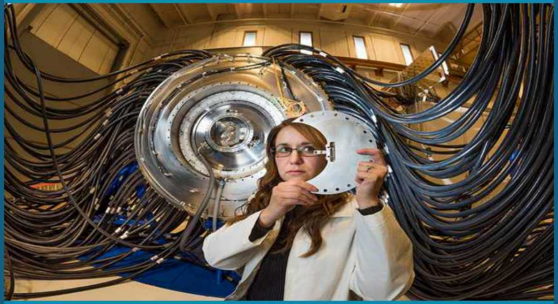
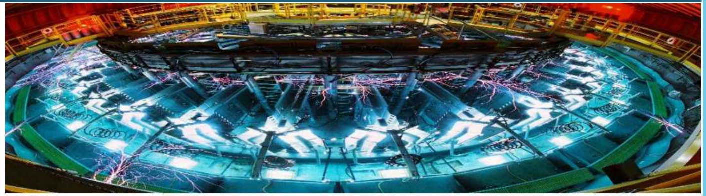
SAND2019-12632C

A conservative approach to scaling magneto-inertial fusion concepts to larger drivers





PRESENTED BY

Paul F. Schmit

61st Annual Meeting of the APS-DPP

October 24th, 2019

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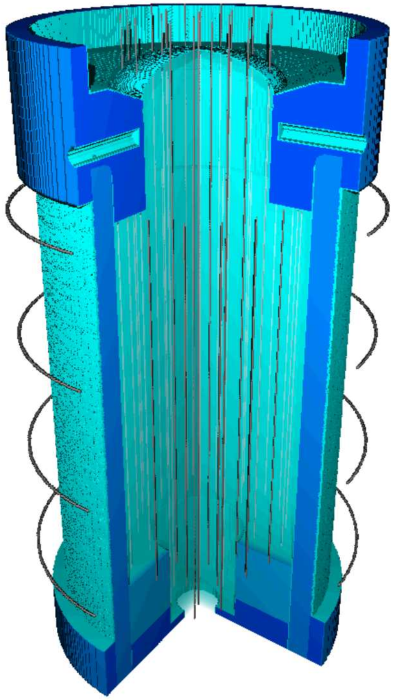
Acknowledgments

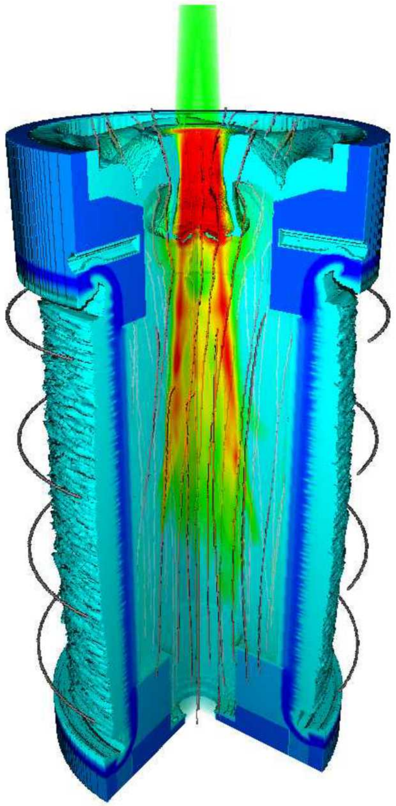
My sincere gratitude to my collaborator, Daniel E. Ruiz (SNL).

Many thanks as well to my SNL colleagues, S. A. Slutz, R. A. Vesey, D. A. Yager-Elorriaga, J. R. Fein, M. R. Gomez, D. B. Sinars, T. R. Mattsson, K. J. Peterson, and G. A. Rochau, for helpful discussions.

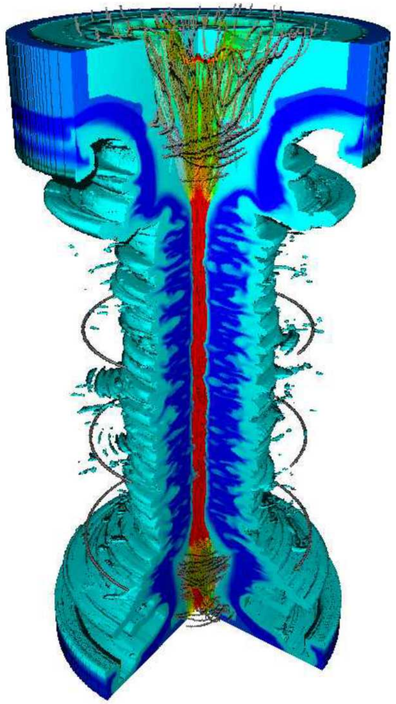
MagLIF is a magneto-inertial fusion (MIF) concept that relies on three components to produce fusion conditions at stagnation



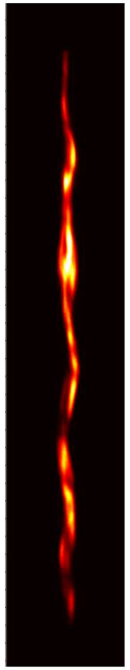
Magnetization
- Suppress radial thermal conduction losses
- Enable slow implosion with thick target walls



Preheat
- Increase fuel adiabat to limit required convergence



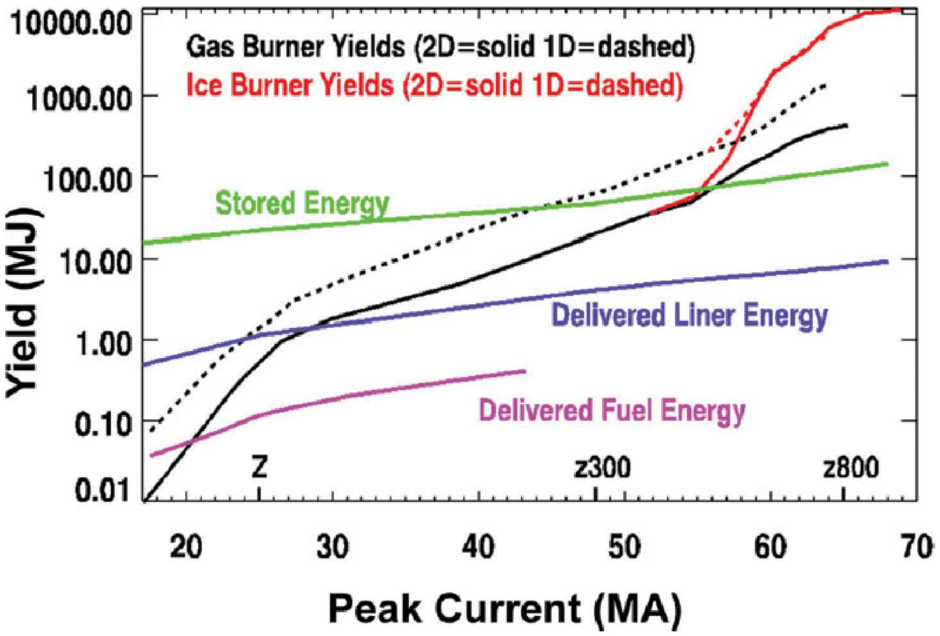
Implosion
- PdV work to heat fuel
- Amplify B-field through flux compression



Stagnation
- Several keV temperatures
- Several kT B-field to trap charged fusion products

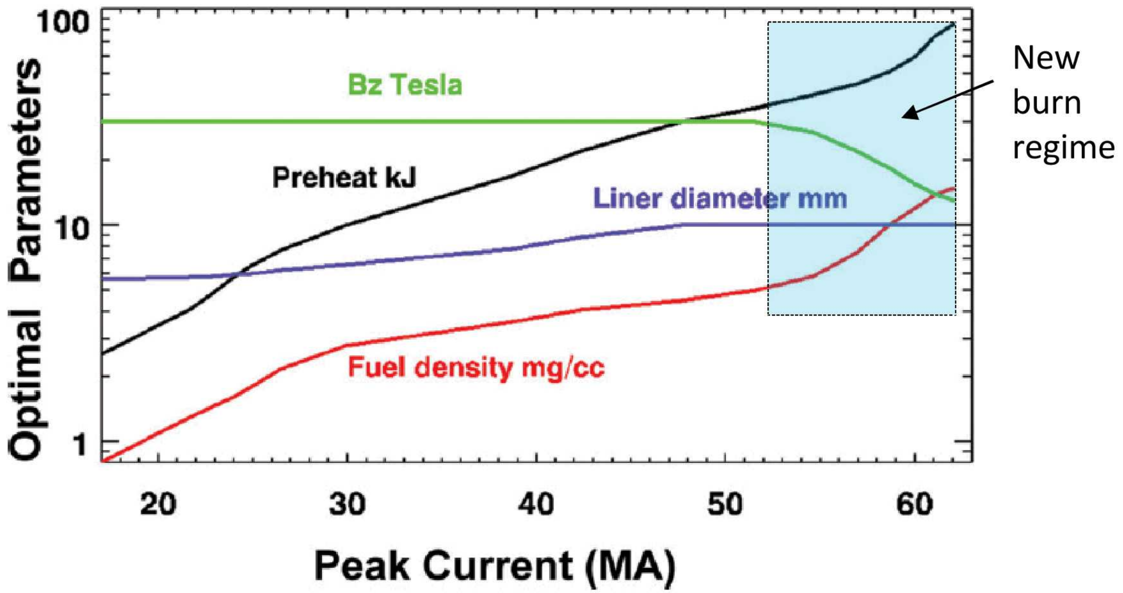
There is great interest in understanding how MIF concepts like MagLIF scale to ignition and high yields

Yield-optimized MagLIF solutions out to 70 MA [1]



Detailed 2D axisymmetric rMHD calculations (LASNEX) show the potential for MagLIF to attain ignition and significant (10’s to 100’s of MJ) yields on feasible pulsed-power architectures [2]

Design parameters for optimal yield [1]



Broad parameter space considered, limited constraints on initial liner diameter, AR, and Bz. Optimal solutions can deviate away from present-day physics regimes.

[1] Slutz *et al.*, Phys. Plasmas 23, 022702 (2016) **[2] Stygar *et al.*, PRSTAB 18, 110401 (2015)**

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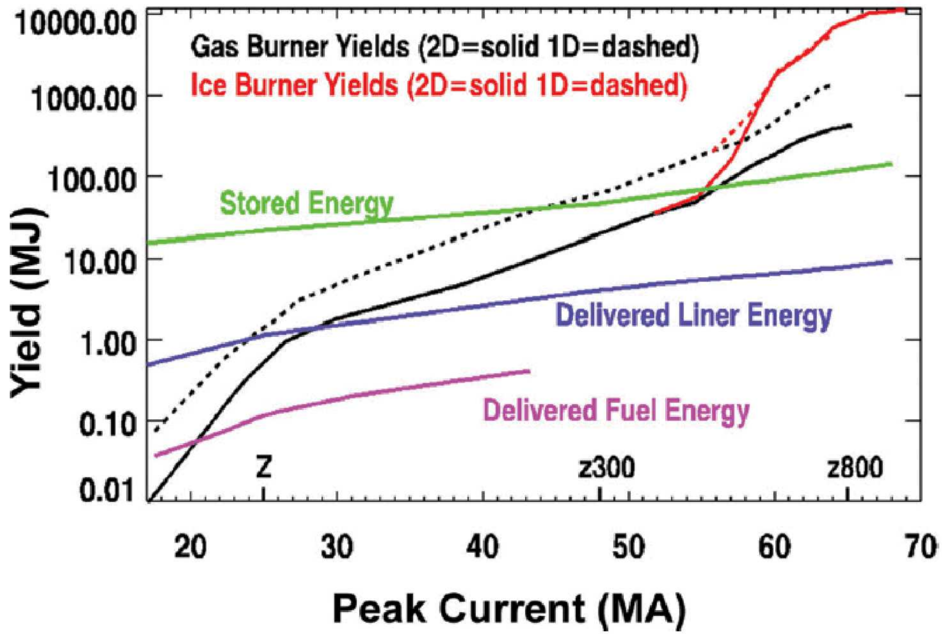

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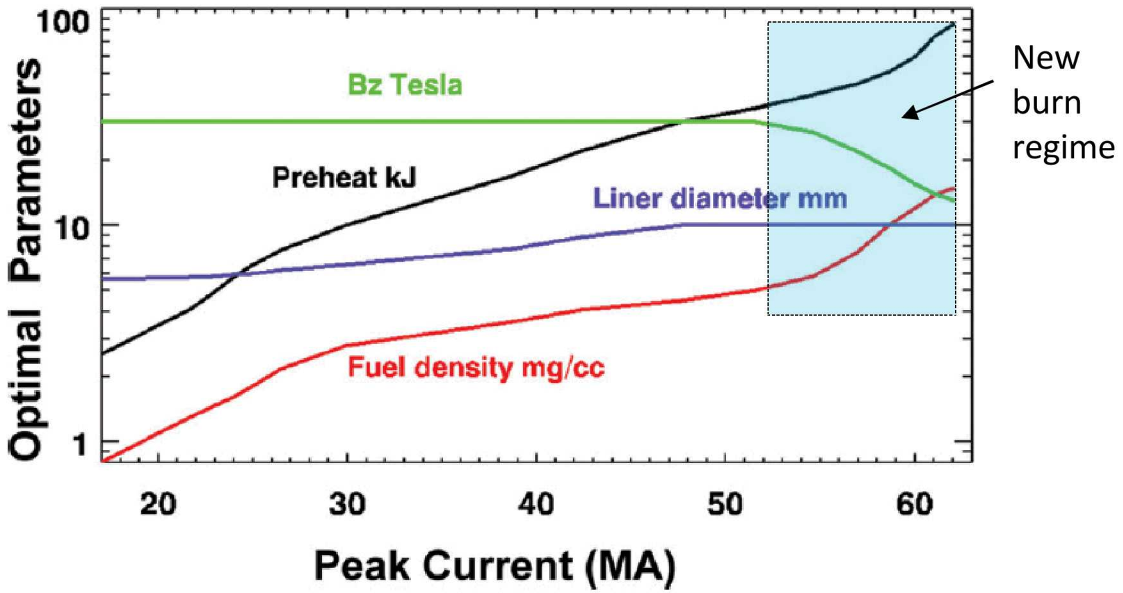


Broad parameter space considered, limited constraints on initial liner diameter, AR, and Bz. Optimal solutions can deviate away from present-day physics regimes.

We derive scaling rules connecting present-day platforms to future candidate designs while avoiding significant changes in key physical regimes that could degrade projected performance.

[1] Slutz *et al.*, Phys. Plasmas 23, 022702 (2016) **[2] Stygar *et al.*, PRSTAB 18, 110401 (2015)**

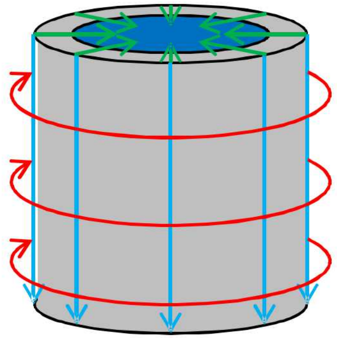
A simple model describing MIF implosions leads to conservative scaling rules based on 3 dimensionless parameters

Simple model of a "0D" magneto-inertial fusion implosion [1]:

$$\ddot{R} = -\frac{2\pi R}{\hat{m}}\left(P_{\text{out}} - P_{\text{in}}\right)$$

Imploding Force

$j_z \times B_\theta$



Azimuthal B field

Axial current

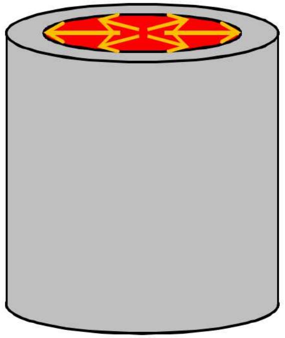
$$P_{\text{out}} = \frac{B^2}{2\mu_0} = \frac{\mu_0 I^2}{8\pi^2 R^2}$$

I is the axial current

R is the liner radius

*$\hat{m}$ is the liner mass per unit length

Exploding pressure force



$$P_{\text{in}} = P_1 \left(\frac{R_1}{R}\right)^{2\gamma} \Theta(t - t_1)$$

P_1 is the preheat pressure

R_1 is the liner radius at preheat

t_1 is the preheat time

[1] Schmit & Ruiz, *A conservative approach to scaling magneto-inertial fusion concepts to larger pulsed-power drivers*, in preparation.

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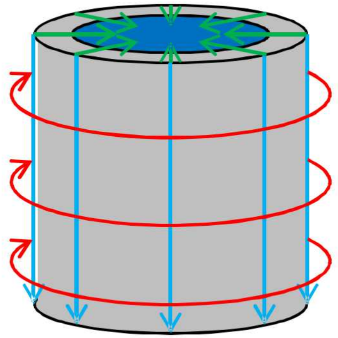

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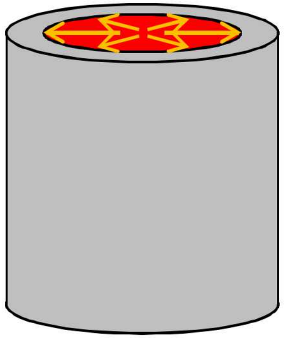
Exploding pressure force



$$P_{in} = P_1\left(\frac{R_1}{R}\right)^{2\gamma}\Theta(t - t_1)$$

Three dimensionless parameters govern the system

$$\tilde{R}\ddot{\tilde{R}} = -\Pi\tilde{I}^2 + \Phi\tilde{R}^{2-2\gamma}\Theta(\tilde{t} - \tilde{t}_1)$$

Liner-only dynamics [2]

(1) $\Pi \rightarrow$ how fast does liner implode?

Hot-fuel + liner dynamics

(2) $\Phi \rightarrow$ how energetic is preheat?

(3) $\tilde{t}_1 \rightarrow$ when does preheat occur?

Conserving these 3 quantities and $\tilde{I}(t)$:

- Leads to self-similar shell implosion dynamics
- Conserves convergence ratio
- Provides detailed guidance for scaled designs

[1] Schmit & Ruiz, *A conservative approach to scaling magneto-inertial fusion concepts to larger pulsed-power drivers*, in preparation.

[2] e.g., see Ryutov et al, RMP 72, 167 (2000)

By enforcing implosion self-similarity and conserving IFAR, we reduce risks posed by MHD implosion instabilities and mix

Scaling the magneto-Rayleigh-Taylor instability

IFAR is the primary scaling parameter for MRT
(*even including MHD growth-rate corrections*)

$$\Gamma_{\max} \approx \frac{1}{4\Delta}\left(\int_0^t g^{1/2}dt\right)^2 \propto \mathrm{IFAR}$$

Like laser-driven capsules [1], can derive IFAR scaling

$$\mathrm{IFAR}(t) = \frac{R(t)}{\Delta(t)} \propto \mathrm{AR}\, P_{\mathrm{out}}^{1/\gamma}$$

Aim to preserve growth of most-damaging MRT mode

Our approach preserves trajectory and IFAR, so that initial wall thickness increases as pressure increases

$$\tilde{R}\ddot{\tilde{R}} = -\Pi\tilde{I}^2 + \Phi\tilde{R}^{2-2\gamma}\Theta(\tilde{t} - \tilde{t}_1)$$

$$+$$

$$\mathrm{IFAR} \propto \mathrm{AR}\, P_{\mathrm{out}}^{1/\gamma} \doteq \Psi$$

[1] e.g., Lindl (1995), Nora, Betti *et al*. (2014)

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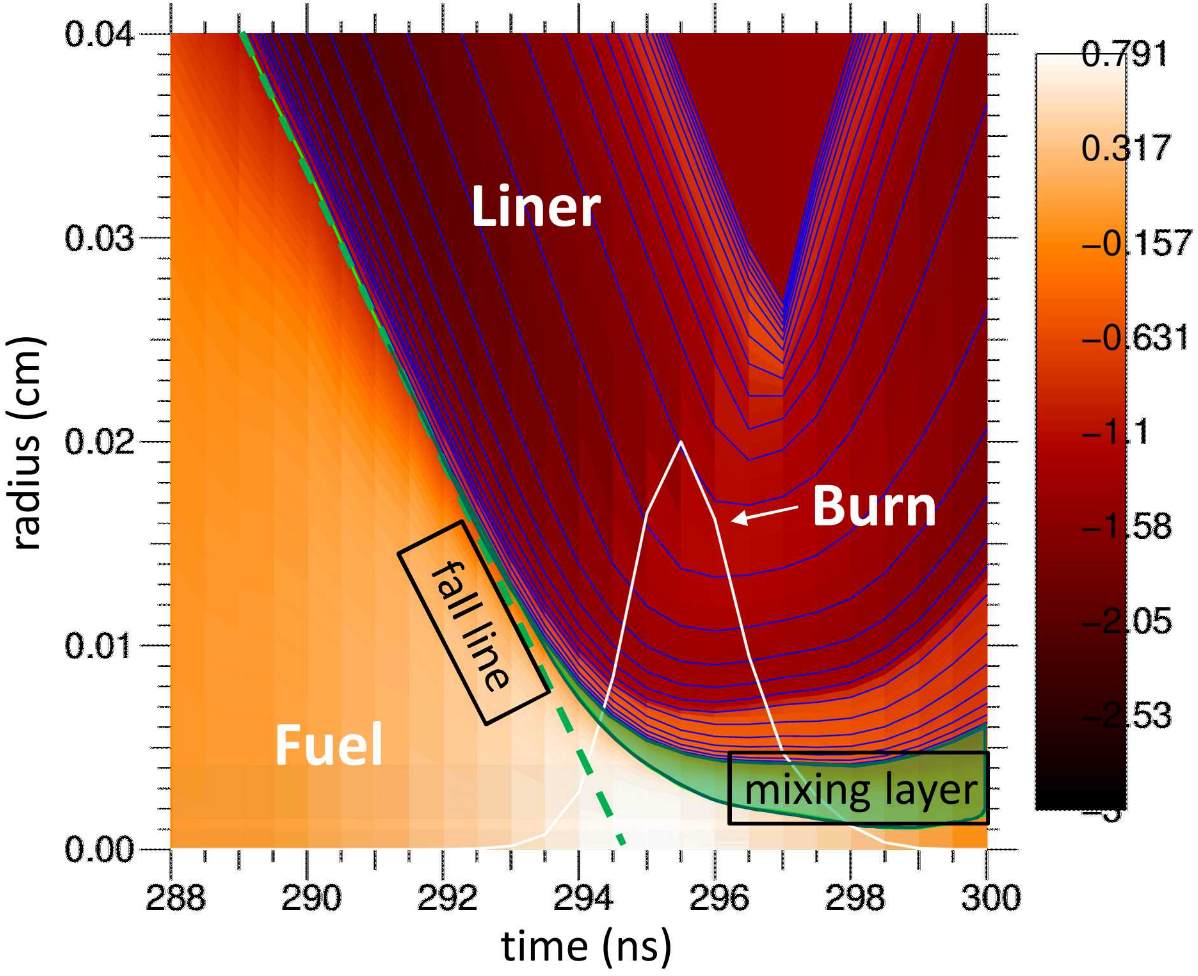
Implosion self-similarity also conserves metrics describing mix environment (e.g., fall line, turbulent layer growth [2])

Lineout of $\log_{10}[T_{\mathrm{fuel}}\ (\mathrm{keV})]$ near stagnation



[1] e.g., Lindl (1995), Nora, Betti *et al*. (2014)

[2] Dimonte & Schneider, Phys. Fluids 12, 304 (2000).

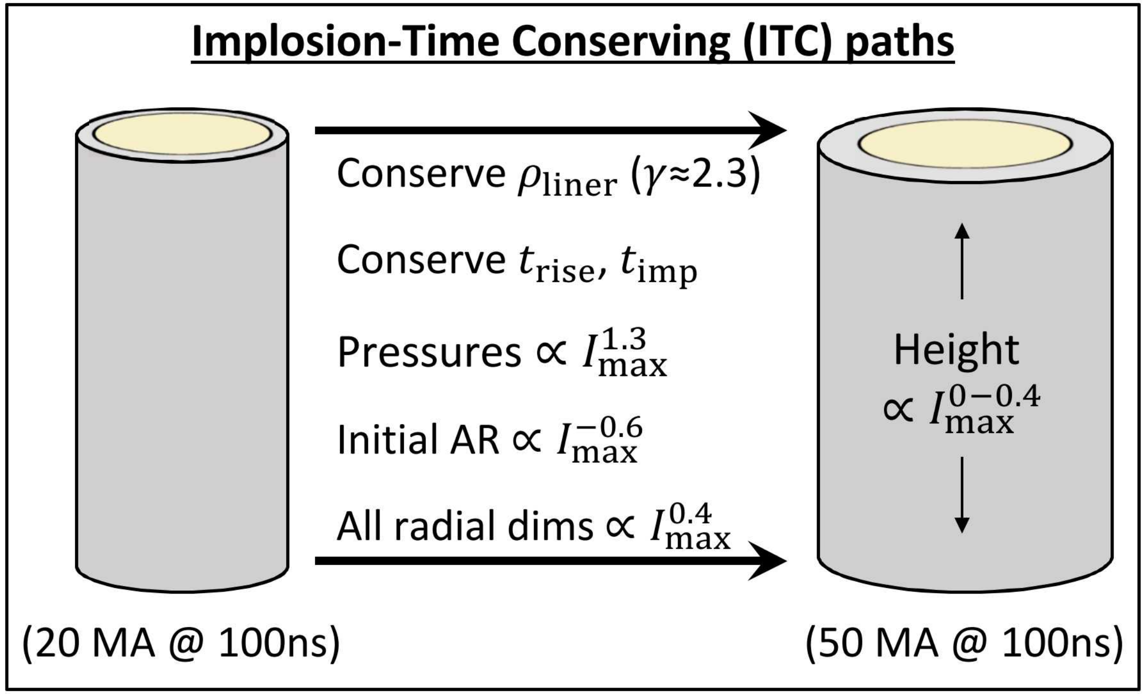
Multiple conservative scaling paths offer unique benefits and risks

All paths conserve Π, Φ, Ψ, $\tilde{t}_1$, and $\tilde{I}(\tilde{t})$, thus preserving:

- Implosion trajectories and IFAR histories
- Convergence ratios
- Growth of most-unstable MRT modes
- Mix characteristics

…and conserve end losses, reduce heat conduction losses, with fuel options that conserve radiation losses, too.

Multiple conservative scaling paths offer unique benefits and risks



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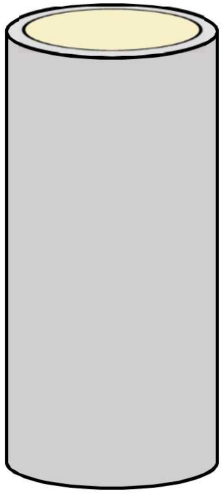
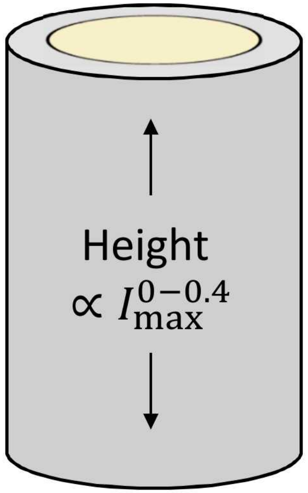
Multiple conservative scaling paths offer unique benefits and risks

Implosion-Time Conserving (ITC) paths

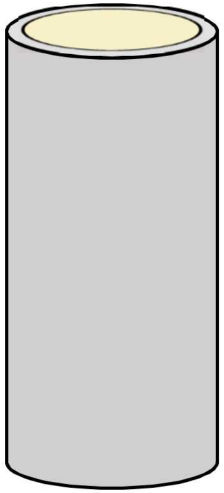


- Conserve ρ_{liner} ($\gamma \approx 2.3$)
- Conserve t_{rise}, t_{imp}
- Pressures $\propto I_{\max}^{1.3}$
- Initial AR $\propto I_{\max}^{-0.6}$
- All radial dims $\propto I_{\max}^{0.4}$



(20 MA @ 100ns) (50 MA @ 100ns)

Pressure-Velocity Conserving (PVC) paths



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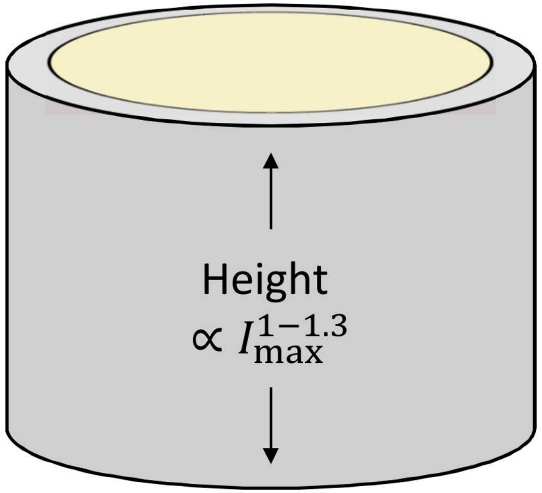
- Conserve initial AR
- Conserve pressures
- t_{rise}, $t_{\text{imp}} \propto I_{\max}$
- All radial dims $\propto I_{\max}$



(20 MA @ 100ns) (50 MA @ 250ns)

All paths conserve Π, Φ, Ψ, $\tilde{t}_1$, and $\tilde{I}(\tilde{t})$, thus preserving:

- Implosion trajectories and IFAR histories
- Convergence ratios
- Growth of most-unstable MRT modes
- Mix characteristics

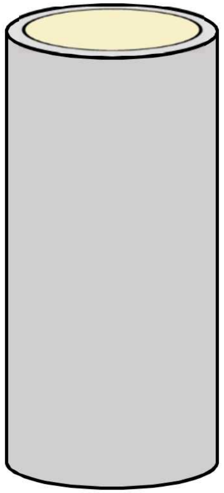
…and conserve end losses, reduce heat conduction losses, with fuel options that conserve radiation losses, too.

The MIF version of "hydro-equivalent scaling" appearing in the laser-ICF literature [1]

[1] e.g., Lindl (1995), Nora, Betti *et al.* (2014)

Multiple conservative scaling paths offer unique benefits and risks

Implosion-Time Conserving (ITC) paths



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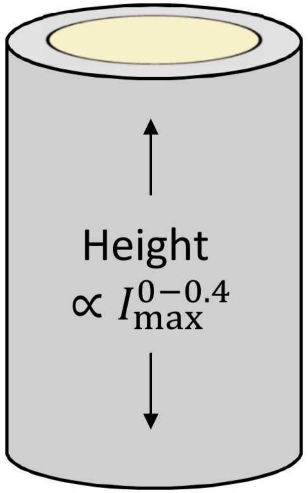

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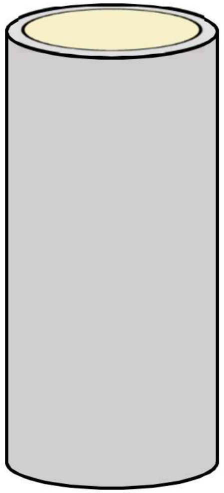

Conserve ρ_{liner} ($\gamma \approx 2.3$)

Conserve initial AR

Conserve pressures

t_{rise}, $t_{\text{imp}} \propto I_{\text{max}}$

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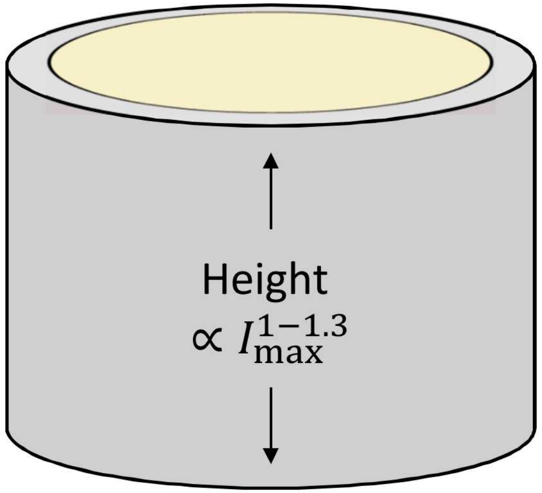


(20 MA @ 100ns) (50 MA @ 250ns)

Energy requirements (ITC)

End losses set target length scaling:

$$h \propto \boldsymbol{I}_{\textbf{max}}^{\mathbf{0-0.4}}$$

All energies scale like $I_{\text{max}}^2 \times$ length:

$$E \propto \boldsymbol{I}_{\textbf{max}}^{\mathbf{2-2.4}}$$

Significantly lower energy requirements for ITC paths…

Energy requirements (PVC)

End losses set target length scaling:

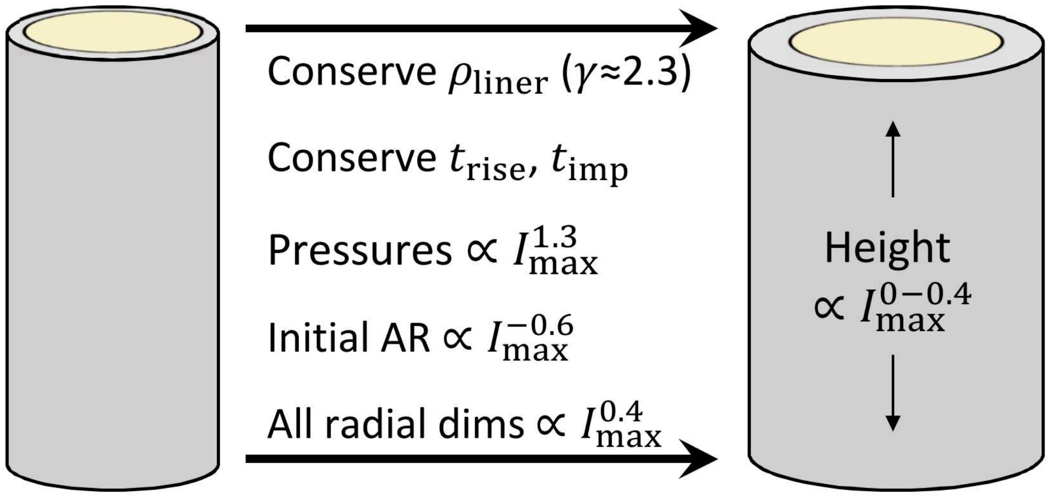
$$h \propto \boldsymbol{I}_{\textbf{max}}^{\mathbf{1-1.3}}$$

All energies scale like $I_{\text{max}}^2 \times$ length:

$$E \propto \boldsymbol{I}_{\textbf{max}}^{\mathbf{3-3.3}}$$

Multiple conservative scaling paths offer unique benefits and risks

Implosion-Time Conserving (ITC) paths



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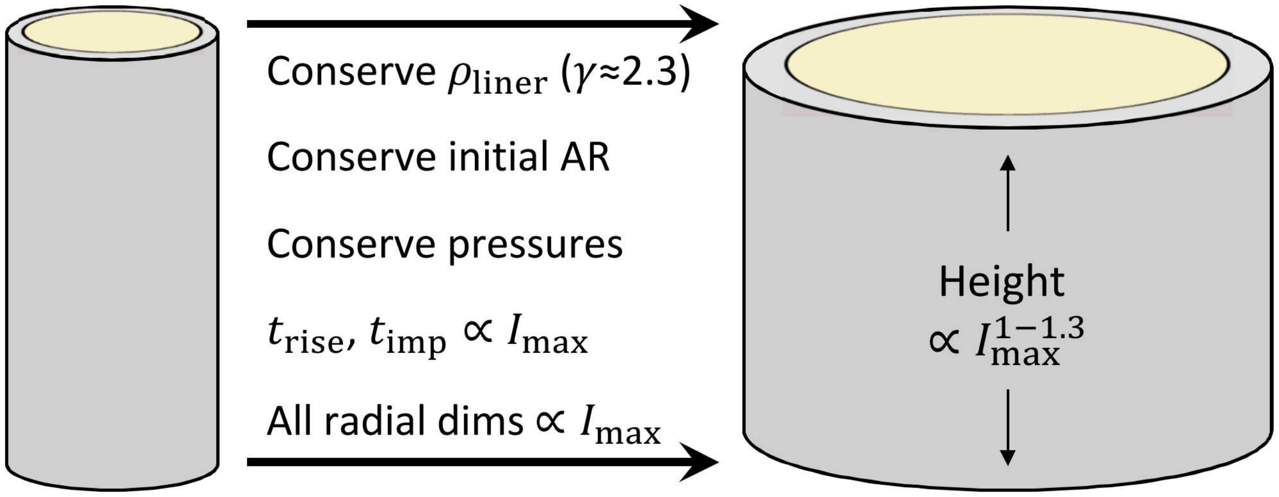

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Energy requirements

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$h \propto \boldsymbol{I_{\max}^{0-0.4}}$

All energies scale like $I_{\max}^2 \times$ length:

$E \propto \boldsymbol{I_{\max}^{2-2.4}}$

…BUT, PVC paths afford operation at longer current rise times.

Energy requirements

End losses set target length scaling:

$h \propto \boldsymbol{I_{\max}^{1-1.3}}$

All energies scale like $I_{\max}^2 \times$ length:

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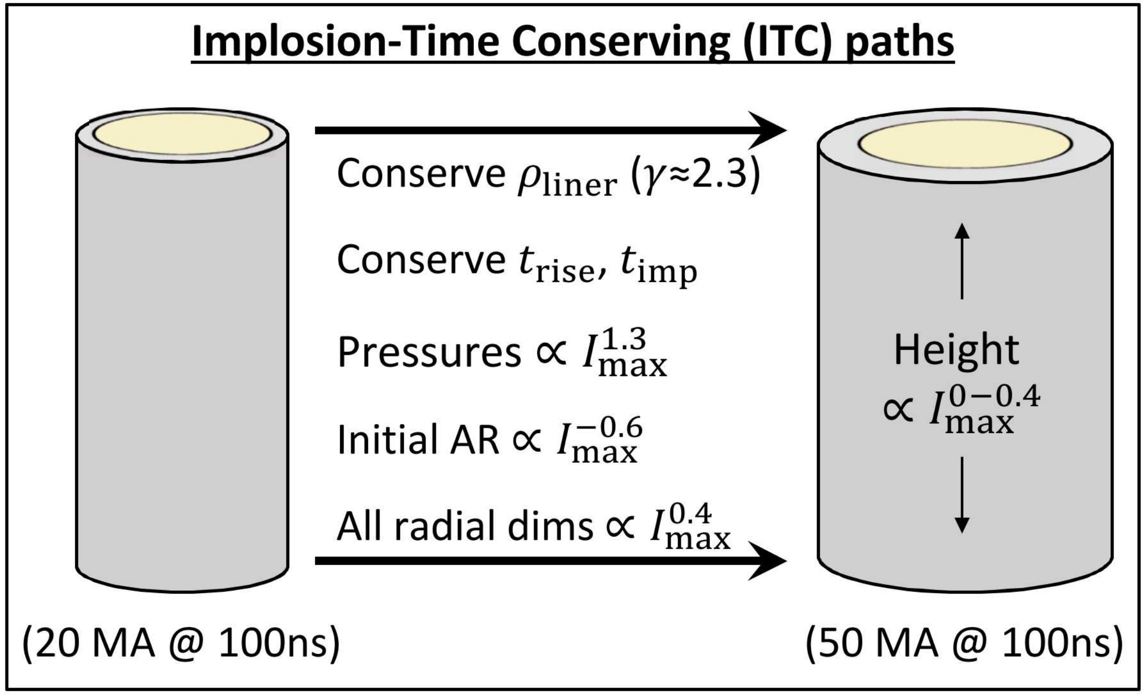
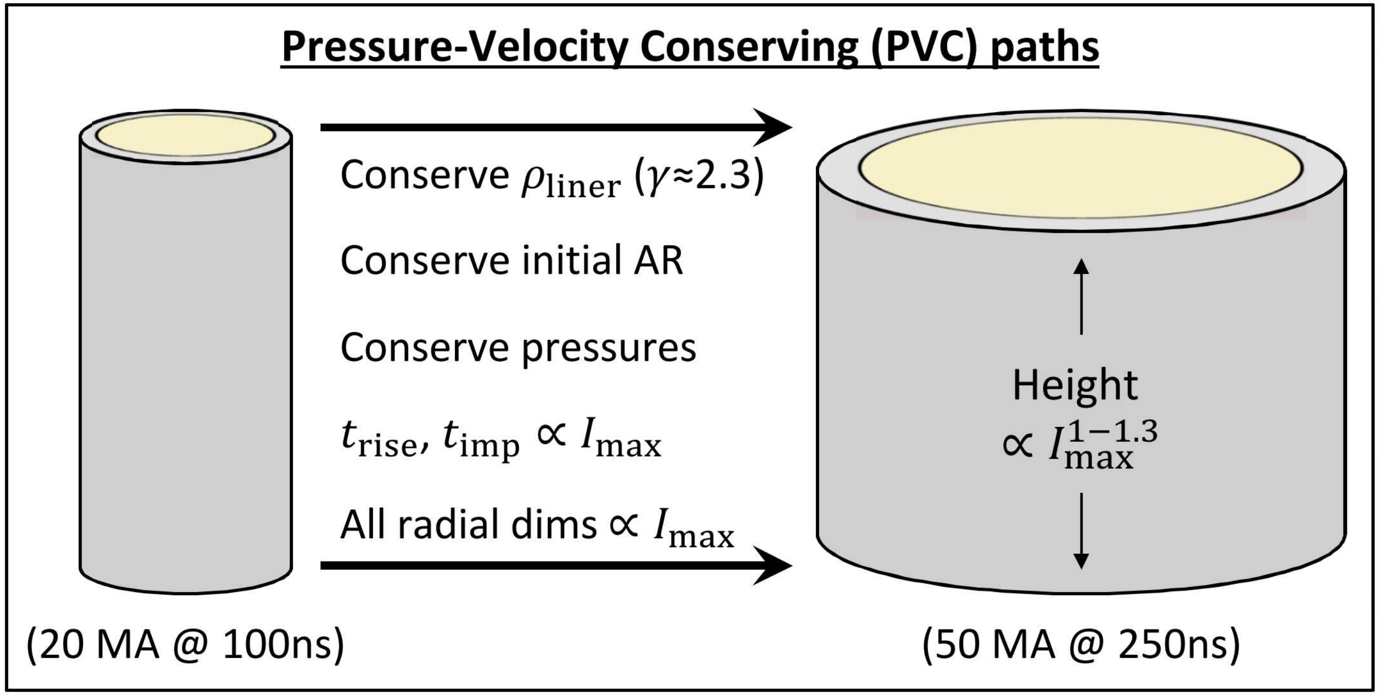
Multiple conservative scaling paths offer unique benefits and risks





Outcomes for ICF – ITC paths

Yield/height scaling (“no-α”):

$$Y/h \propto \boldsymbol{I}_{\max}^{3.3-4.1}$$

Ignition scaling (“no-α”):

$$\chi \propto S(T)P\tau \propto \boldsymbol{I}_{\max}^{1.3-2.1}$$

Slightly stronger scaling of ignition metrics when following ITC scaling paths, but not huge differences…

Outcomes for ICF – PVC paths

Yield/height scaling (“no-α”):

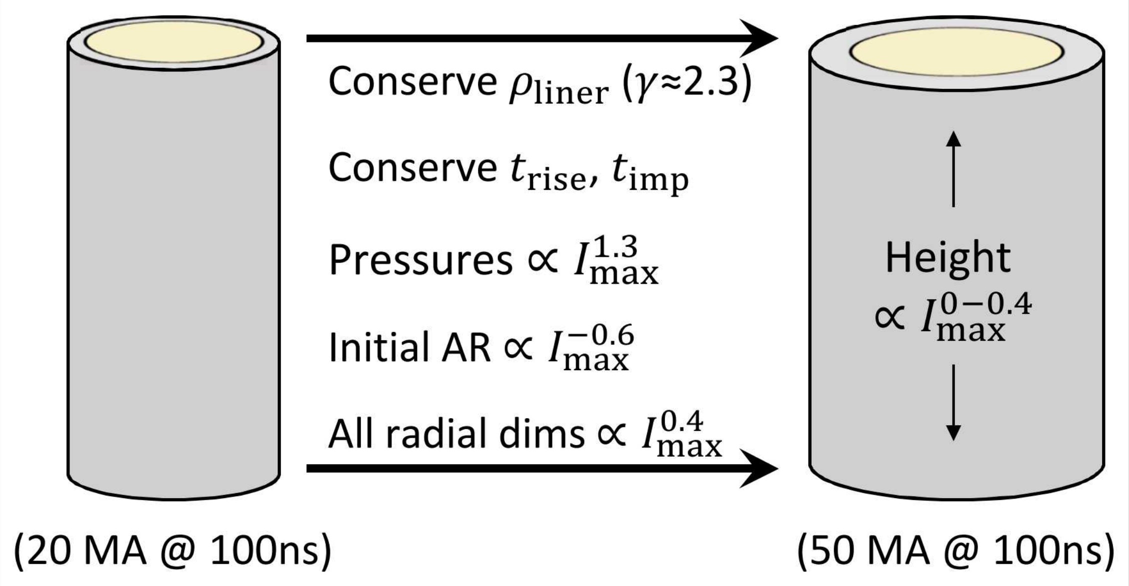
$$Y/h \propto \boldsymbol{I}_{\max}^{3-3.7}$$

Ignition scaling (“no-α”):

$$\chi \propto S(T)P\tau \propto \boldsymbol{I}_{\max}^{1-1.7}$$

Multiple conservative scaling paths offer unique benefits and risks

Implosion-Time Conserving (ITC) paths



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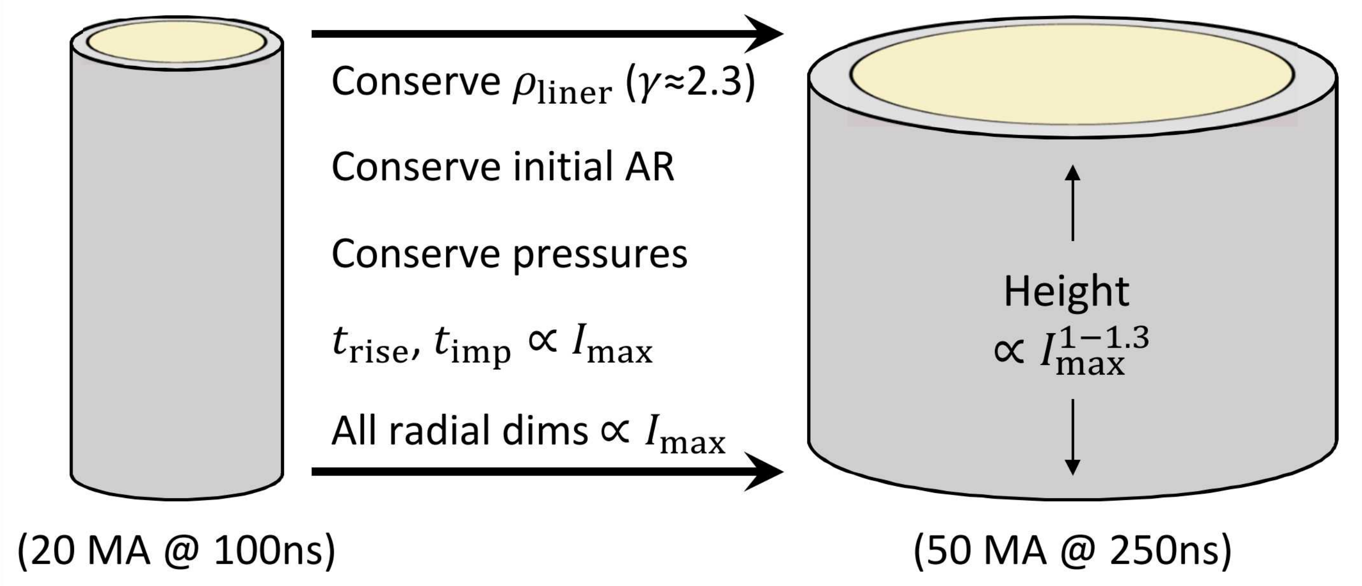


Outcomes for ICF – ITC paths

Yield scaling ("no-α"):

$Y \propto \boldsymbol{I}_{\mathbf{max}}^{\mathbf{3.3-4.6}}$

Ignition scaling ("no-α"):

$\chi \propto S(T)P\tau \propto \boldsymbol{I}_{\mathbf{max}}^{\mathbf{1.3-2.1}}$

…AND, added length associated with PVC paths leads to stronger yield scaling overall, at cost of additional driver energy.

Outcomes for ICF – PVC paths

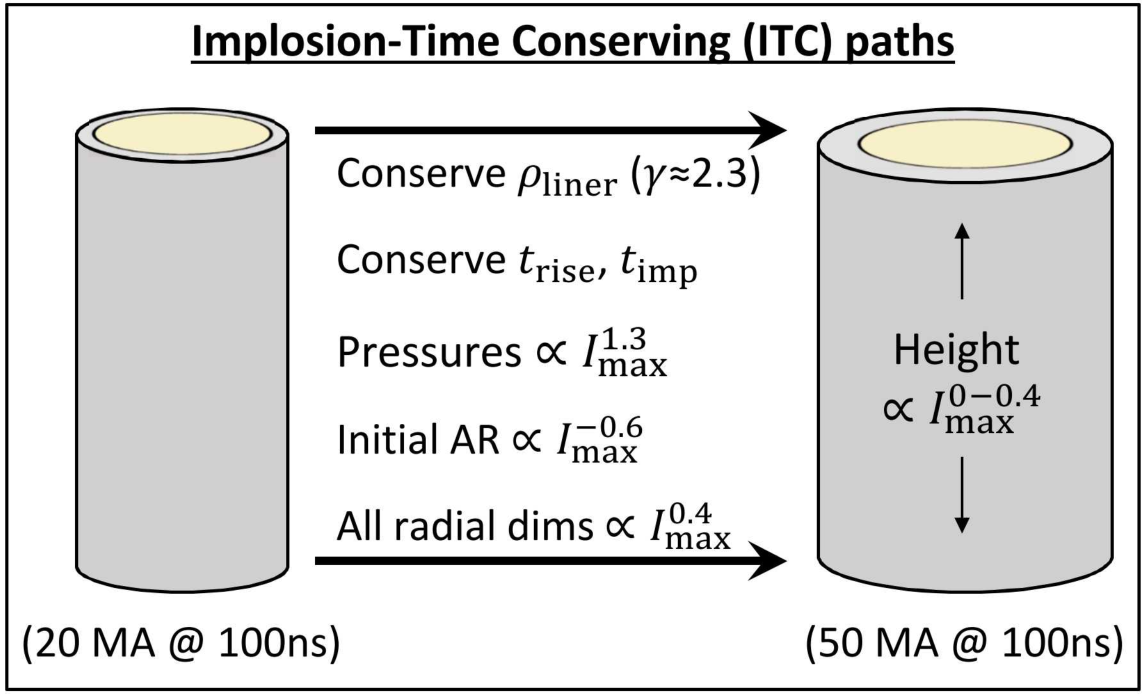
Yield scaling ("no-α"):

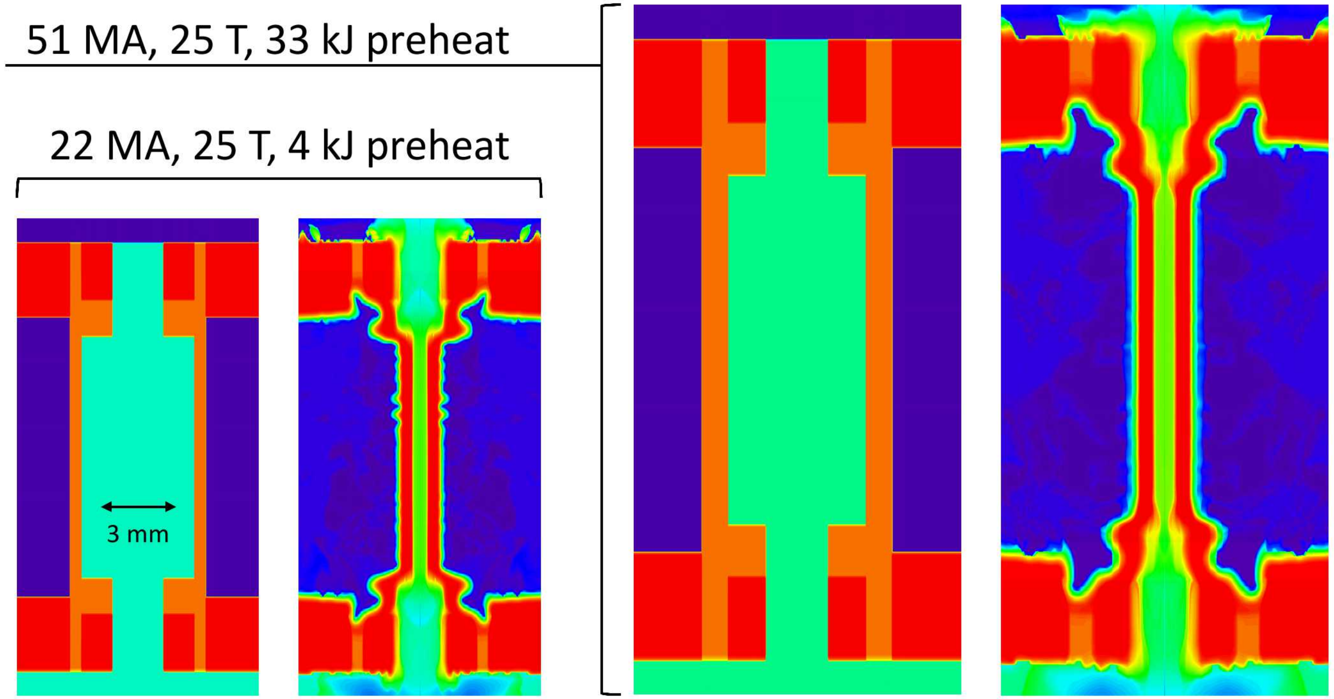
$Y \propto \boldsymbol{I}_{\mathbf{max}}^{\mathbf{4-5}}$

Ignition scaling ("no-α"):

$\chi \propto S(T)P\tau \propto \boldsymbol{I}_{\mathbf{max}}^{\mathbf{1-1.7}}$

Preliminary LASNEX studies confirm efficacy of the theory and suggest multiple paths to multi-MJ yields possible for MagLIF





Y_{DT} = **0.13 MJ**

Y_{DT} = **13 MJ**

Theory

$Y_{\text{no}\,\alpha} = 0.12$ MJ

$\chi_{\text{no}\,\alpha} = 0.7$

$Y_{\text{no}\,\alpha} = 6.2$ MJ → 6.3 MJ

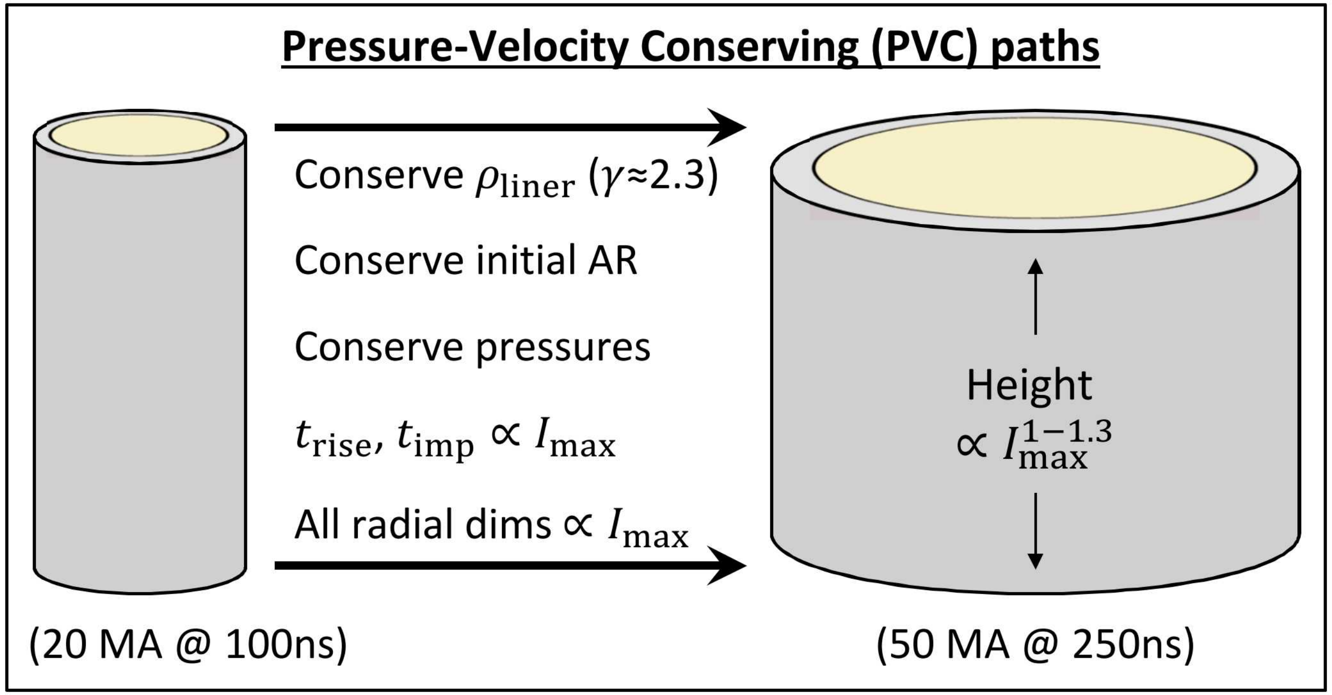
$\chi_{\text{no}\,\alpha} = 4.3$ → 4.5

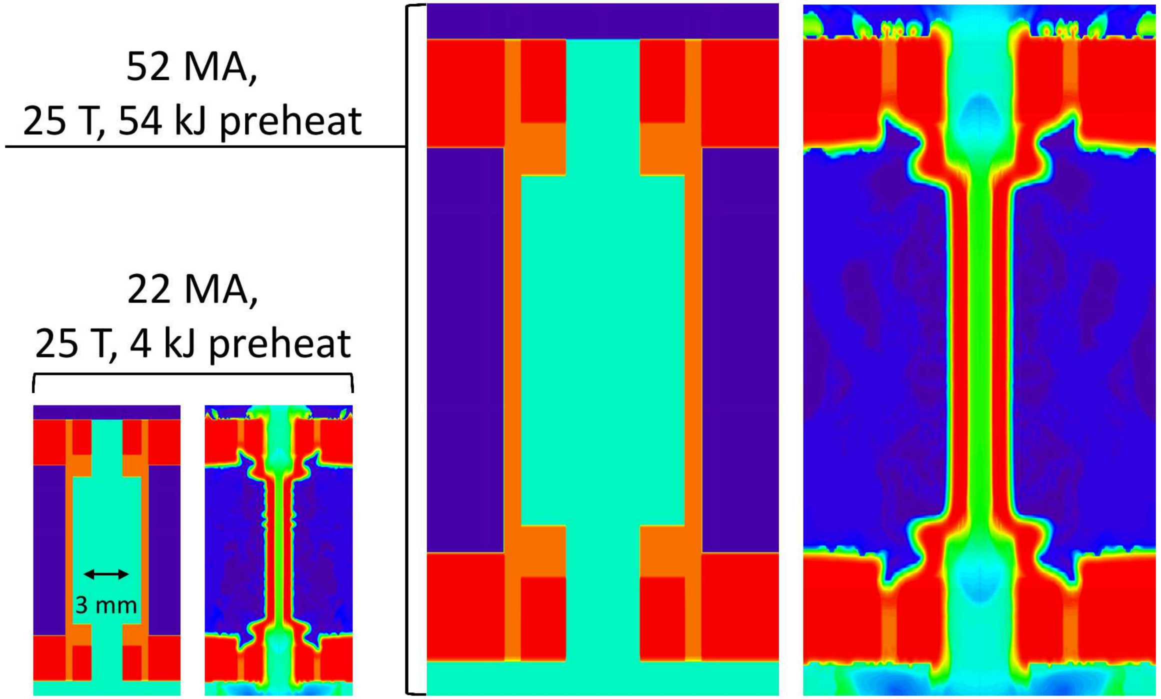
Scaling a target signifying a multi-year capability-development effort on Z [1] to ~50 MA along **ITC** path shows **>10 MJ DT yields possible** in a self-heating regime.

IFAR conserved to 4%, CR conserved to 9%.

[1] Slutz *et al.*, Phys. Plasmas 25, 112706 (2018).

Preliminary LASNEX studies confirm efficacy of the theory and suggest multiple paths to multi-MJ yields possible for MagLIF





$\boldsymbol{Y_{DT}} \rightarrow$ **0.13 MJ**

$\boldsymbol{Y_{DT}} \rightarrow$ **25 MJ**

Theory

$Y_{\text{no }\alpha} \rightarrow 0.12$ MJ

$\chi_{\text{no }\alpha} \rightarrow 0.7$

$Y_{\text{no }\alpha} \rightarrow 10.6$ MJ → 3.9 MJ

$\chi_{\text{no }\alpha} \rightarrow 4.0$ → 1.7

Scaling a target signifying a multi-year capability-development effort on Z [1] to ~50 MA along **PVC** path shows **>20 MJ DT yields** possible in a self-heating regime ***at much longer current rise time!***

IFAR conserved to 15%, CR conserved to 8%.

[1] Slutz *et al.*, Phys. Plasmas 25, 112706 (2018).

Our framework can guide near-term experimental scaling studies, unambiguously tie present-day platforms to future point designs

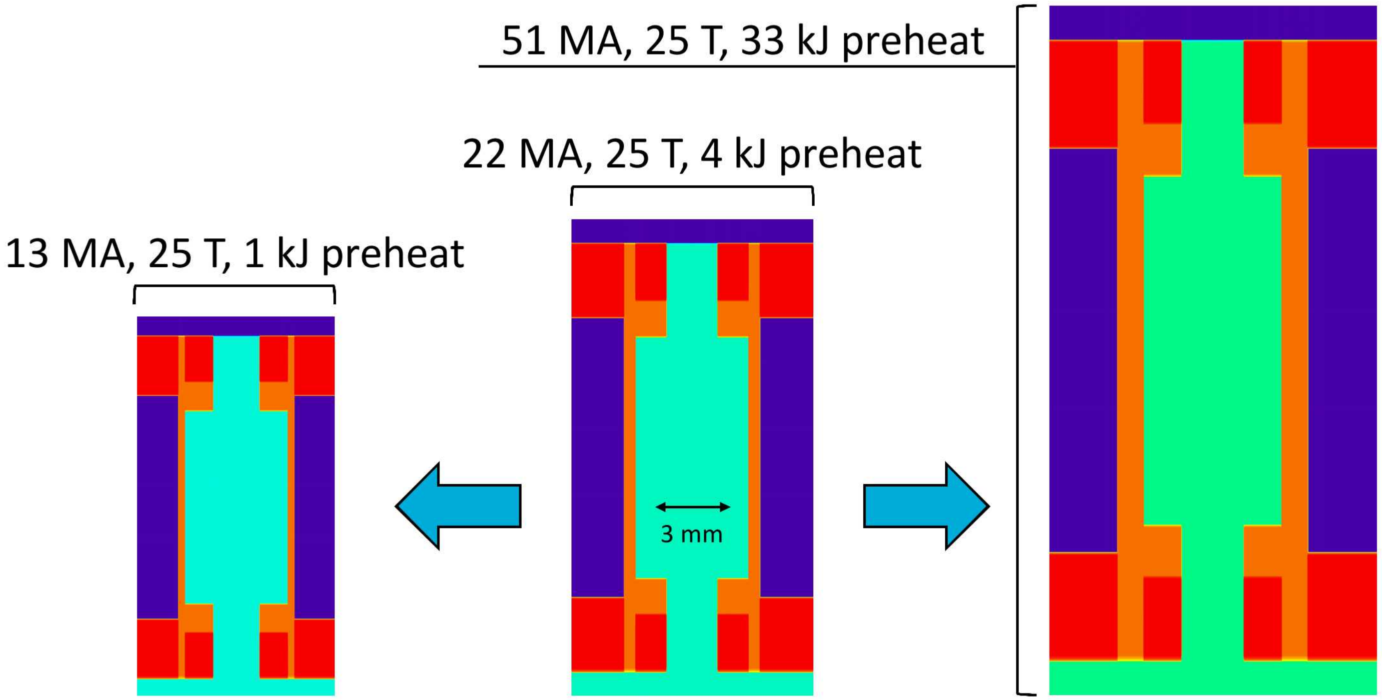
This work [1] builds on encouraging MagLIF scaling studies by providing scaling rules that aim to improve performance while minimizing deviations in the target physics regimes to help alleviate risks posed by physics model uncertainties.

$$\tilde{R}\ddot{\tilde{R}} = -\Pi \tilde{I}^2 + \Phi \tilde{R}^{2-2\gamma}\Theta(\tilde{t} - \tilde{t}_1)$$

$$+$$

$$\text{IFAR} \propto \text{AR}\, P_{\text{out}}^{1/\gamma} \doteq \Psi$$

Our results apply to near-term and long-term thrusts, helping build confidence in future point designs tied to present-day experiments, and guiding direct scaling investigations at lower energies on present-day drivers.



THANK YOU!

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