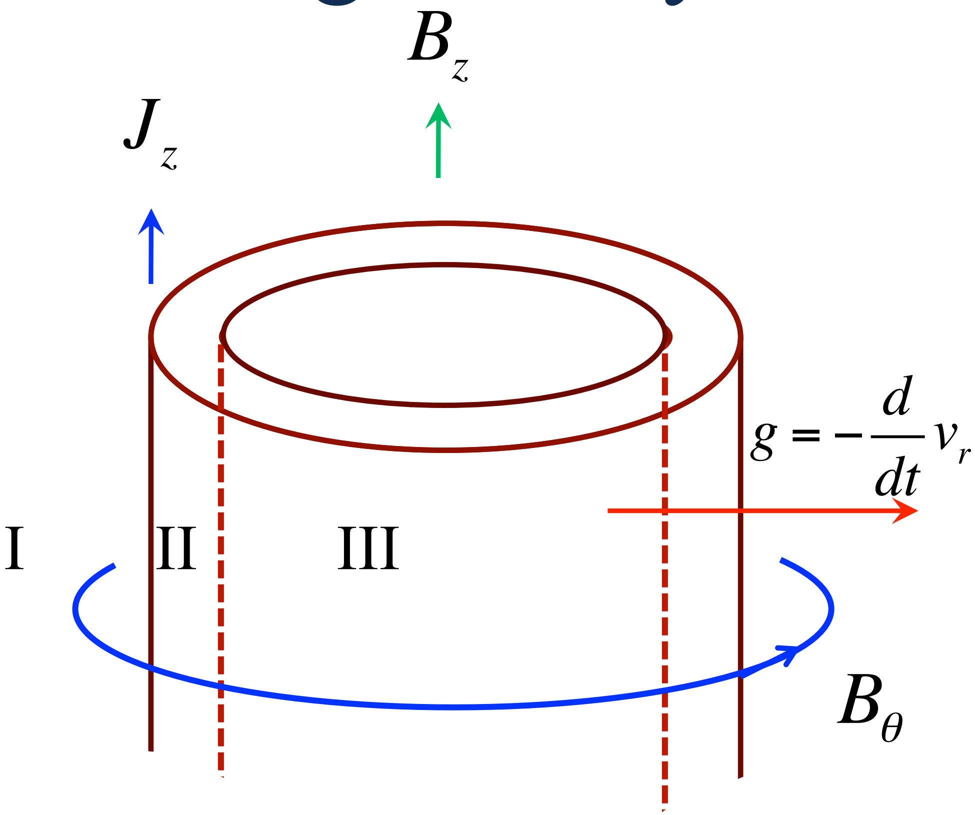
- Initial calculations suggest Z-Beamlet laser can do the preheat
  - Preheating the fuel reduces the required compression ratio to obtain ignition temperatures to about 30 on Z
  - Preheating reduces the implosion velocity needed to about 5-10 cm/μs
- Axial magnetic field strength required (about 5-10 T) feasible
  - Similar coil design parameters to coils for dynamic materials tests
- Simulations suggest 100 kJ yields on Z are possible
- Success of MagLIF hinges on <u>maintaining sufficient liner integrity</u>

* S. A. Slutz *et al.*, "Pulsed power driven cylindrical liner implosions with magnetized and preheated fuel", Phys. Plasmas **17** 056303 (2010).

Cylindrical geometry instabilities







g > 0: Implosion

g < 0: Stagnation

g = effective gravity in rest frame of interface

MRT (acceleration)

Sausage / m=0

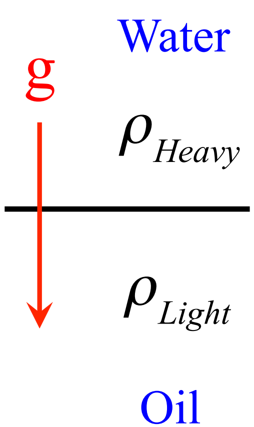
Kink / m=1

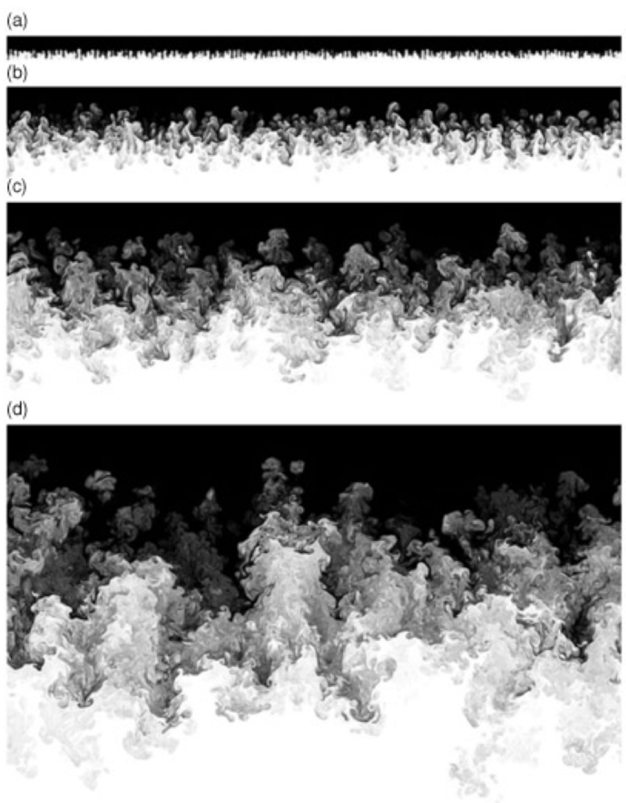
(present with no acceleration in a cylindrical current carrying plasma)

Rayleigh-Taylor Instability (RTI)

- Interchange instability from a light fluid pushing a heavy fluid
  - Water on top of oil in Earth's gravity
  - Deep water waters are the stable form of RTI (water supporting air)

Instability arises for: $\nabla p \cdot \nabla \rho < 0$





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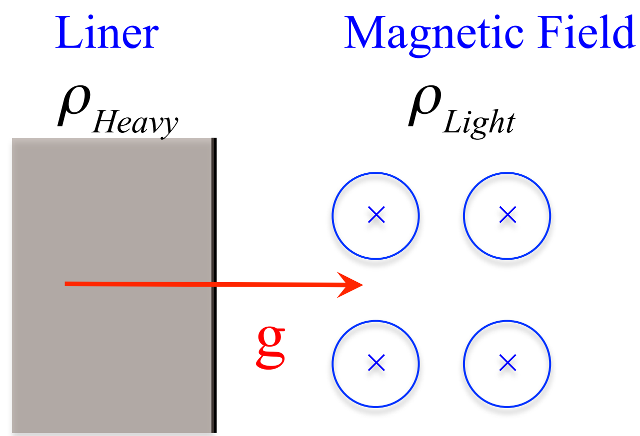
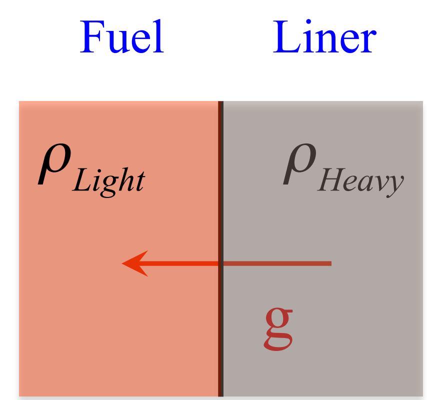




* LLNL ST & R Dec. 2004

Model equations

Mass Conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Momentum Conservation:

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = -\nabla p + \mathbf{J} \times \mathbf{B} + \rho \mathbf{g}$$

Ampere's Law:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

Faraday/Ohm Law:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Perturbation of equilibrium

We assume that the time scale for perturbation growth is fast compared to liner dynamics, yielding an approx. instantaneous equilibrium:

$$\frac{dp}{dr} + \frac{1}{\mu_0}\left[B_z \frac{dB_z}{dr} + \frac{B_\theta}{r}\frac{d}{dr}\left(rB_\theta\right)\right] = \rho g$$

We perturb this equilibrium by a small displacement of the form:

$$\vec{\xi}(\vec{r},t) = \left\langle \xi_r(r), \xi_\theta(r), \xi_z(r) \right\rangle e^{\gamma t + ikz + im\theta}$$

We assume that the perturbed velocity is incompressible:

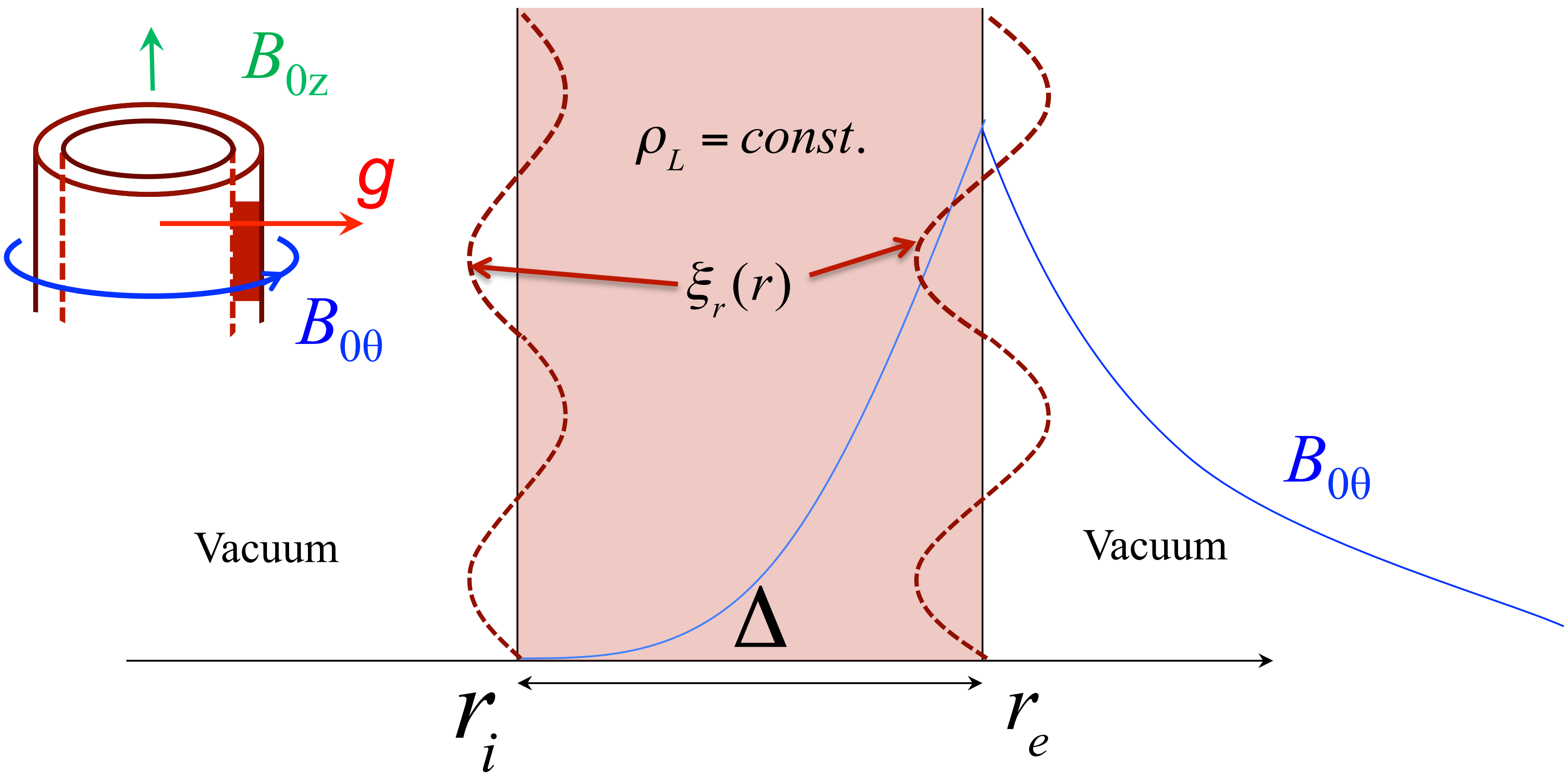
$$\nabla \cdot \frac{\partial \vec{\xi}}{\partial t} = \nabla \cdot \vec{\xi} = 0$$

The growth rate, ω, is of the form:

$$\gamma^2 \approx kg - \frac{\left(\mathbf{k}\cdot\mathbf{B}\right)^2}{\mu_0 \rho} + C(m,\mathbf{k})$$

Where C includes the effects of azimuthal and current carrying modes

Sharp boundary model



Aspect ratio:

$$AR = \frac{r_e}{r_e - r_i} = \frac{r_e}{\Delta}$$

The *feedthrough* of instability from the outer to inner surface for a given mode, ω, is defined as:

$$\xi_r(r_i) / \xi_r(r_e) \equiv F(\omega)$$

Thus we solve the linearized the ideal MHD equations:

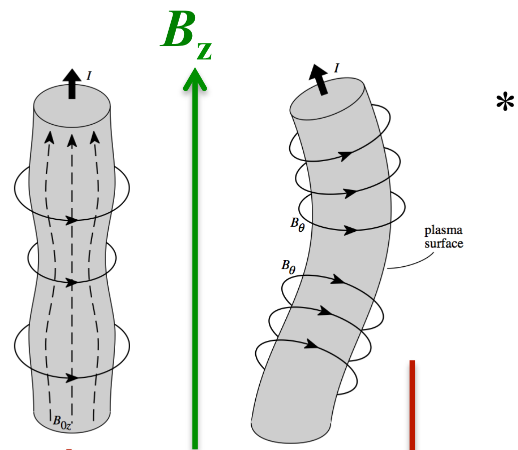
$$\rho \frac{\partial^2 \vec{\xi}}{\partial t^2} = -\nabla p_1 + \vec{J_0} \times \vec{B_1} + \vec{J_1} \times \vec{B_0} + \rho \vec{g} \cdot \vec{\xi}$$

$$= -\nabla p_1 + (\nabla \times \vec{B_0}) \times [\nabla \times (\vec{\xi} \times \vec{B_0})]/\mu_0 + \{\nabla \times [\nabla \times (\vec{\xi} \times \vec{B_0})] \times \vec{B_0}\}/\mu_0 + \rho \vec{g} \cdot \vec{\xi}$$

- Subject to the boundary conditions of continuity of total pressure at each interface, which is an eigenvalue problem for the eigenfunction, ξ, and eigenvalue, ω
- The solution is analytically tractable for:
  - Constant density profiles (may be different in each region)
  - Constant Bz profiles (may be different in each region)
  - No magnetic diffusion of drive field
- Otherwise the problem is solved numerically using a shooting method

Sausage and kink modes are successfully recovered

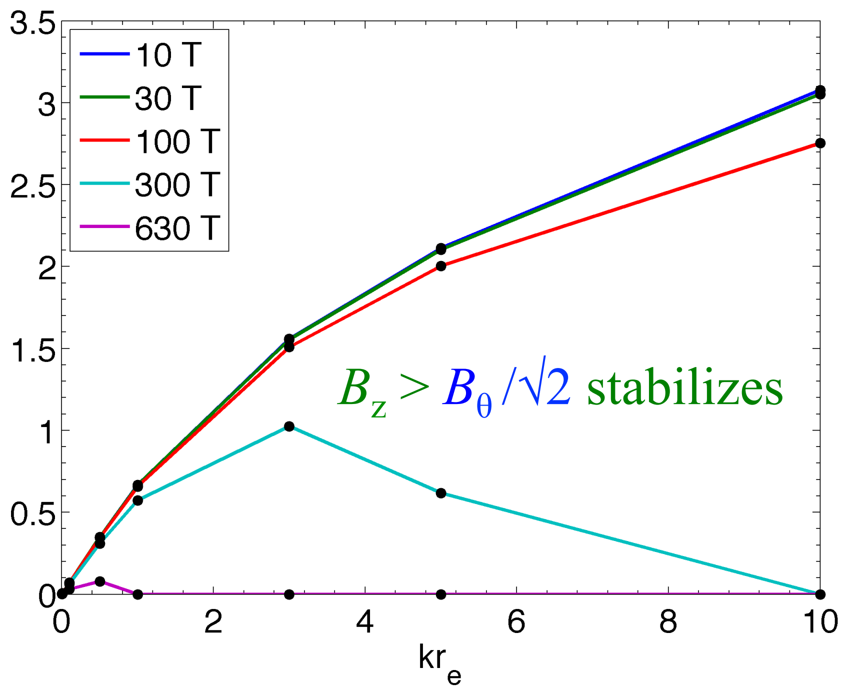
- For **g = 0** and AR = 1 (solid plasma column undergoing no acceleration) give well known test problem

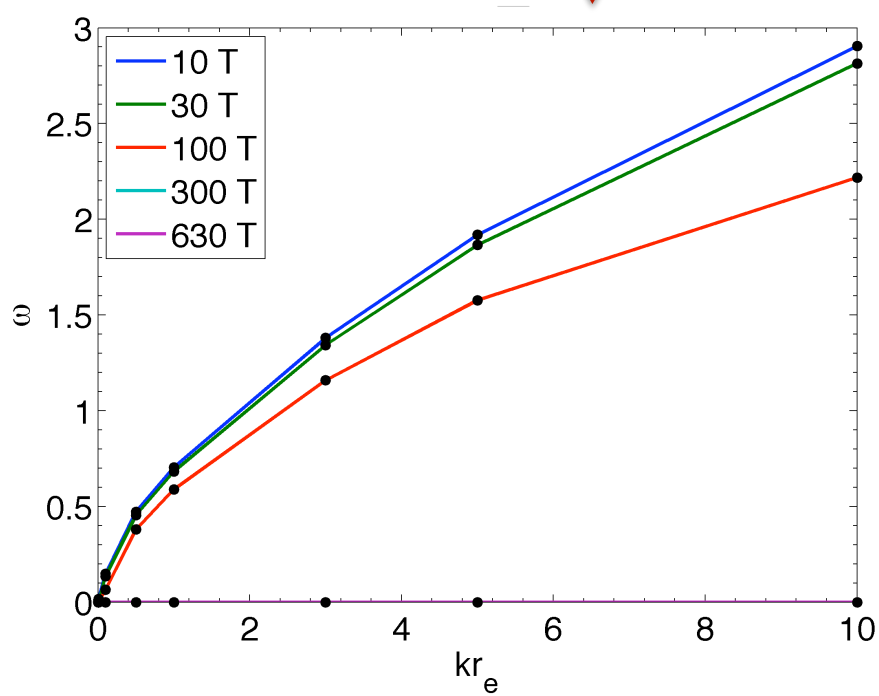


B_θ=1000 T

m = 0

m = 1





* Boyd and Sanderson. *The Physics of Plasmas*, Cambridge Press, 2003

AR = 6 liners show stabilization with Bz as well

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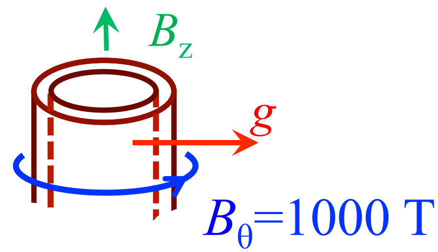
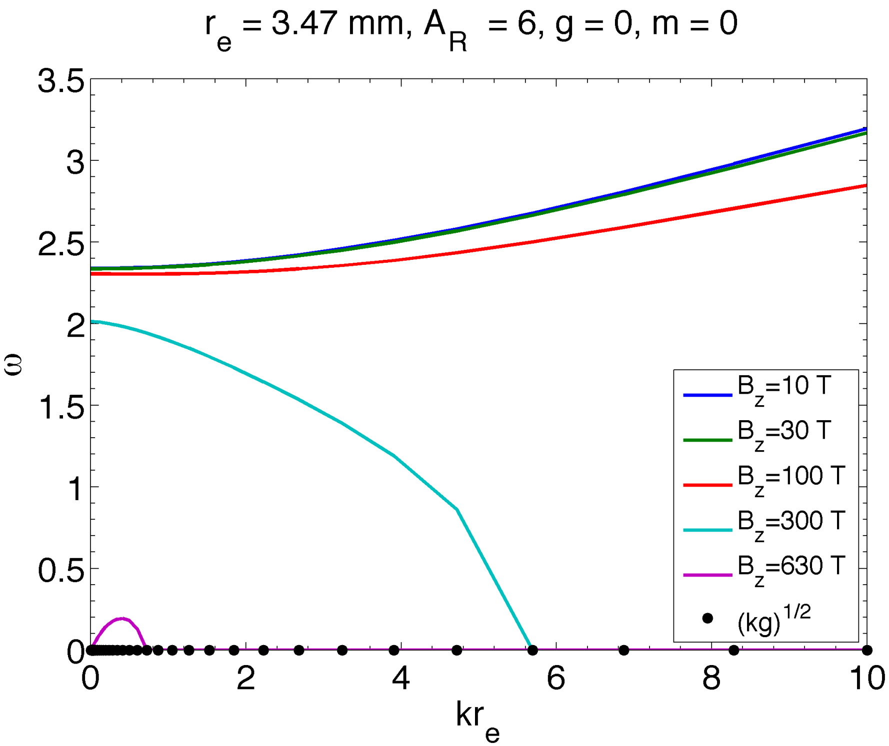
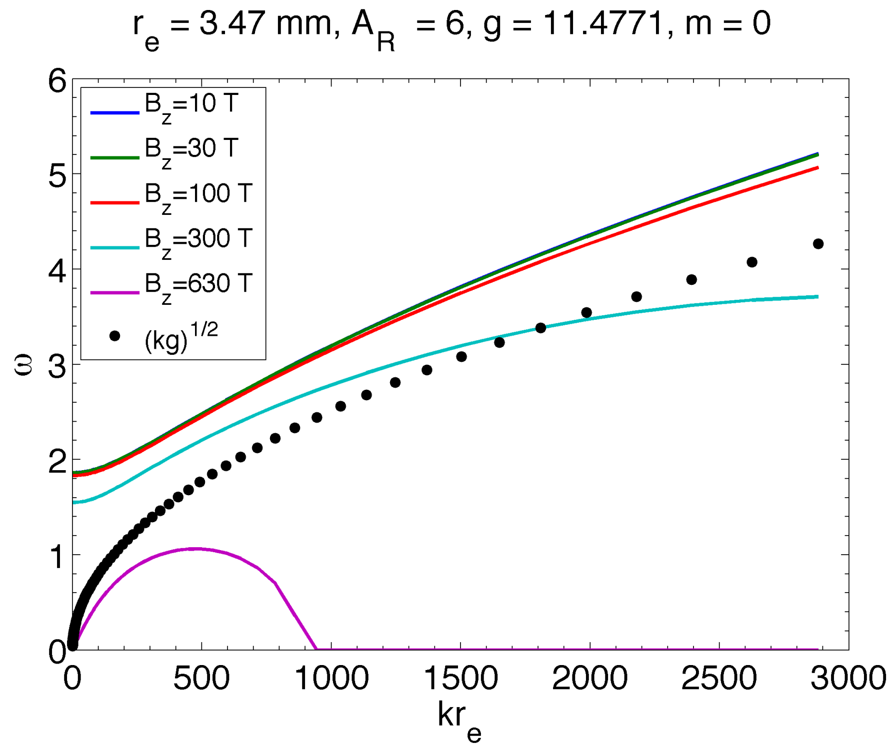


No acceleration

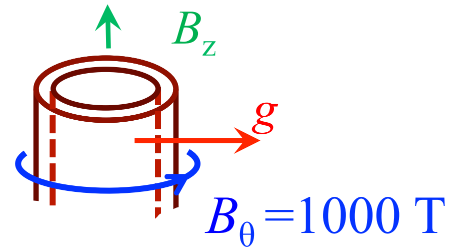
Implosion acceleration





Results look similar to current carrying modes, but longer wavelengths are not cut off (kr <<1)

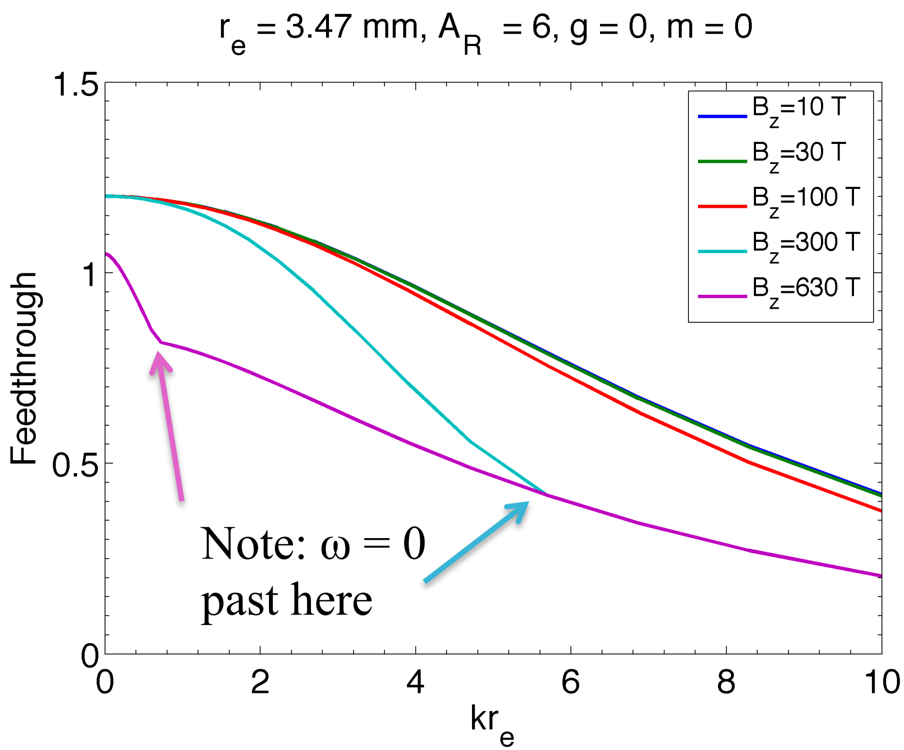
AR=6 liners show feedthrough reduction with Bz as expected



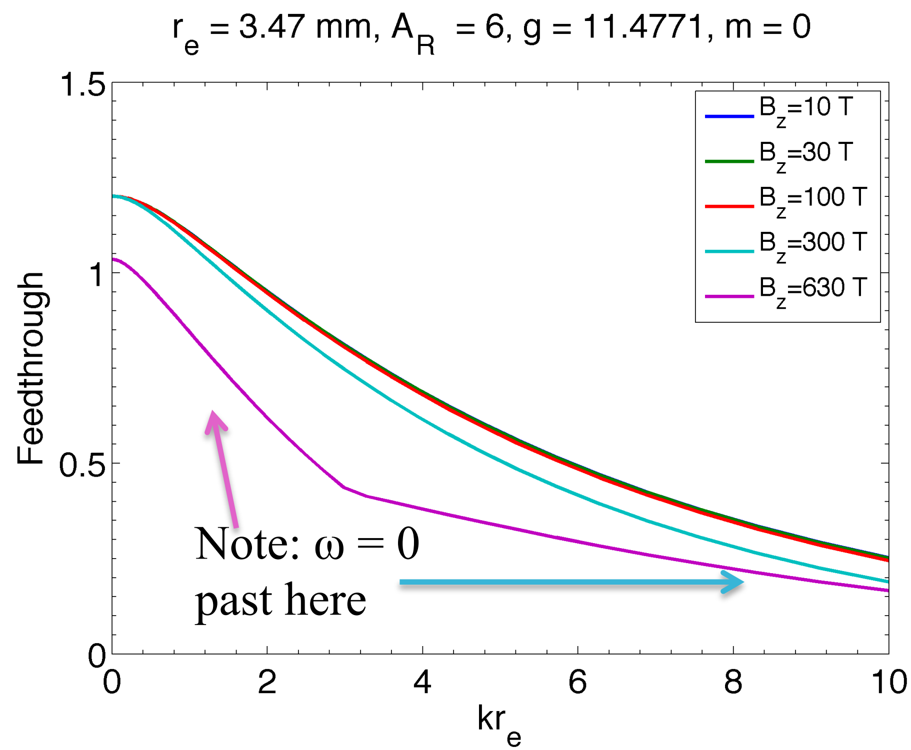
Reverse feedthrough also exists for small kr

- **This is not present in planar results!**
- **Increasing g reduces this effect**

No acceleration



Implosion acceleration



For significant feedthrough and MRT stabilization, require: $B_z \approx B_\theta$

- This is obtained by compressing the applied Bz seed field:

$$B_z(t) = B_{z0}\left(\frac{r_{i0}}{r_i(t)}\right)^2$$

$$= B_{z0} C_R^2$$

  - This assumes no loss of field from Nernst term
- The outer surface MRT will never be stabilized but there is hope to slow growth on the inner surface
  - Minimize initial seeding from feedthrough
  - Stabilize growth via strong Bz
- The limits for: $kr << 1$ will need to be examined more closely due to the peculiar behavior seen
  - Sausage and kink mode may complicate this stabilization

Using realistic data as input into linearized model

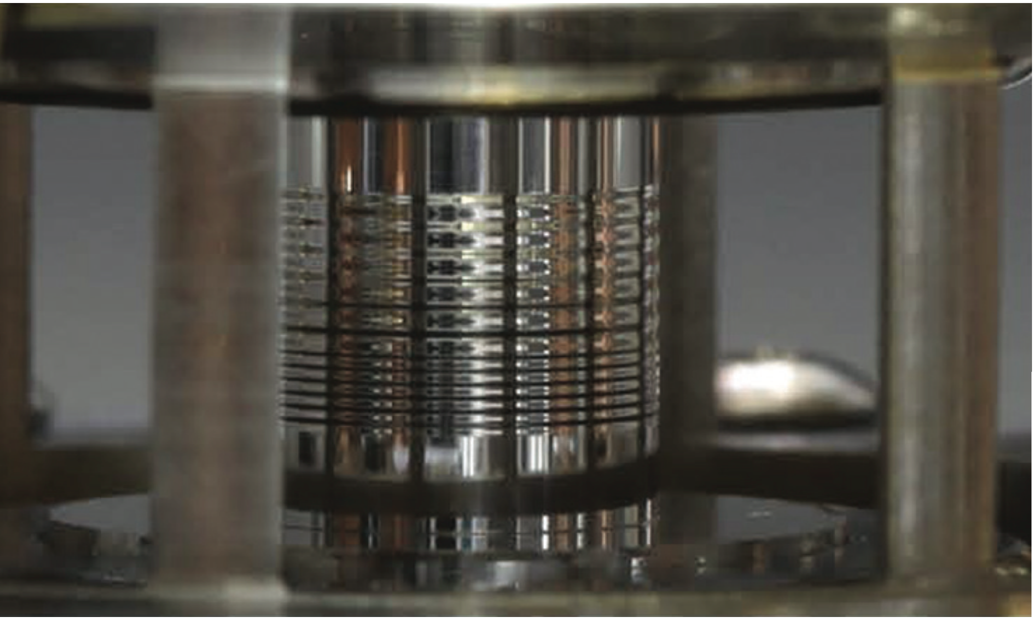
- Average physical quantities from 1D Hydra data in each 'region'
  - Running Lagrangian zones can be used to find liner/vacuum interfaces and, hence, the boundaries for averaging
- For a given wavelength we can calculate the instantaneous growth rate, $\omega(t)$ for each time step
  - The amplitude, η, of the instability is then determined by

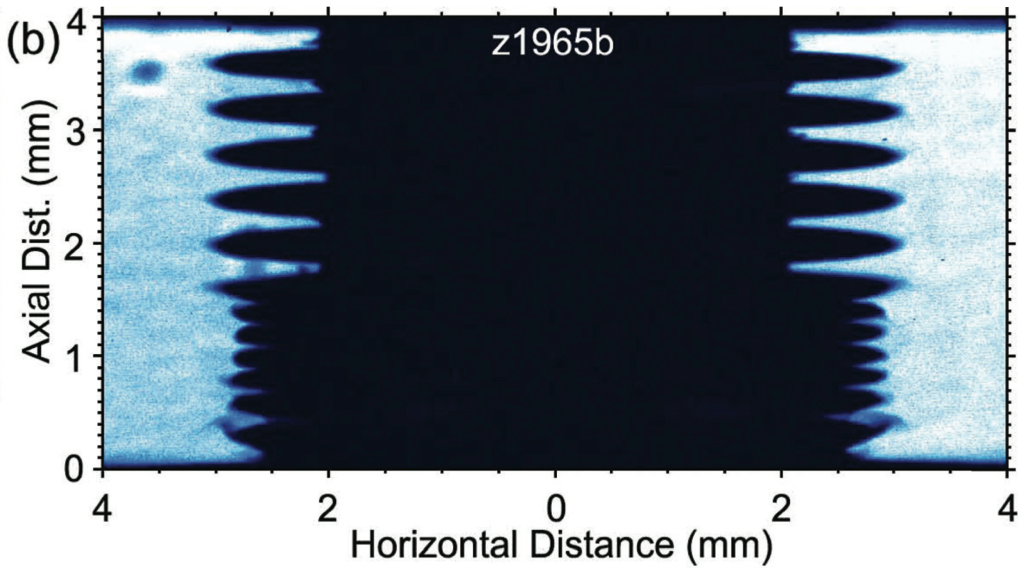
$$\frac{d^2}{dt^2}\eta(t) = \omega(t)^2\eta(t)$$

  - The feedthrough between interfaces is just the ratio of the eigenfunction at the inner and outer interface

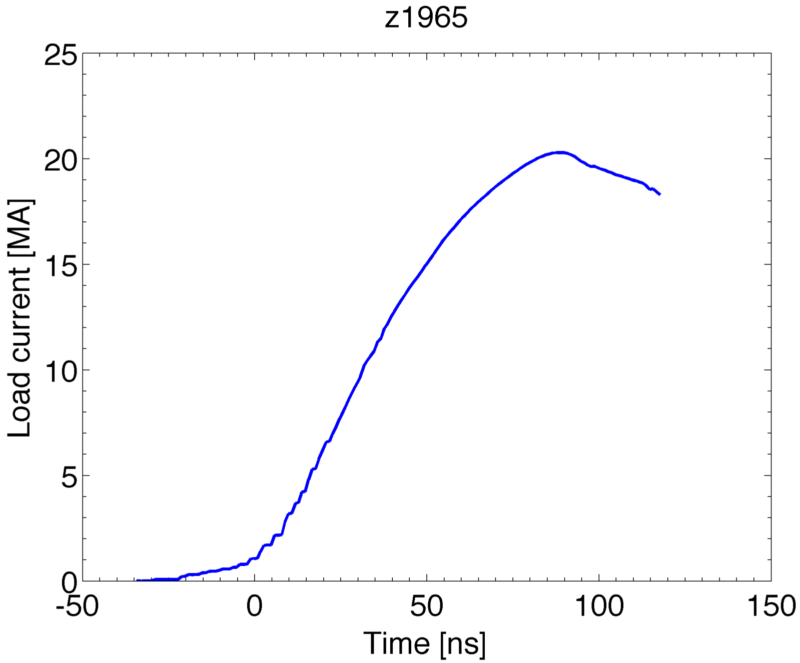
$$F(\gamma) = \xi(r_i)/\xi(r_e)$$

Aluminum liner experiments on Z with seeded MRT *





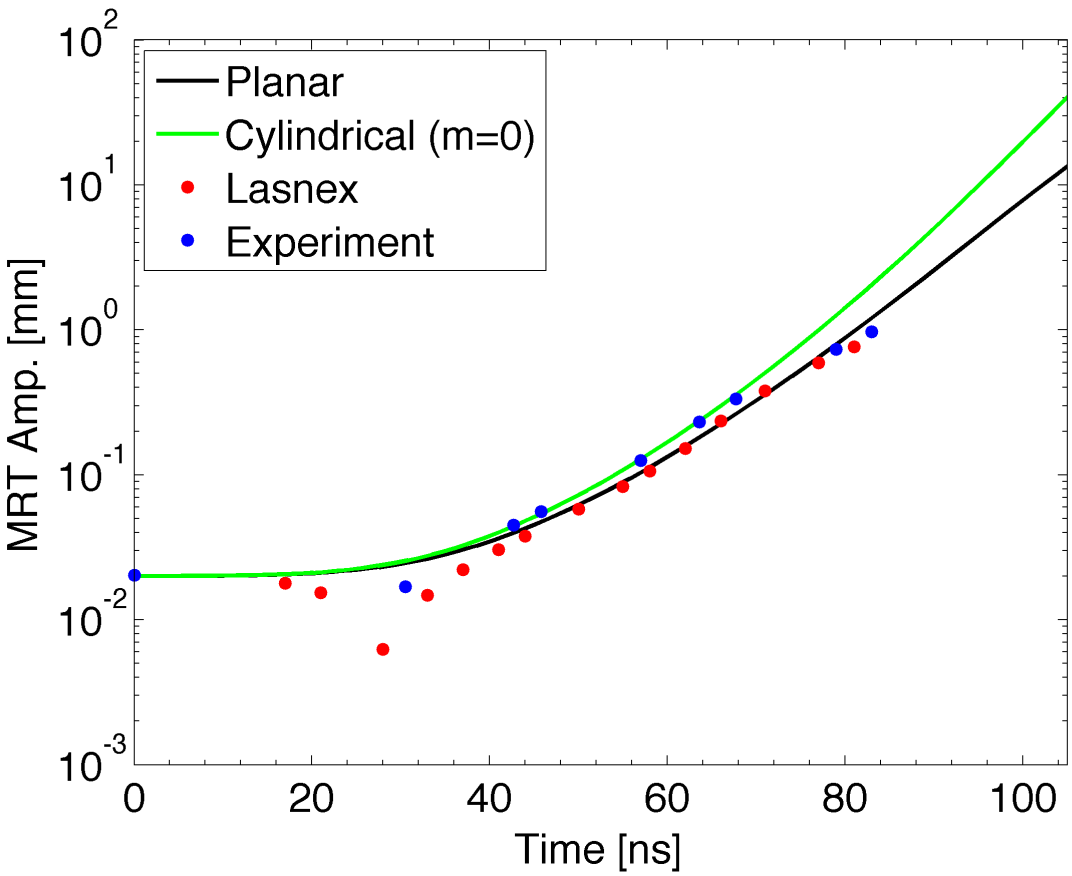
A 1D simulation with Hydra can be driven with the measured load current from which we can extract our averaged physical quantities

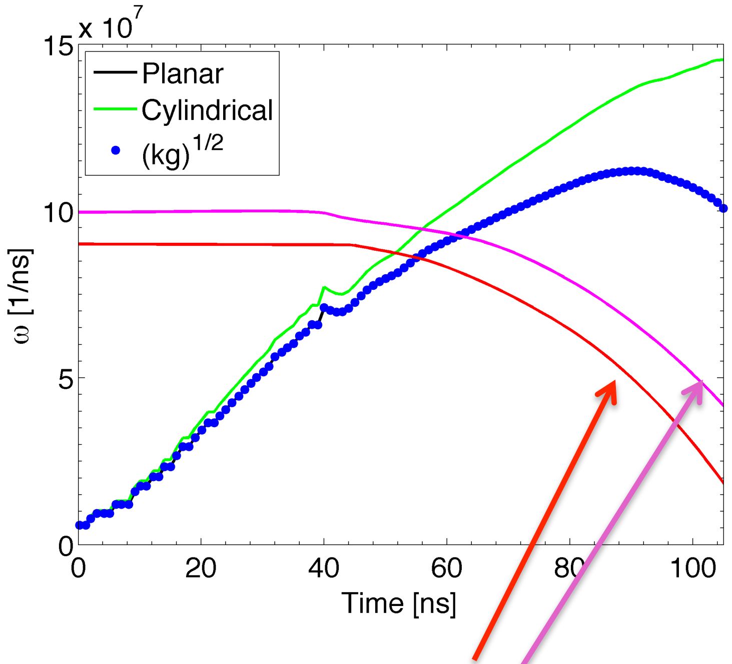


* Sinars et. al. Phys. Plasmas **18**, 056301 (2011)

Applying linearized model to Sinars et. al. * experiments shows good agreement while convergence is low

- Aluminum liner seeded with 400 um surface perturbation





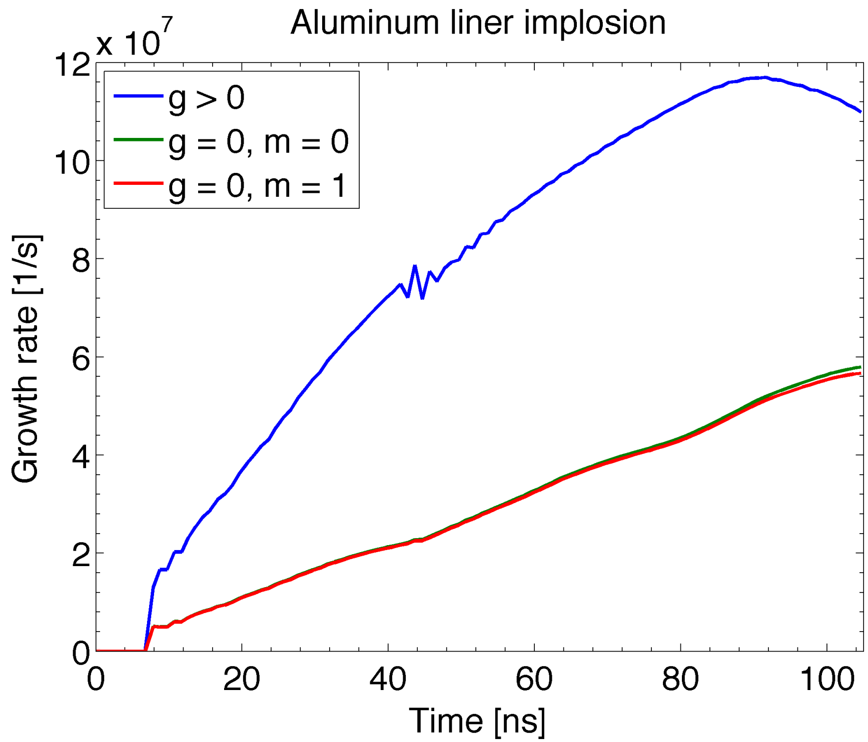
Inner/outer radii

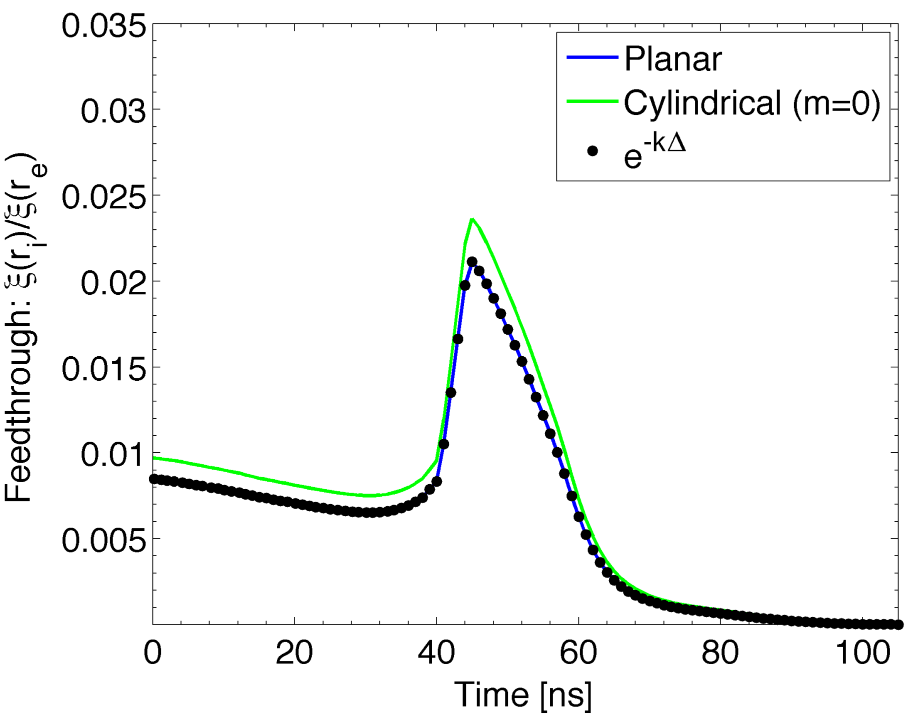
As convergence increases, growth rate becomes more complicated

* Sinars et. al. Phys. Plasmas **18**, 056301 (2011)

While g is large and convergence is small, growth is dominated by classical Rayleigh-Taylor growth rate:

$$\omega^2 \approx kg >> -\frac{(\mathbf{k}\cdot\mathbf{B})^2}{\mu_0\rho} + C(m,\mathbf{k})$$





If we remove g for the same problem, we see the remaining physics gives much lower growth

Feedthrough is similarly dominated by the classical expression

Future work with the linearized model

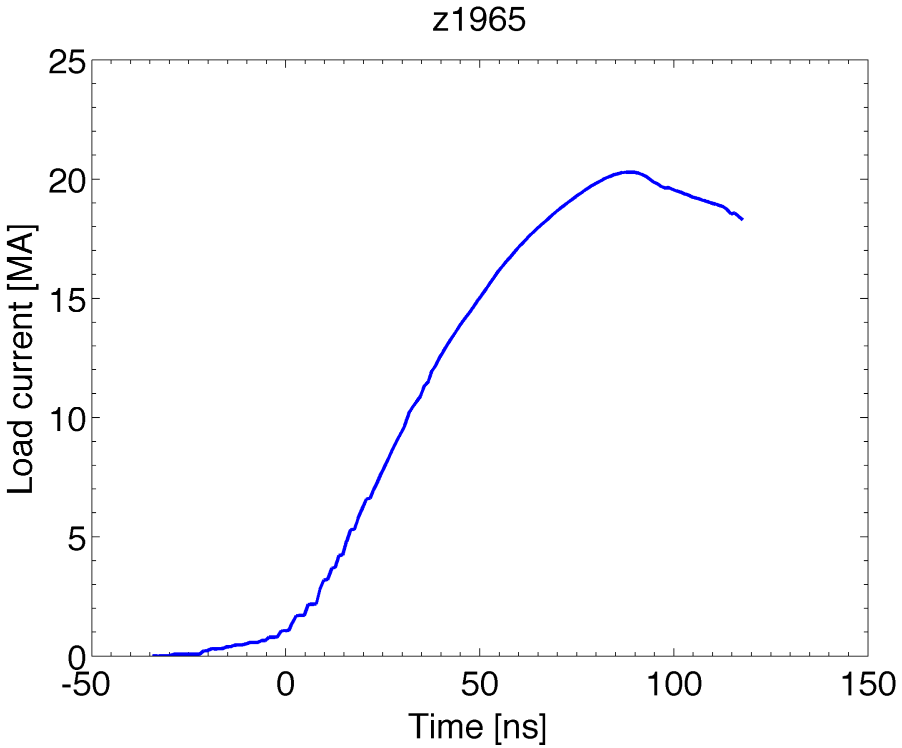
- Current work involves:
  - Determining the best way to use 1D Hydra data in our model
  - Adding a model of the diffusion of the drive field into the liner which can be de-stabilizing.
  - Incorporate propagation of shock through liner

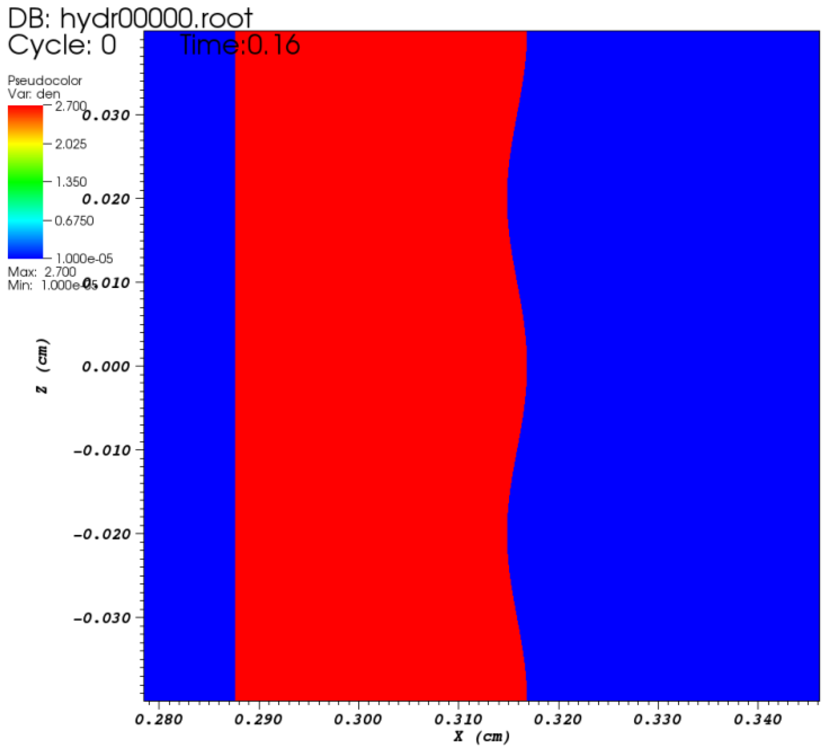
Summarizing:

- Large R and g seem to make $\sqrt{kg}$ a good approximation
- Feedthrough is mostly dependent upon liner thickness
  - Can be reduced by strong Bz
- Bz is relatively unimportant for stabilization until high convergence

Hydra has been used to model Al liner implosions with seeded MRT

- A sinusoidal perturbation of λ=400 um was applied to the surface of an Al liner and an implosion was driven using the load current on shot z1965 in attempt to replicate the MRT growth rates shown earlier *





* Sinars et. al. Phys. Plasmas **18**, 056301 (2011)

Determining MRT growth rates can be done many ways using 2D data

- An FFT can be applied to the mass per unit length and the amplitude at 400 um can be tracked as a function of time
  - The more wavelengths included in the simulation the better, but this may not be computationally feasible
- The bubble and spike radii can also be tracked
  - The diffuse nature of the ‘interface’ makes this prone to error depending on the amount of ablation
  - Bounds on the radii can be determined by tracking density contours around high gradients
- Simulated radiographs can be computed using Spect3D and compared visually to the experimental data, as well as be analyzed similarly to the above

ZBL is used to create the one or two frame 6.151 eV radiograph images

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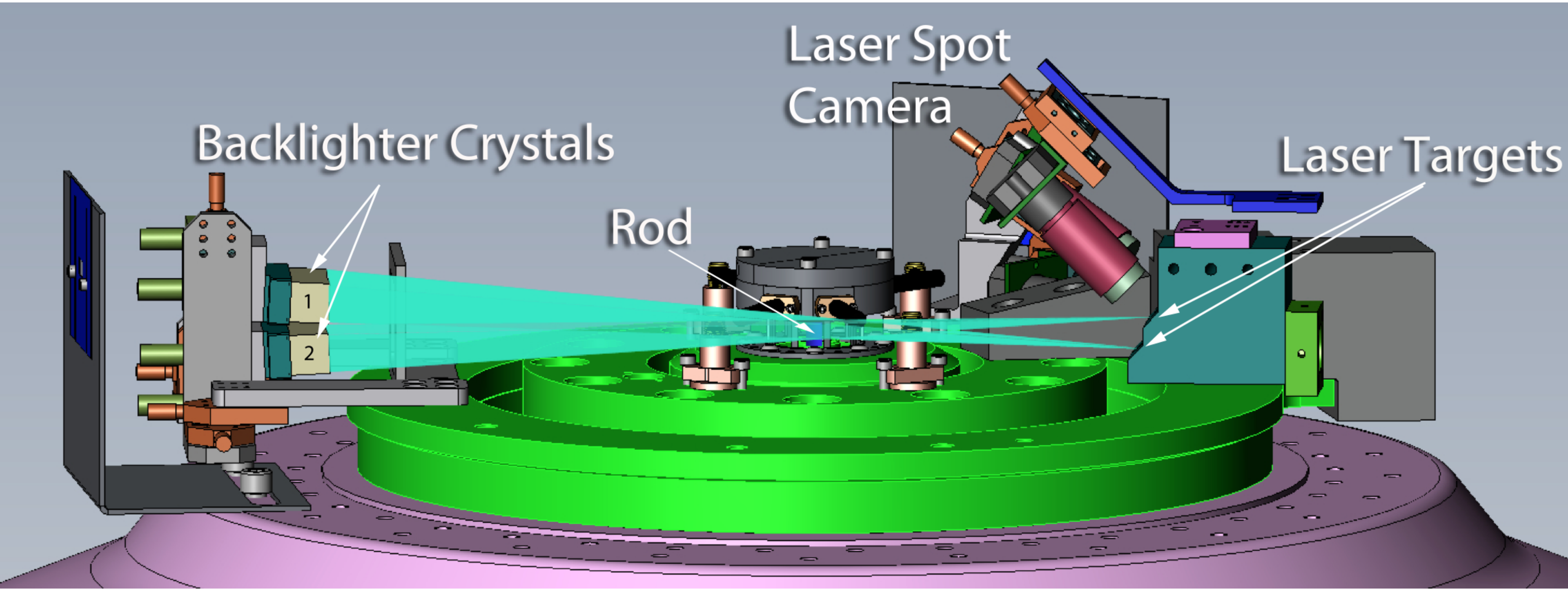
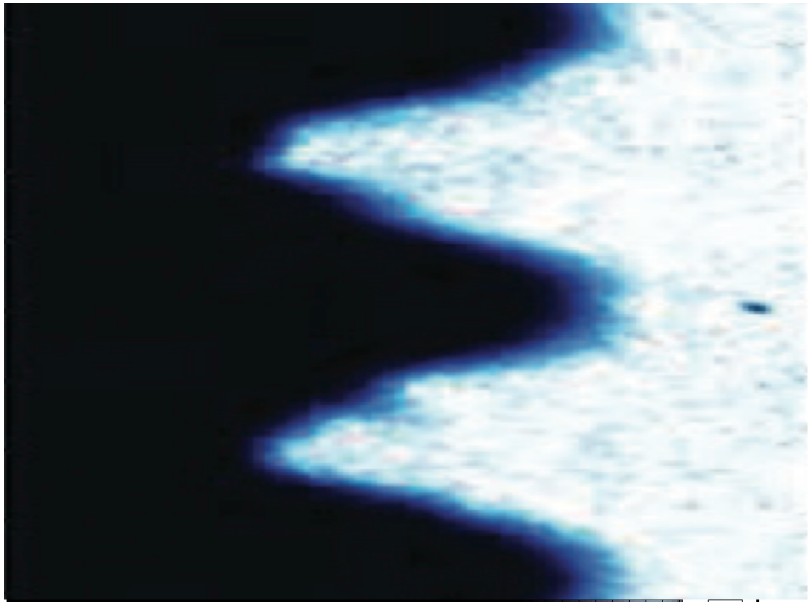
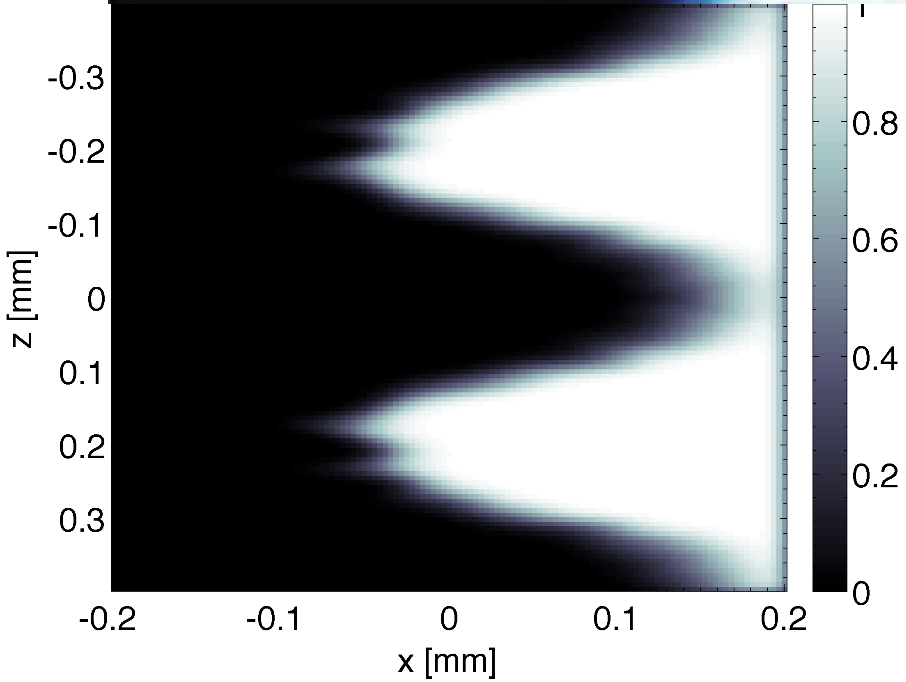


- **Radiograph lines of sight are ± 3° from horizontal when using two frame radiograph**
  - **This can introduce shadowing of short wavelength modes**
- **Straight on (0°) radiographs can alleviate this but only can take one frame**





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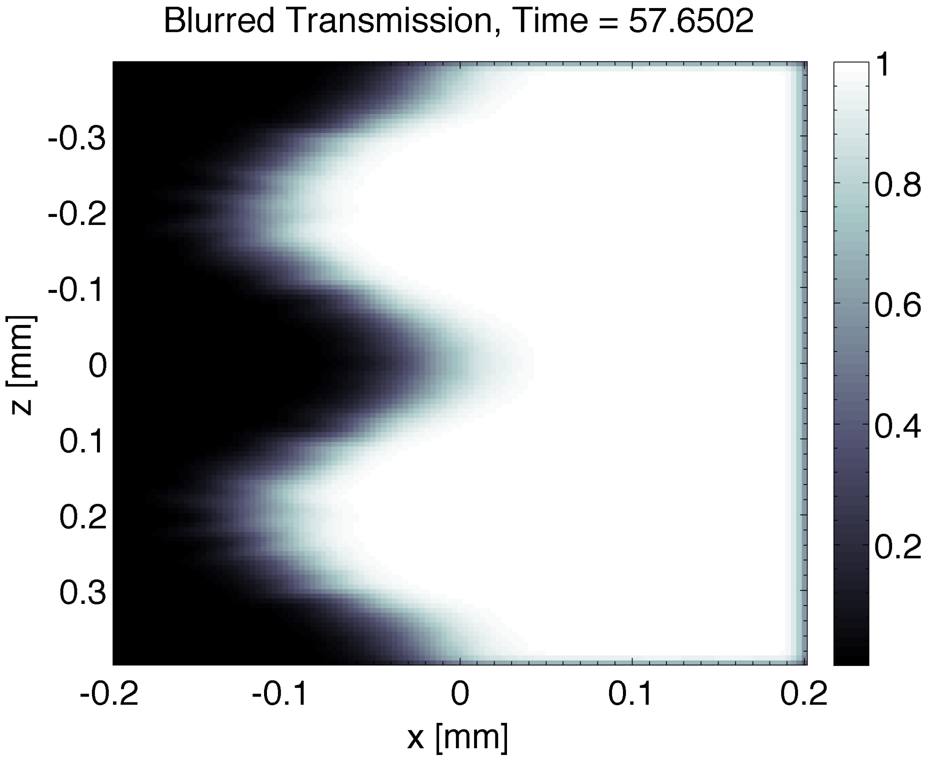
Simulated radiographs are generated from X-ray transmission through plasma onto a submicron resolution detector and a 15 um blur is added (ZBL resolution)

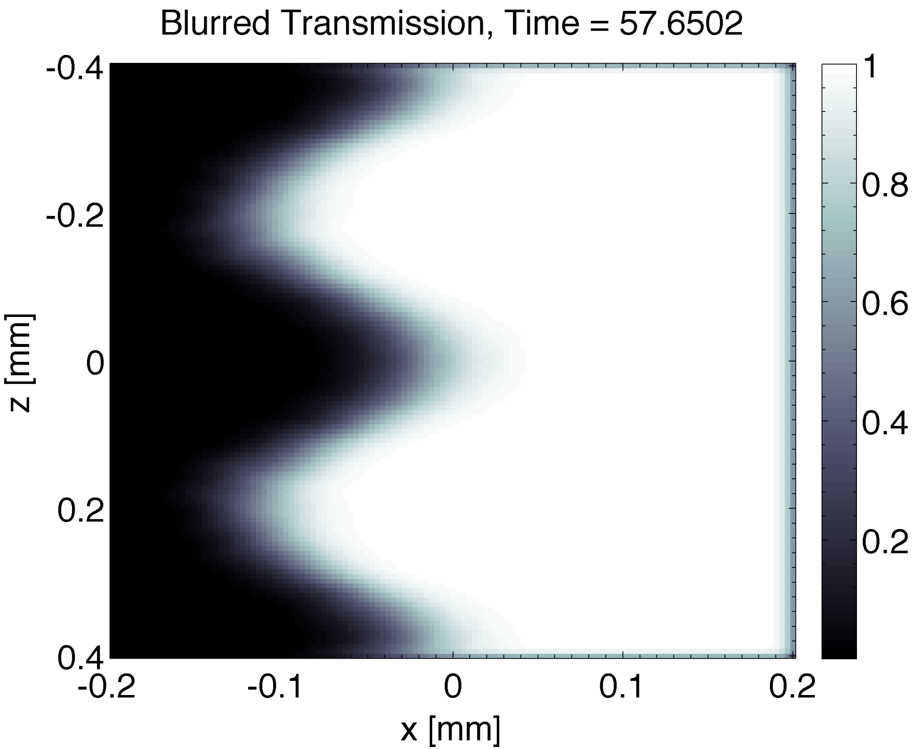
Comparing to radiographs from Sinars et. al. (2011) at t = 63.6 ns show excellent agreement both in amplitude and gross features even at 0°

Before substantial non-linear behavior inclination makes little difference

0° from horizontal



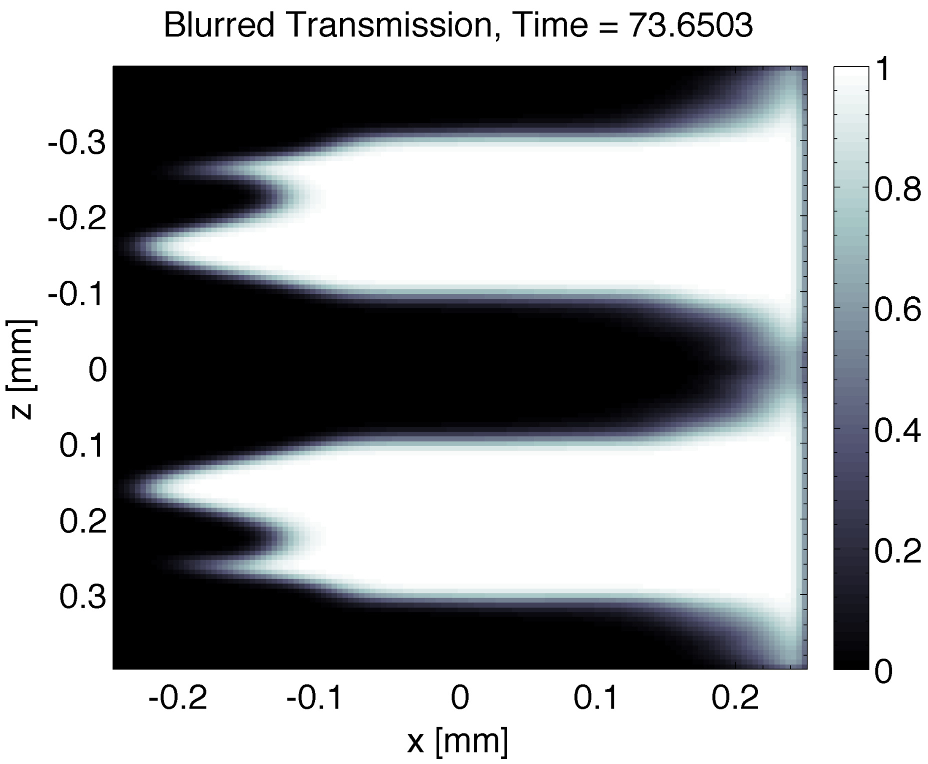
3° from horizontal



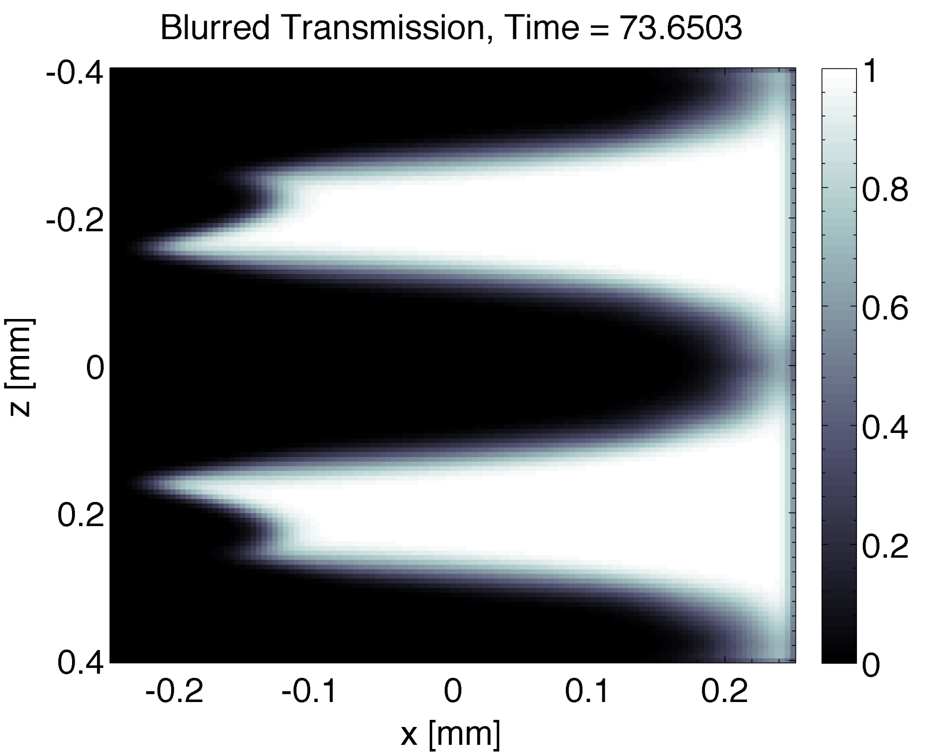
Shadowing of the shorter wavelengths (numerical effects) is quite apparent but structure is nearly the same

Later times show substantially different structure

0° from horizontal

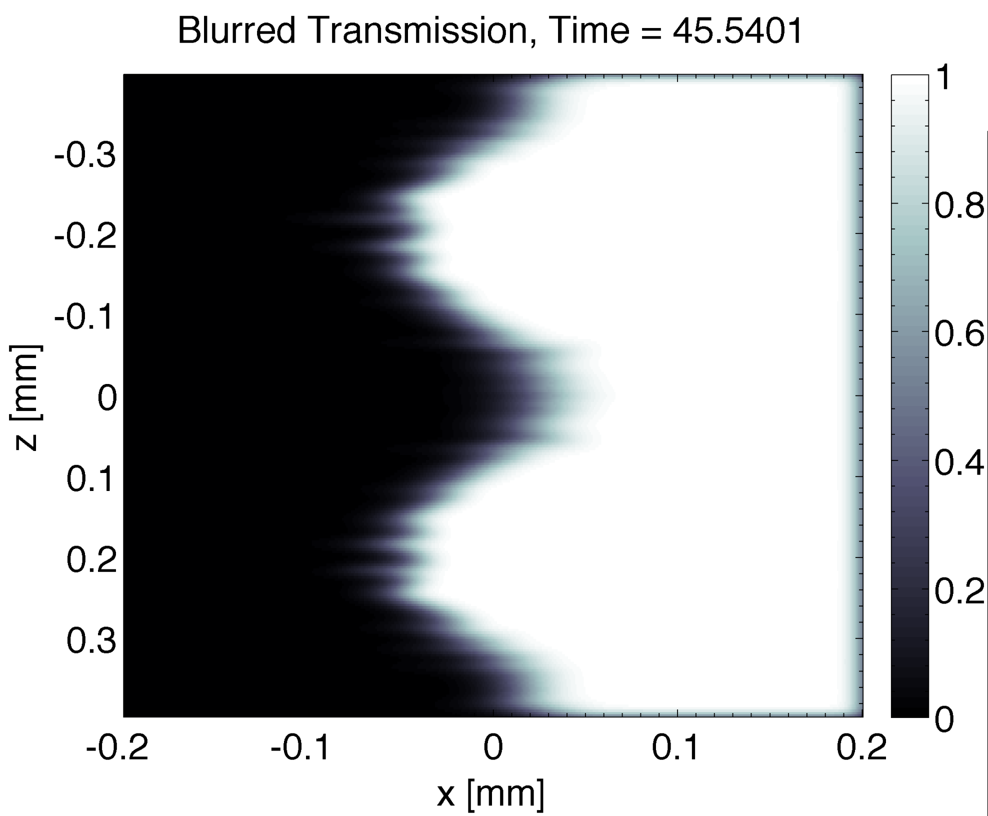


3° from horizontal



We can quantify the MRT growth using FFTs

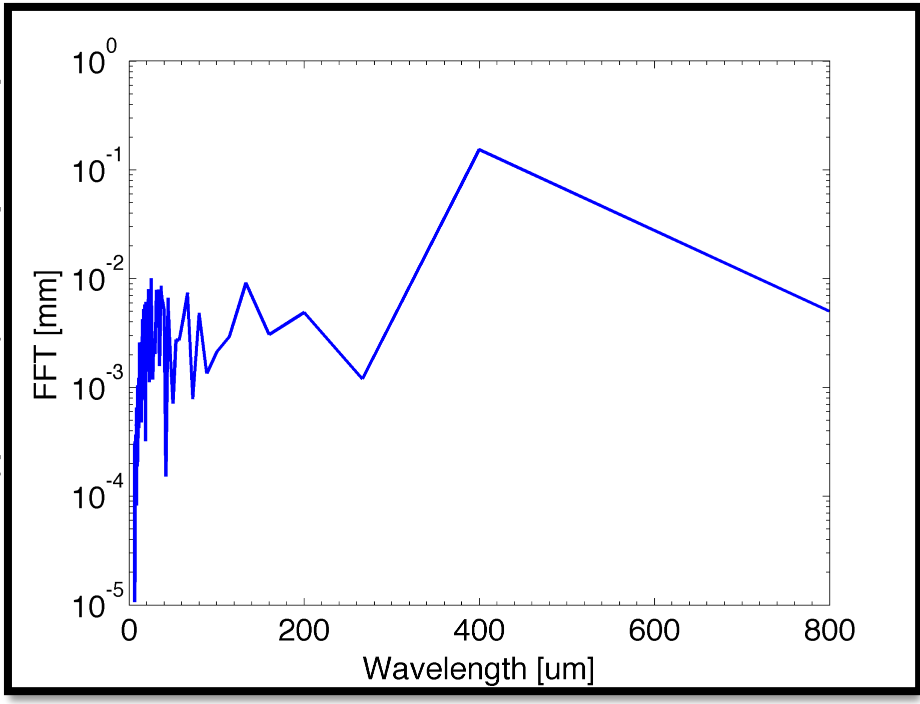
Hydra simulated radiograph



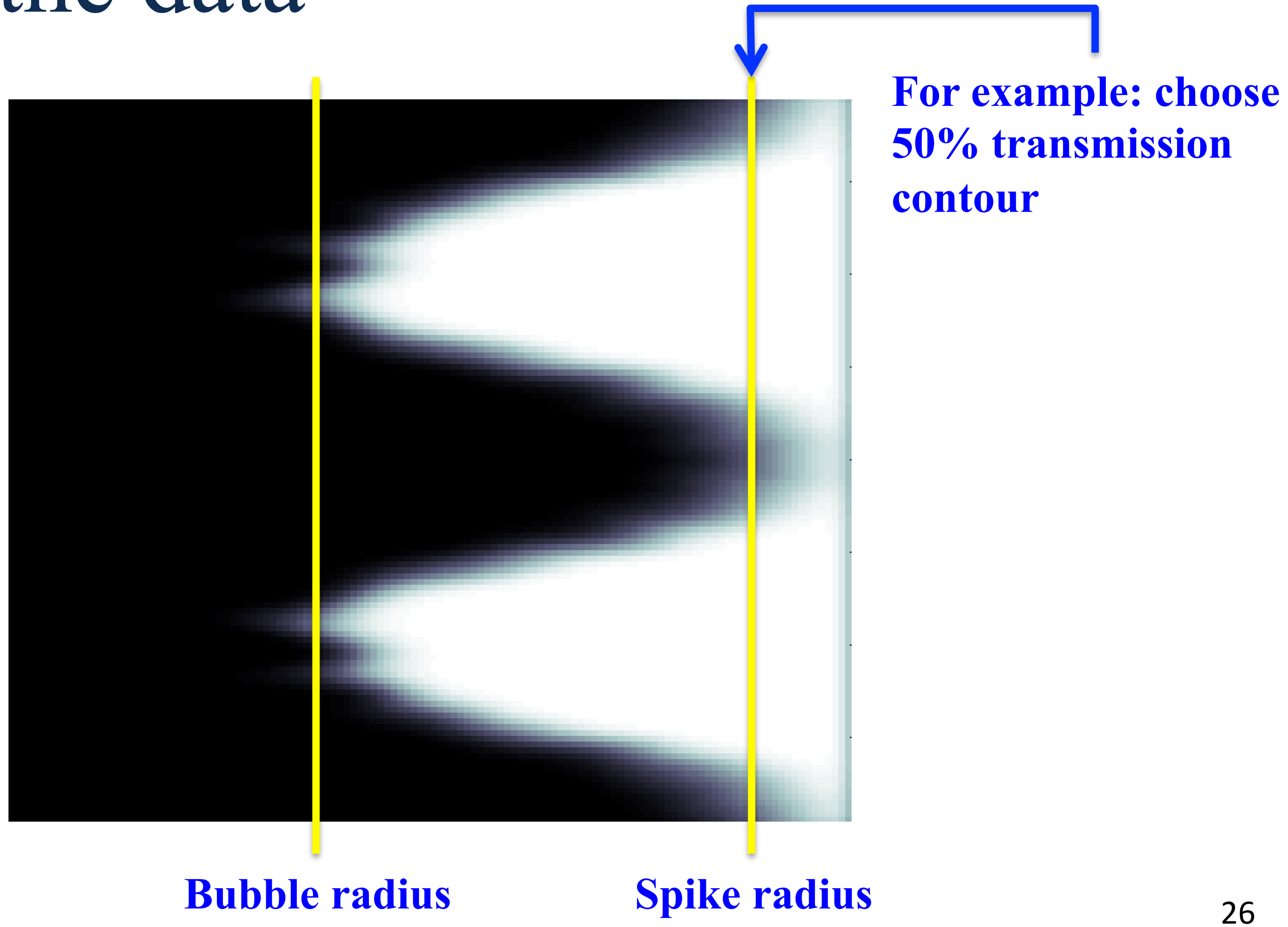
Axial FFT of result

$$\int \rho(r,z) r\, dr = m_L(z)$$

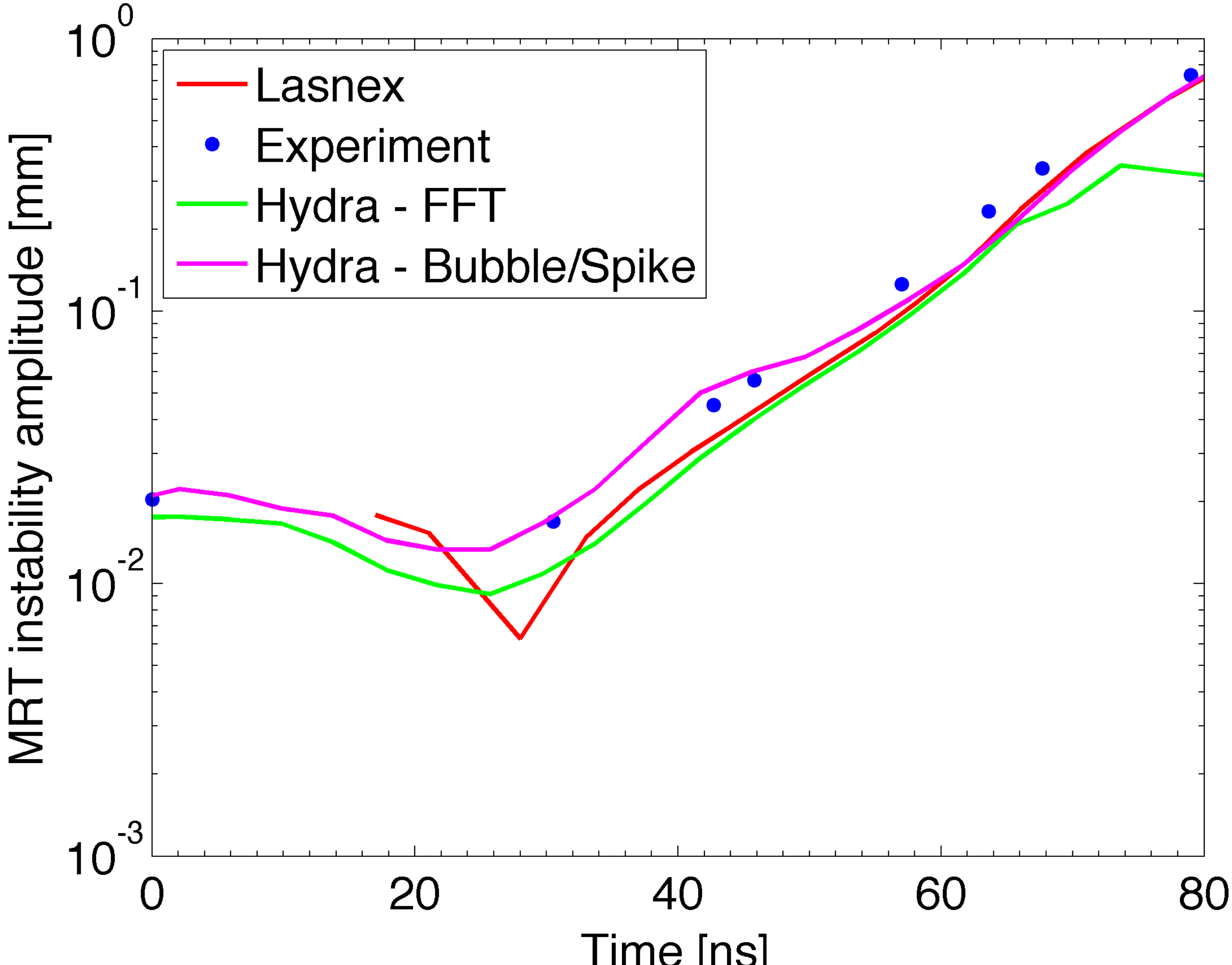
$$m_L(k) \approx \int m_L(z) e^{-ikz}\, dz$$



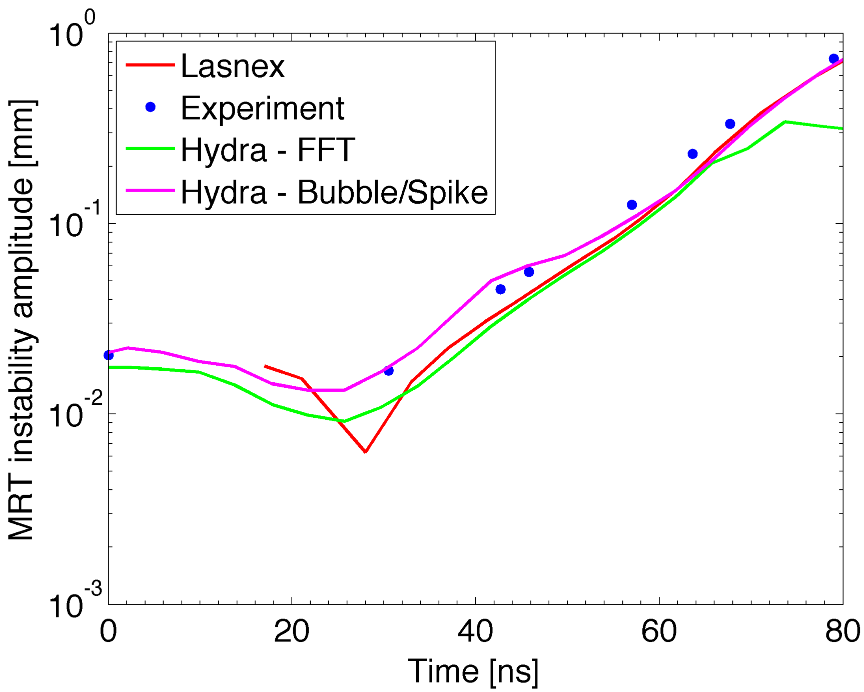
We can also estimate the growth by directly obtaining the bubble and spike radii from the data



Hydra agreement is excellent



Results illuminate the differences in amplitude calculation



- FFT method chronically underestimates growth
  - Possibly due to resolution issues
  - Later times show 400 um peak is broadening to couple with nearby modes
  - Would expect mode saturation to eventually occur
- Though the FFT growth calculation slows, bubble/spike shows continued growth as expected

Summary of Hydra results

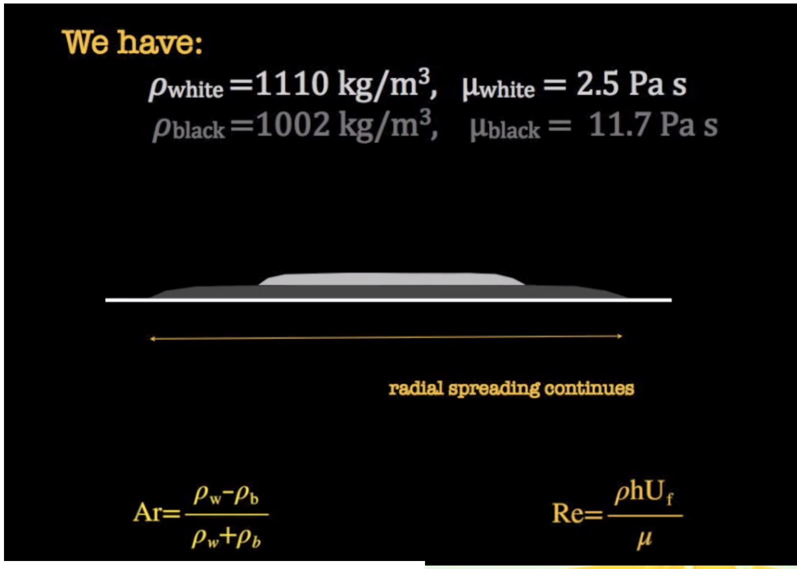
- Hydra seems to do a good job of getting MRT correct
  - Amplitude growth as a function of time matches data well
  - Simulated radiographs match data well for most times
    - Tilted views tend to smooth over stranger structure and give better agreement
- As non-linear MRT starts to dominate agreement with radiographs begins to degrade which could be due to any number of issues
  - Insufficient resolution
  - Meshing issues
  - Missing physics (3D, Hall, etc.)
- However, the predictive capability of Hydra is looking better

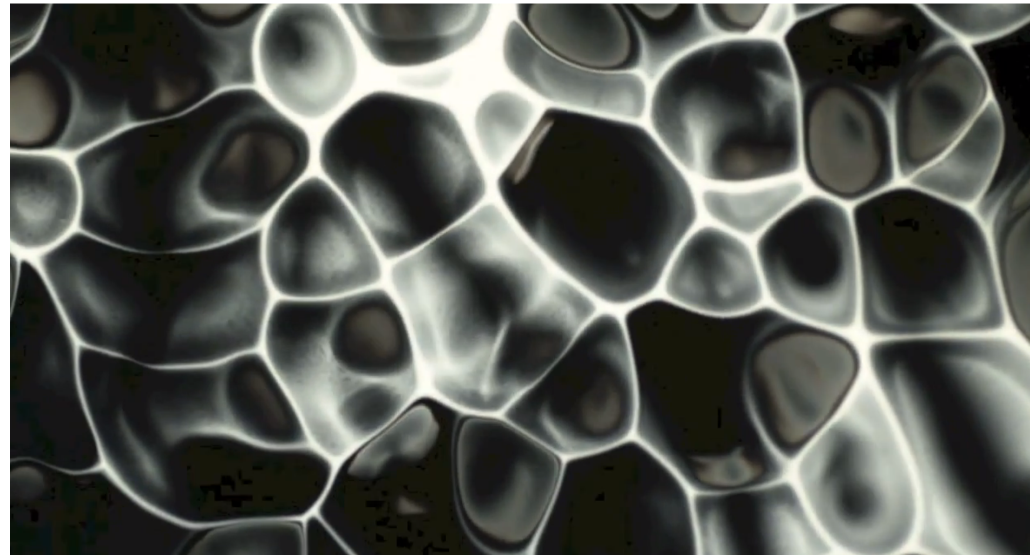
Future work

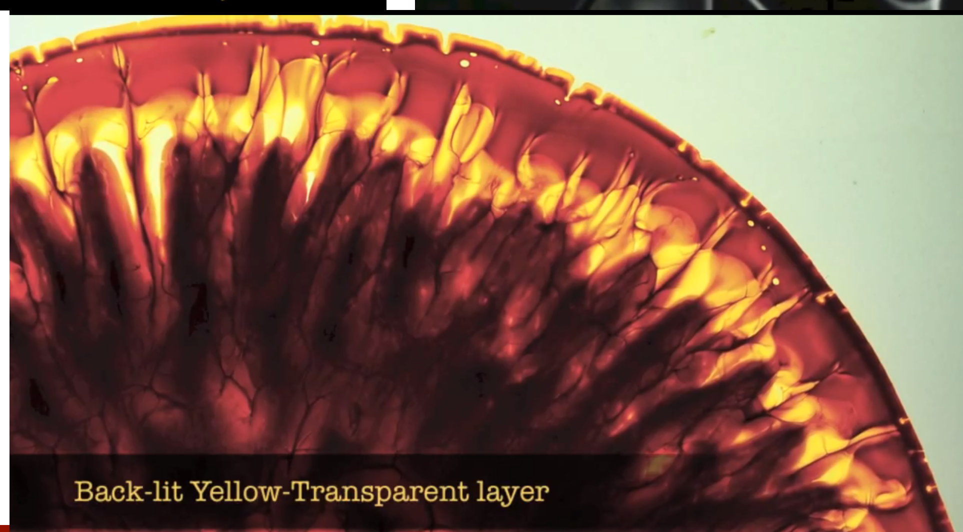
- Analyze MagLIF implosions with analytic calculations
  - Add fuel
  - Add axial field
- Attempt to get superior late time agreement between Sinars et. al. data and Hydra
- Use Hydra output to characterize feedthrough and compare to analytic theory
  - Inner interface is invisible to radiography for aluminum
  - Feedthrough should be most important at high convergence which is difficult to image anyway
- Further stress Hydra's predictive capabilities with the latest experiments on the Z-machine

BACKUPS

Rayleigh-Taylor Instability (RTI) Examples

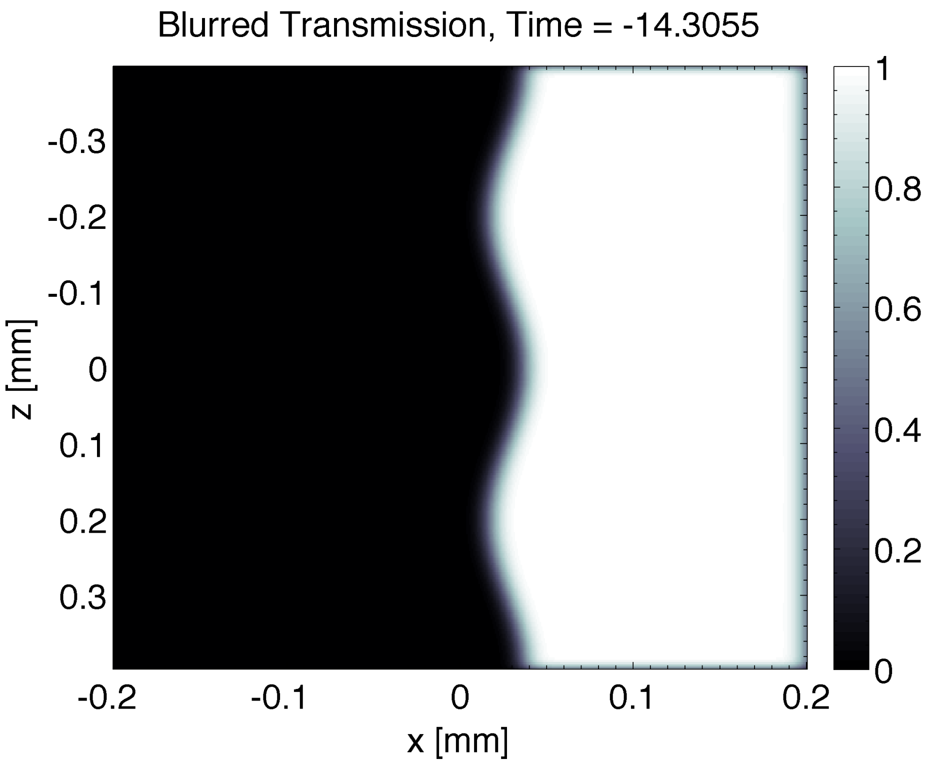


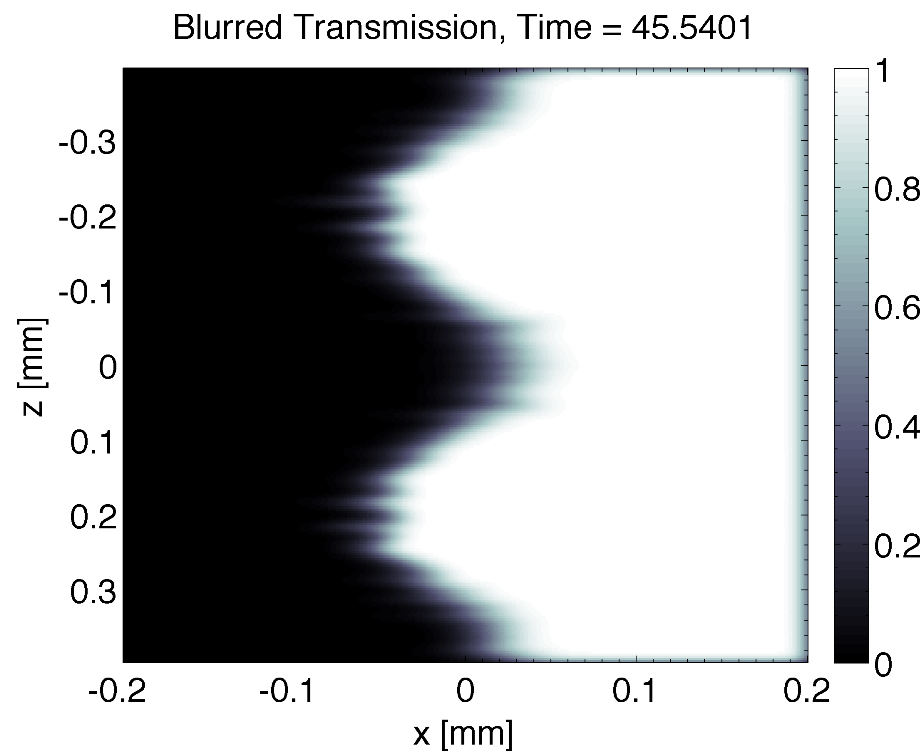




*http://arxiv.org/abs/1210.2770

Simulated radiographs are generated from X-ray transmission through plasma onto a submicron resolution detector





15 micron Gaussian blur is added to model ZBL resolution

Taking the inclination into account seems important for radiograph comparisons at later times

Experiment

t = 77 ns

0°

Hydra

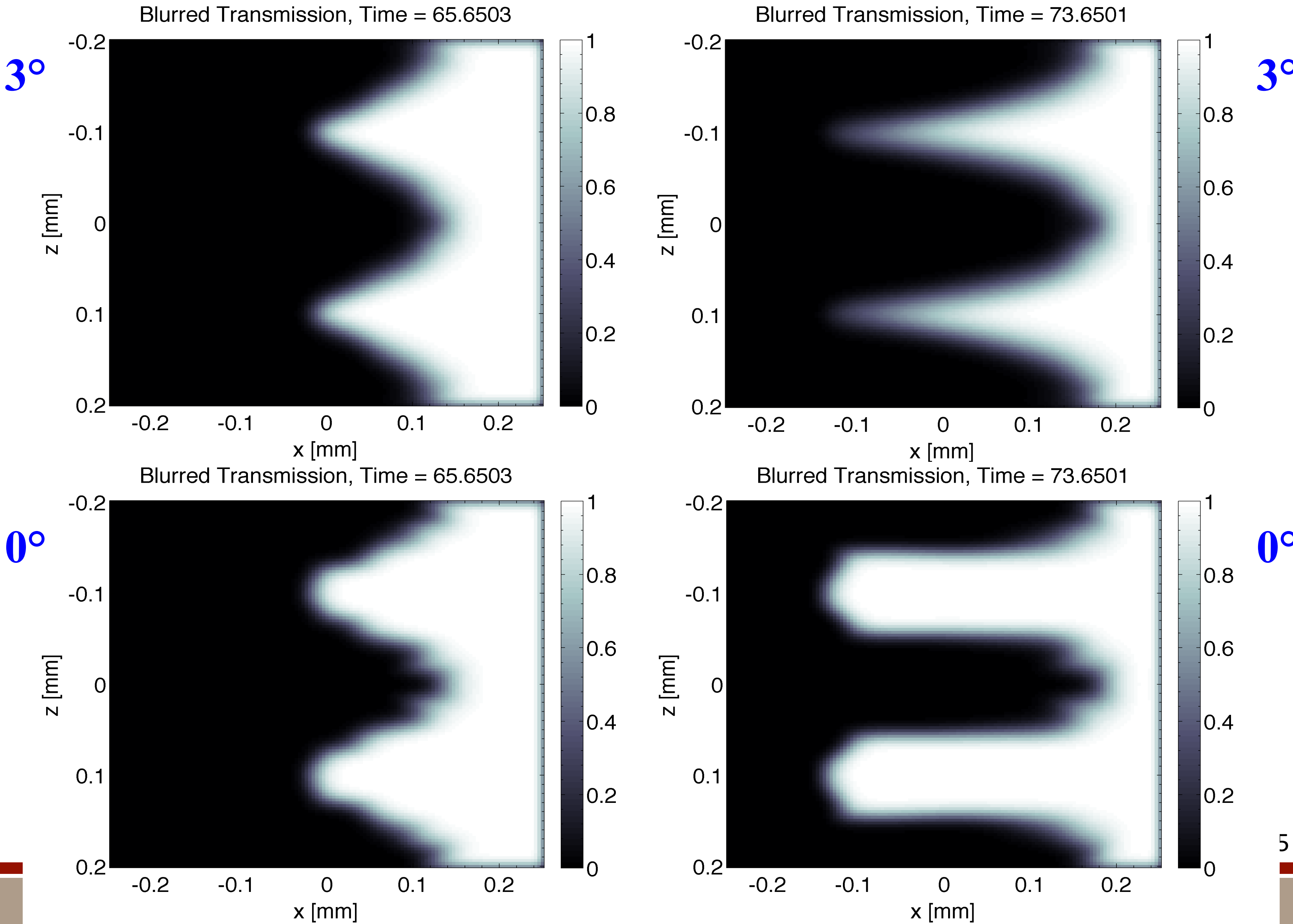
Experiment

t = 77 ns

3°

Hydra

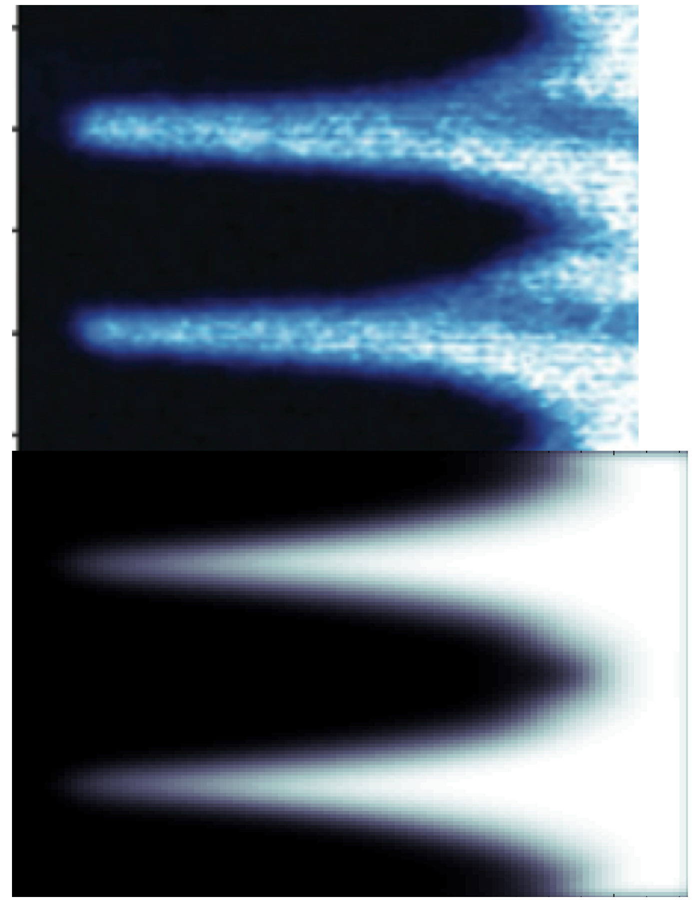
J x B with 200 um perturbation



J x B with 200 um perturbation shows fairly good agreement as well

t = 68 ns

t = 74 ns *



***Note: this is from the 2nd shot series, with higher current and 0° viewing angle**