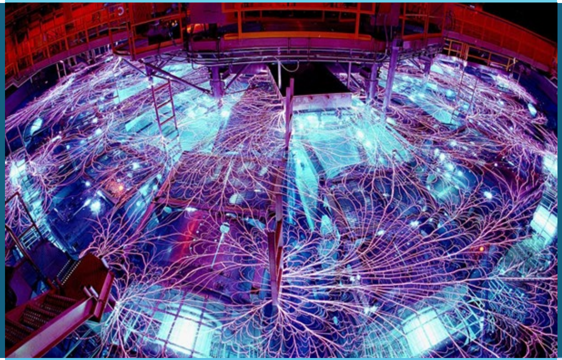
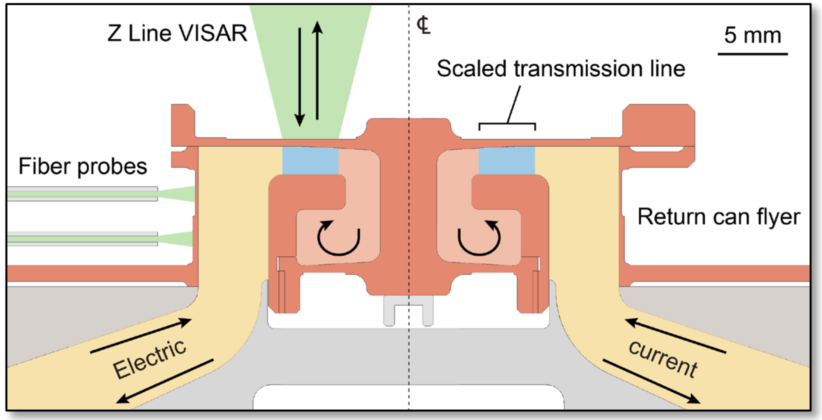
SAND2021-14005C

Sandia National Laboratories

Using scaled power flow experiments at 20 MA to establish the efficacy of load current delivery on a >50 MA next-generation pulsed power facility





PRESENTED BY

Clayton E. Myers

APS-DPP – November 8, 2021

U.S. DEPARTMENT OF ENERGY NNSA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

The Z Power Flow Scaling effort is enabled by a diverse team of collaborators

Simulations & analysis	Chris Jennings
Power flow physics	Nicky Bennett, Kathy Chandler, Will Farmer, Matt Gomez, Mark Hess, Brian Hutsel, Andy Porwitzky, Daniel Ruiz, and Eduardo Waisman
Program support	George Laity, Mike Cuneo, David Ampleford, Kyle Peterson, Greg Rochau, and Dan Sinars
Z Line VISAR operations	Dave Bliss, Neil Butler, Mike Montoya, and Gene Vergel de Dios
Z Line VISAR analysis	Peter Celliers, Dayne Fratanduono, and Trevor Hutchinson
Z Load Hardware	Carlos Aragon, Roger Harmon, Jerry Jackson, Dustin Marshall, Leo Molina, Reny Paguio, Grafton Robertson, Gary Smith, Jerry Taylor, Adam York, and many more
Z Diagnostics	Tom Avila, Chris Delacruz, Jeff Gluth, Michael Jones, Jim Moore, Sonal Patel, Ron Mourning, Ed Scoglietti, and many more

Sandia National Laboratories

Lawrence Livermore National Laboratory

Scaled Power Flow Experiments on Z

1. **Motivation for a next-generation pulsed power (NGPP) facility.**
2. **Design of a 50-MA-equivalent power flow scaling platform at 20 MA on Z.**
3. **Using velocimetry to diagnose the current delivered through scaled transmission lines.**
4. **Results, analysis, and modeling of the first power flow scaling experiments.**
5. **Follow-on scaling experiments and future work.**

The first power flow scaling experiments on Z indicate that the current coupling through a 50-MA-equivalent transmission line (R ~ 1–2 cm) is essentially lossless.

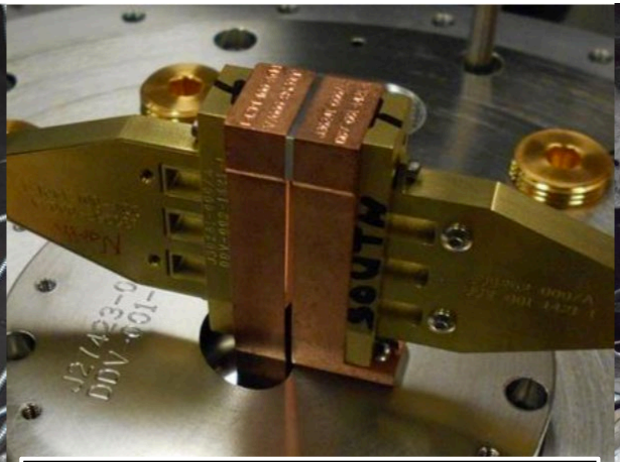
Scaled Power Flow Experiments on Z

1. **Motivation for a next-generation pulsed power (NGPP) facility.**
2. **Design of a 50-MA-equivalent power flow scaling platform at 20 MA on Z.**
3. **Using velocimetry to diagnose the current delivered through scaled transmission lines.**
4. **Results, analysis, and modeling of the first power flow scaling experiments.**
5. **Follow-on scaling experiments and future work.**

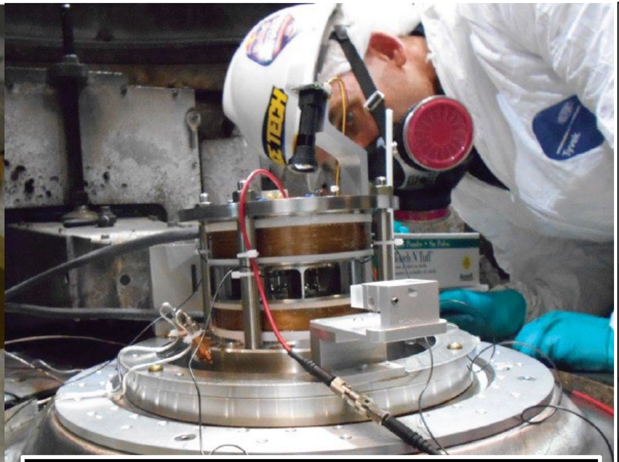
The first power flow scaling experiments on Z indicate that the current coupling through a 50-MA-equivalent transmission line (R ~ 1–2 cm) is essentially lossless.

A next-generation pulsed power (NGPP) facility will provide a world-leading, multi-mission capability for stockpile stewardship and discovery science.

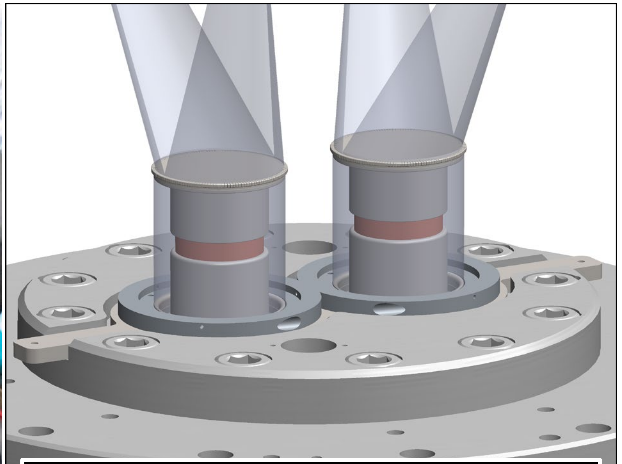
Radiation Science



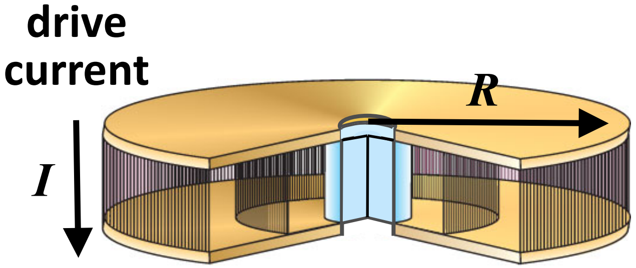
Dynamic Material Properties

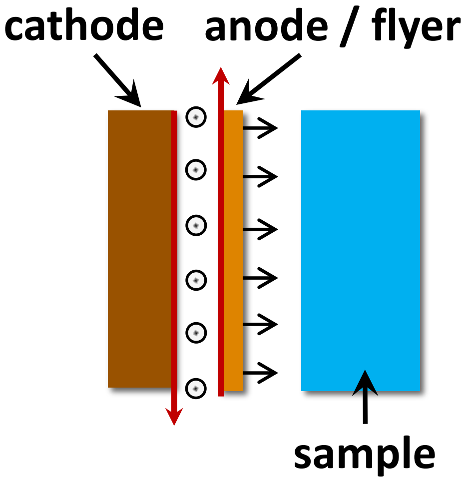


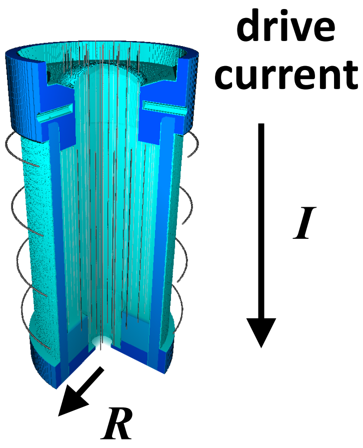
Inertial Confinement Fusion



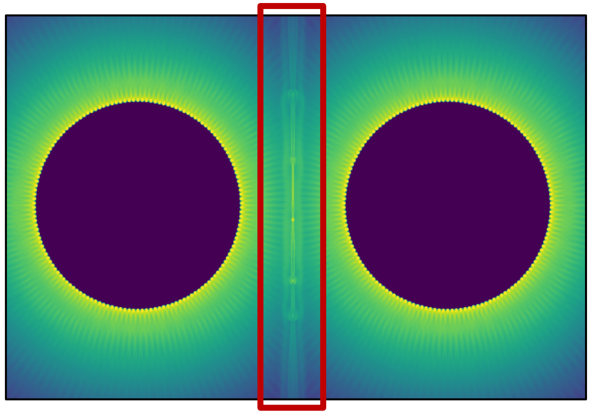
HED Discovery Science







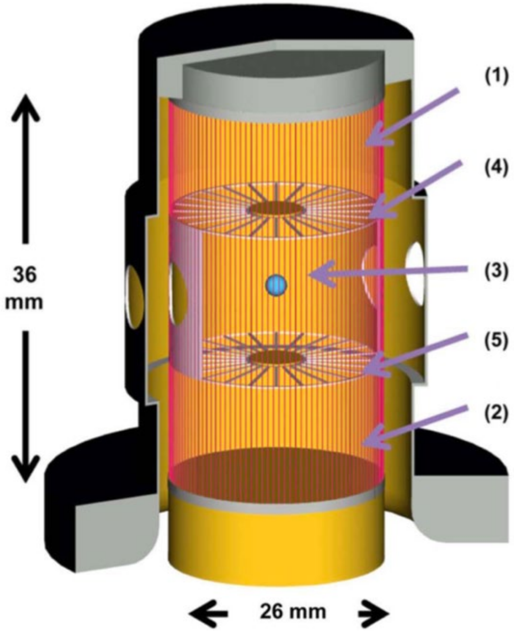
MARZ: Radiative reconnection

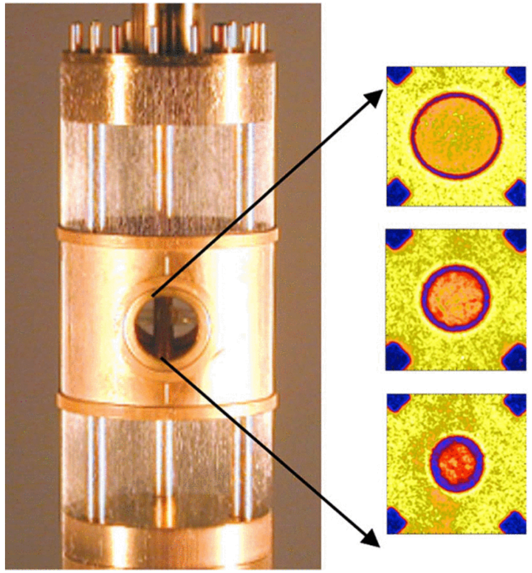


NP11.00102/103/104 – Wed. AM

An NGPP facility will enable the pursuit of high fusion yield from both magnetic indirect drive (MID) and magnetic direct drive (MDD) concepts.

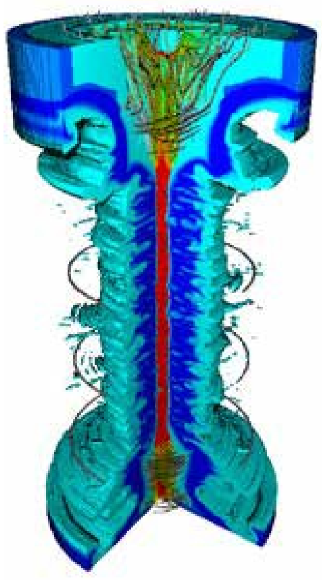
MID – Double-Ended Hohlraum

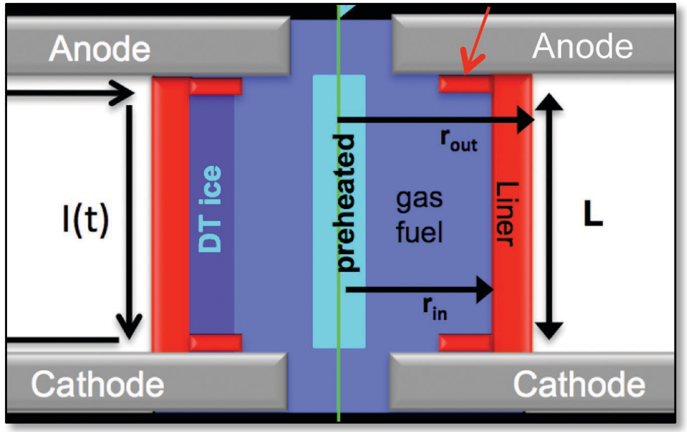




- Studied on Z in the 2000s [Cuneo *IEEE TPS* 2012].
- Generated symmetric capsule implosions to CR 14.
- Scales to ~0.5 GJ at >60 MA [Vesey *PoP* 2007].
- MID research on Z paused in ~2007 with NIF startup.

MDD – MagLIF Ice Burner





Slutz et al. *PoP* 2016

- MagLIF actively studied on Z [e.g., Gomez *PRL* 2020].
- Generates >10^{13} DD neutrons or ~5 kJ DT-equivalent.
- DT "ice burners" scale to high yield (>1 GJ) at >60 MA [Slutz *PoP* 2016, 2018 and NP11.00076 – Wed. AM].

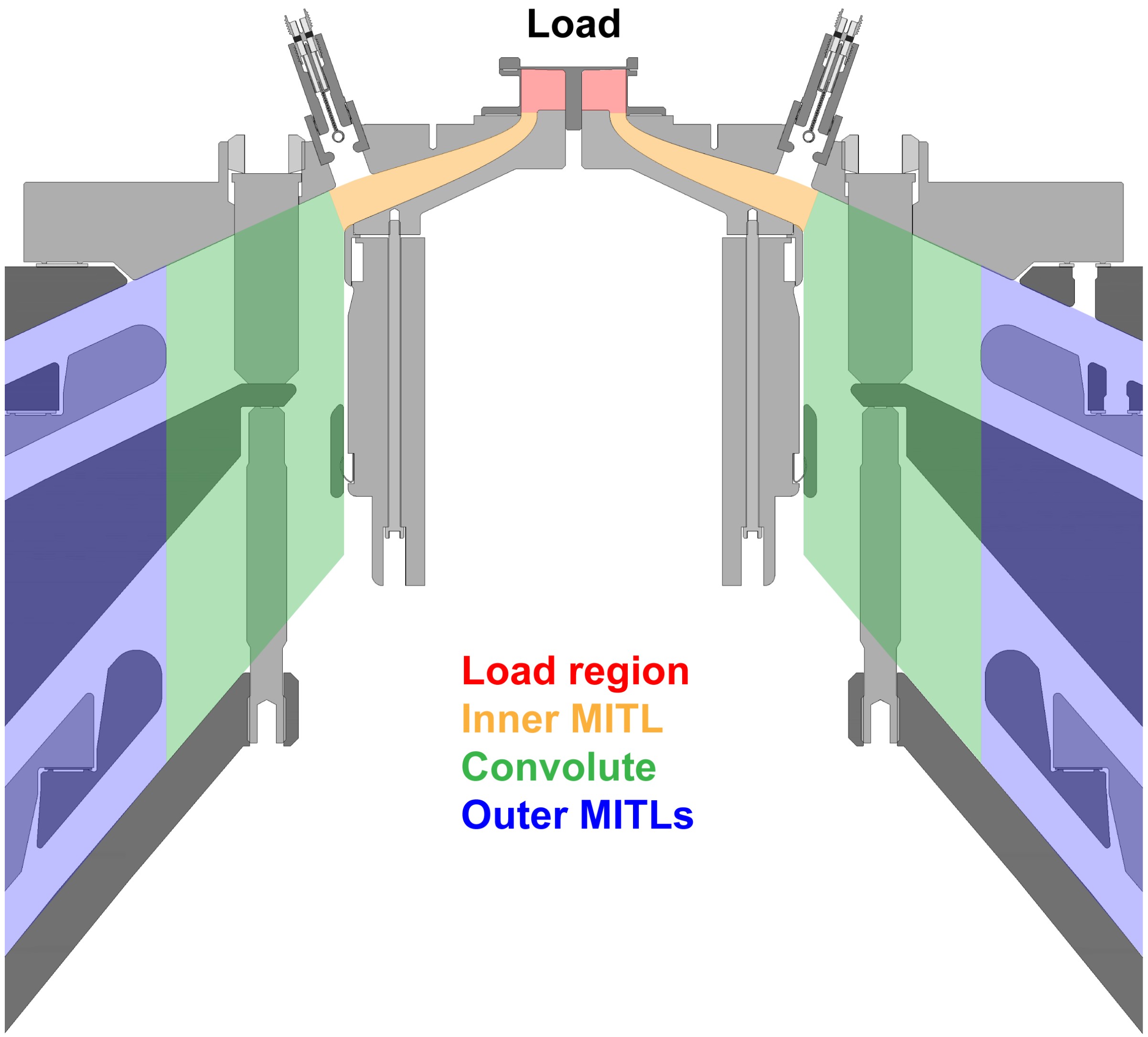
Scaled Power Flow Experiments on Z

1. Motivation for a next-generation pulsed power (NGPP) facility.
2. **Design of a 50-MA-equivalent power flow scaling platform at 20 MA on Z.**
3. Using velocimetry to diagnose the current delivered through scaled transmission lines.
4. Results, analysis, and modeling of the first power flow scaling experiments.
5. Follow-on scaling experiments and future work.

The first power flow scaling experiments on Z indicate that the current coupling through a 50-MA-equivalent transmission line (R ~ 1–2 cm) is essentially lossless.

An NGPP facility will likely use the post-hole convolute transmission line architecture that has been used to great effect on Z and Saturn before it.

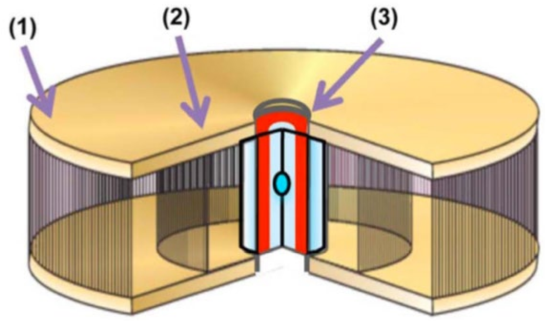
- Four parallel **outer MITLs** (magnetically insulated transmission lines) combine at the **convolute** to form one **inner MITL**.
- The **inner MITL** delivers current to the **load region** where the associated magnetic pressure implodes the load.
- Current loss can occur in the **convolute**, the **inner MITL**, and/or the **load region**.
- **Key question:** Will this architecture hold up under increased electromagnetic stress on an NGPP facility?
- **Approach:** Conduct scaled power flow experiments at 20 MA on Z to test current delivery at 50 MA NGPP conditions.

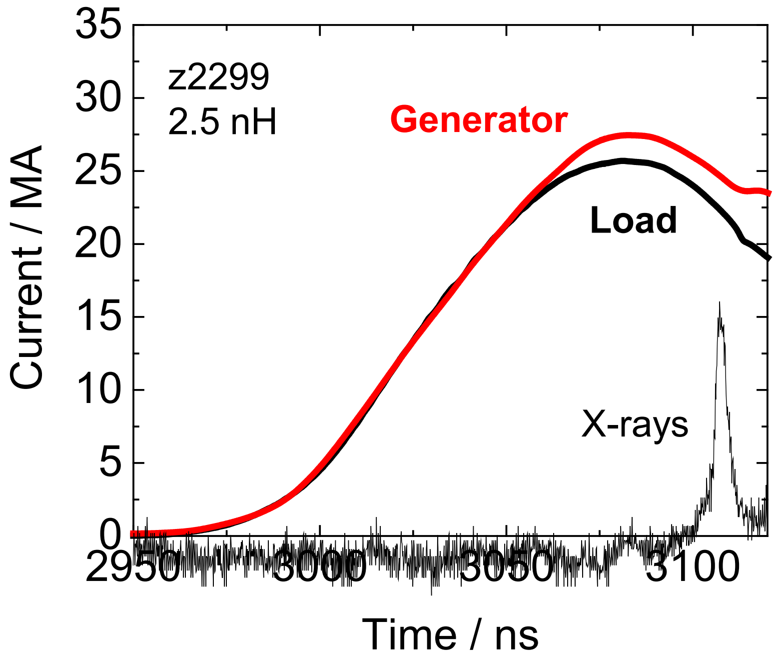


Z is quite successful at driving a number of different physics loads. Current loss depends on the inductive characteristics of the load.

Dynamic Hohlraum

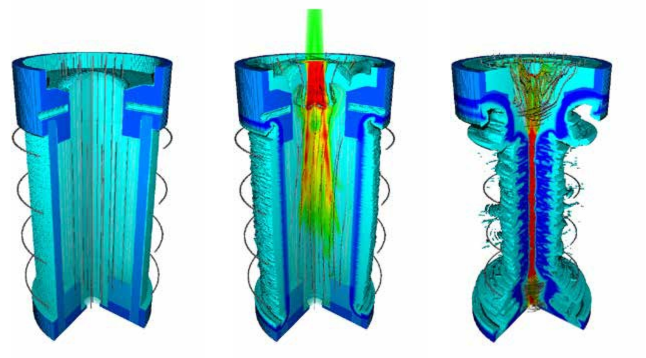
The load that Z was designed to drive.

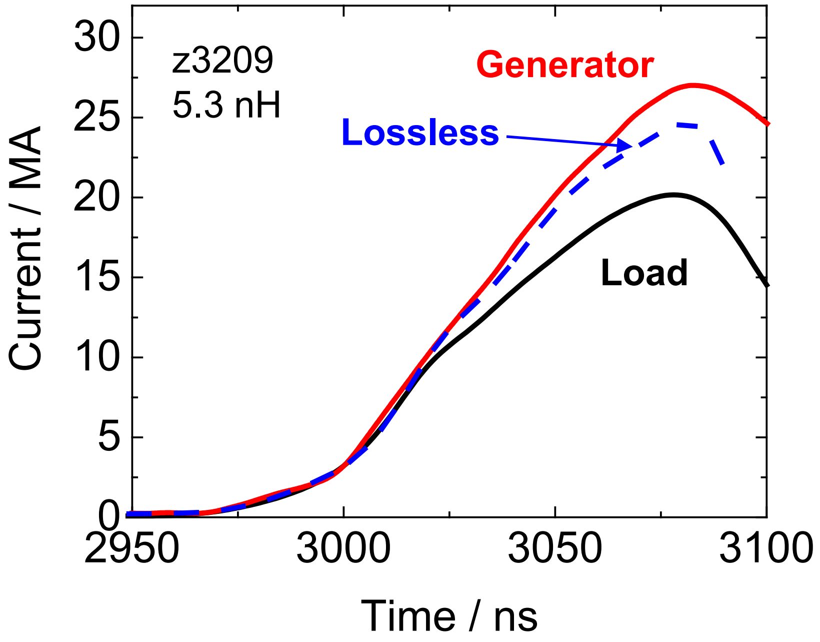




MagLIF

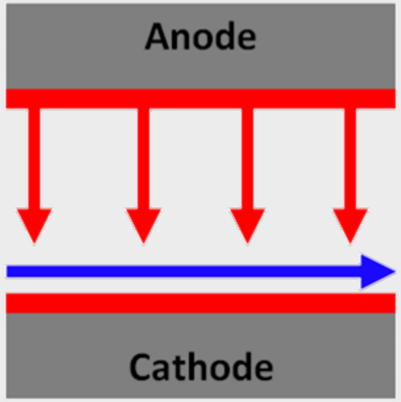
One of the most stressful loads for Z.





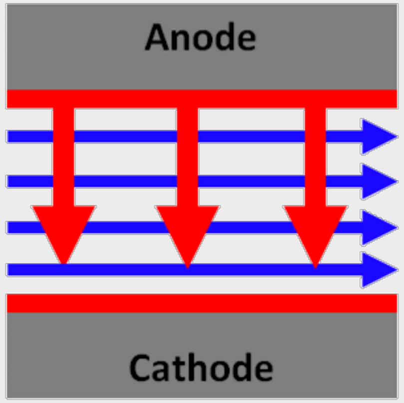
Current loss mechanisms are thought to be self-limiting, and we are building predictive multi-scale models. → Are there any surprises at NGPP conditions?

Power-flow loss mechanisms are generally understood to be self-limiting



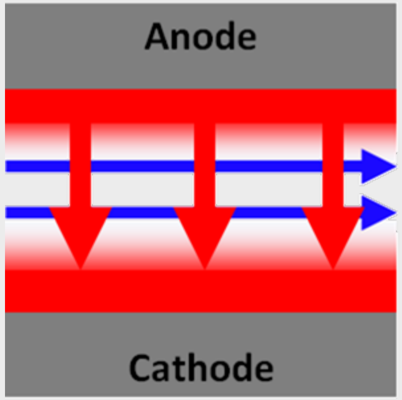
Electron flow current and ion diode losses

Space charge limited, clamped by magnetic insulation



Ion losses enhanced by electron flow

Space charge limited, clamped by negative voltage feedback



Plasma expansion & gap closure

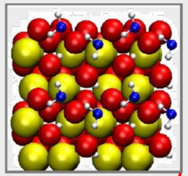
Reducing the effective gap could enhance losses

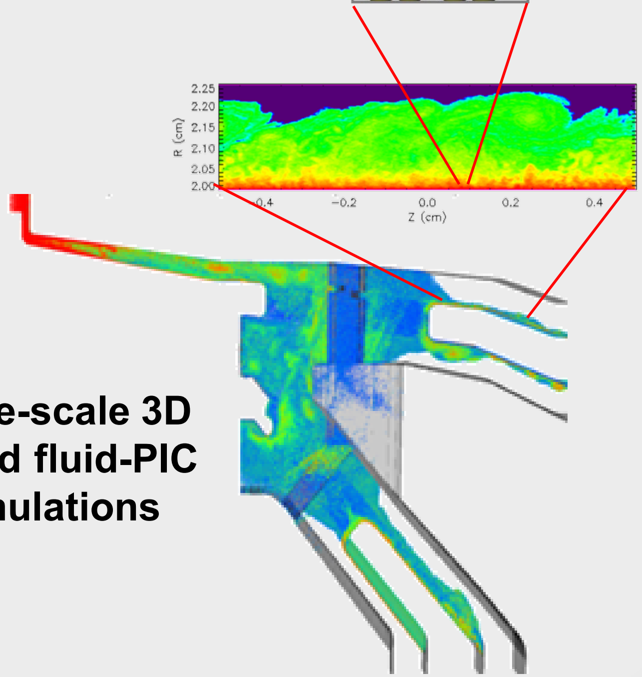
Use both experiments and modeling to test our understanding.

Efficient models will improve our detailed 3D understanding

(DFT on H2O desorption)

Detailed surface science models



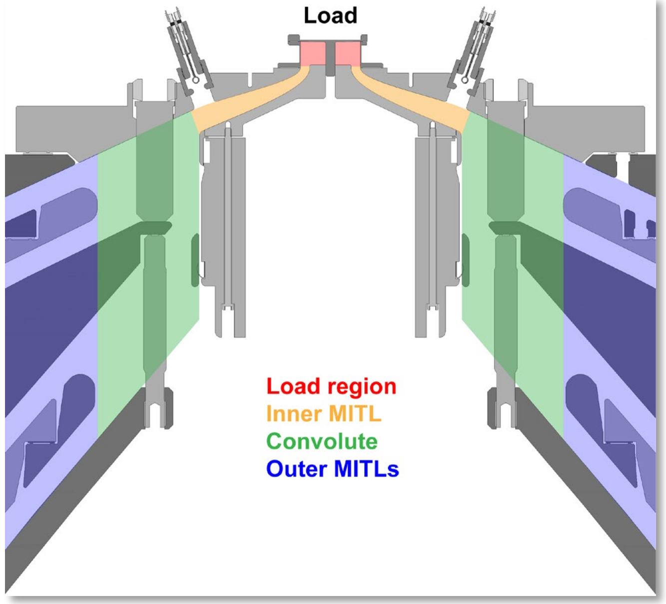


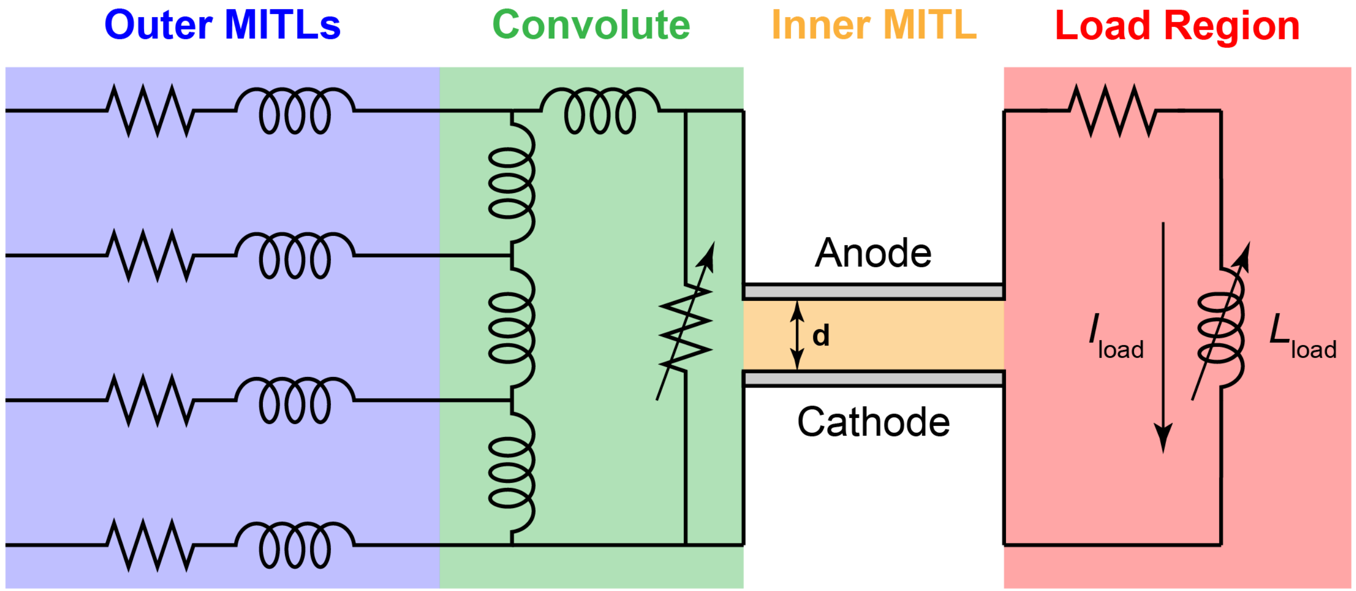
Large-scale 3D hybrid fluid-PIC simulations

Hutsel et al. *PRAB* **21**, 030401 (2018)

Bennett et al. *PRAB* **22**, 120401 (2019)

Here we focus on the inner MITL. → Model as a radial transmission line driven by a generator and stressed by an imploding inductive load.





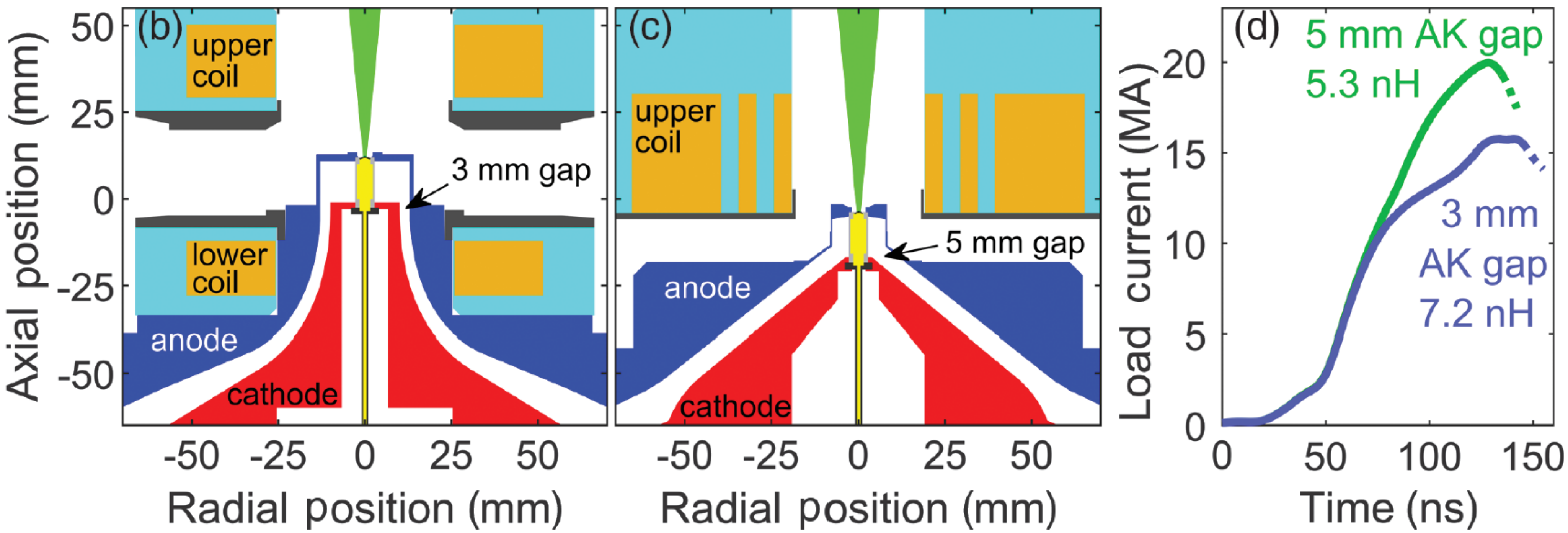
B-field, current density, and ohmic heating

$$B \propto \frac{I_{\text{load}}}{R} \qquad J \propto \frac{I_{\text{load}}}{R} \qquad P_{\text{OH}} \propto \frac{I_{\text{load}}^2}{R^2}$$

Electric field → static + dynamic

$$E = \frac{V}{d} = -\frac{\dot{\Phi}}{d} \sim -\frac{I_{\text{load}}}{d}\left(i\omega L_{\text{load}} + \dot{L}_{\text{load}}\right)$$

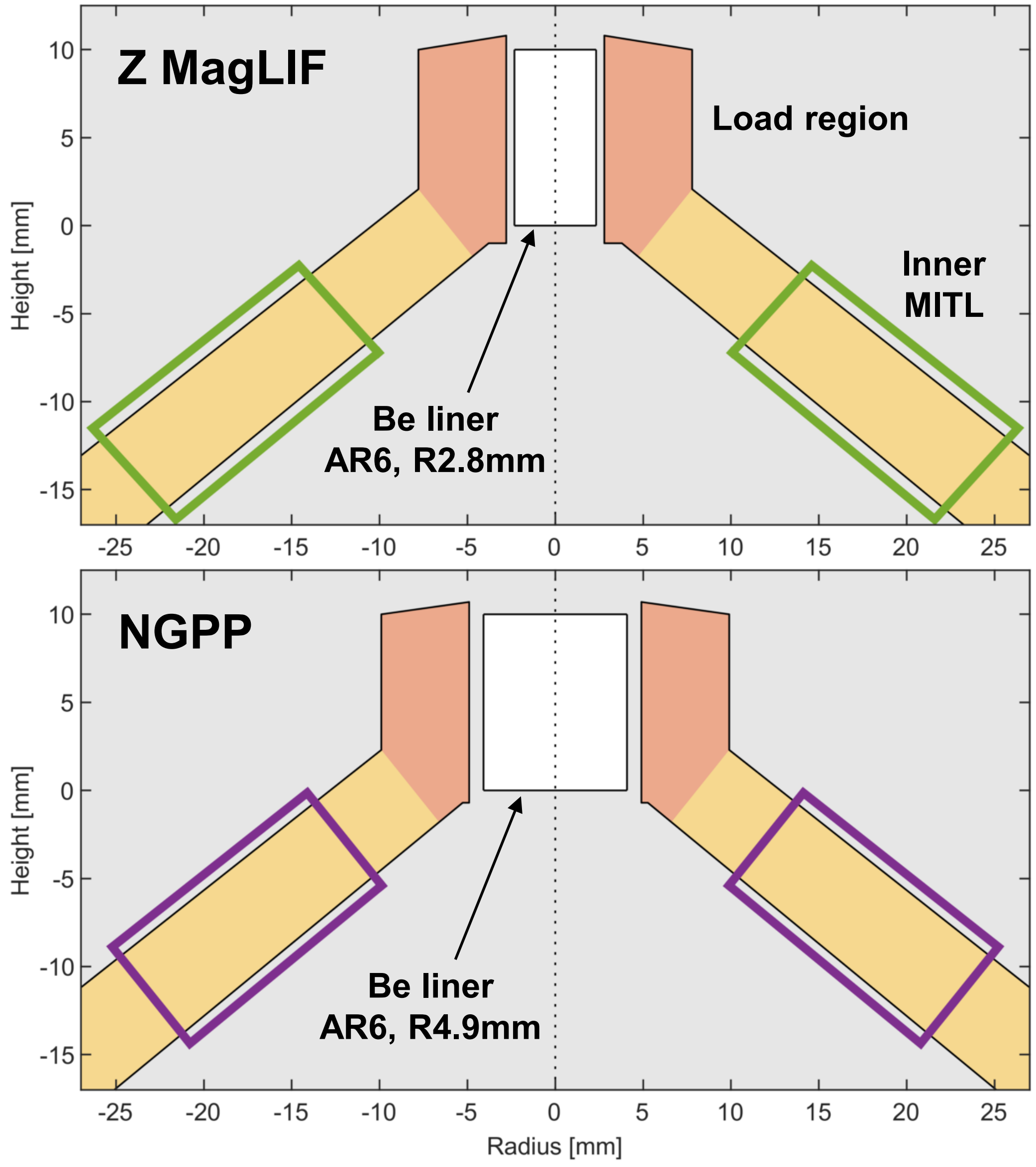
Recent MagLIF experiments demonstrate the importance of understanding and mitigating inner MITL current loss on Z [Gomez *PRL* 2020].



- **Tactics:** Grow the minimum A/K gap and reduce the load region inductance.
- **Result:** MagLIF current delivery increases from ~16 MA to ~20 MA.
- Additional tests indicate that inner MITL current loss is reduced (in addition to the convolute).

Gomez et al. *PRL* **125**, 155002 (2020)

We can't substantially increase the load inductance on NGPP, so can we use a similar inner MITL with similar gaps and still deliver current?

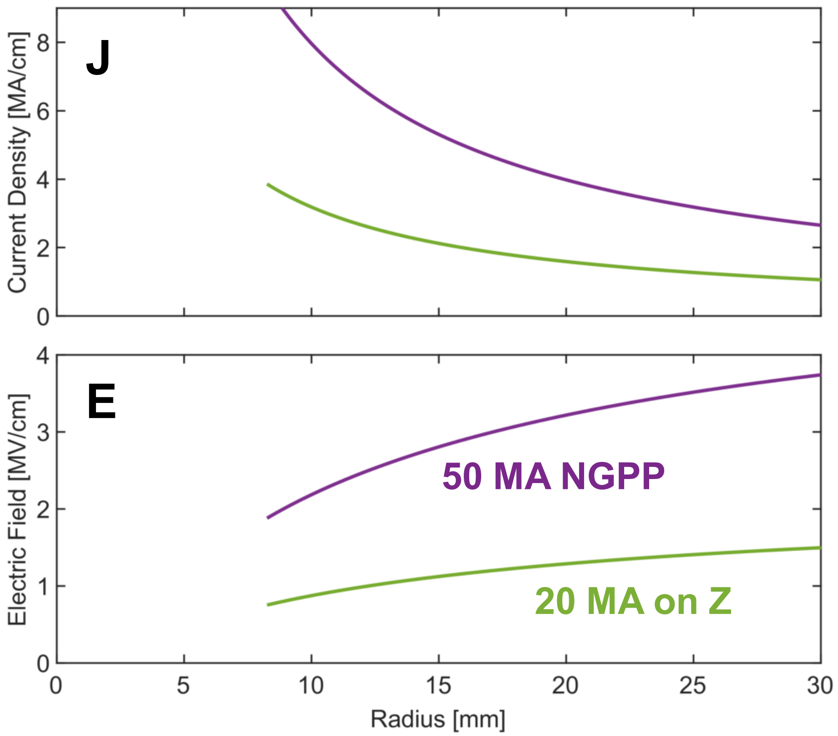


B-field, current density, and ohmic heating

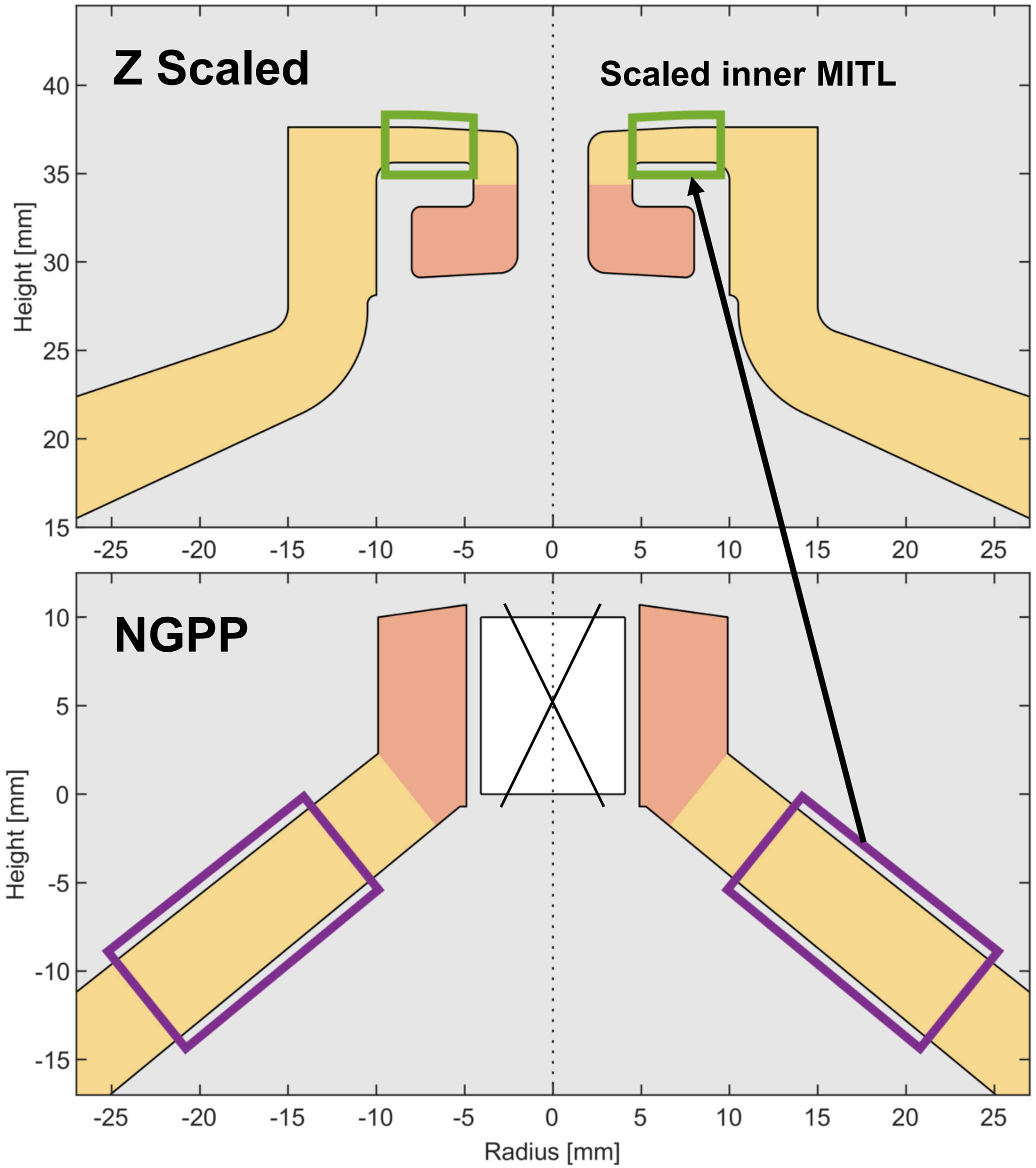
$$B \propto \frac{I_{\rm load}}{R} \qquad J \propto \frac{I_{\rm load}}{R} \qquad P_{\rm OH} \propto \frac{I^2_{\rm load}}{R^2}$$

Electric field → static + ~~dynamic~~

$$E = \frac{V}{d} = -\frac{\dot{\Phi}}{d} \sim -\frac{I_{\rm load}}{d}\left(i\omega L_{\rm load} + \cancel{\dot{L}_{\rm load}}\right)$$



A scaled transmission line with a 2 mm A/K gap that spans R = 5–9 mm on Z can match the **J** and **E** of a 50 MA MagLIF inner MITL.

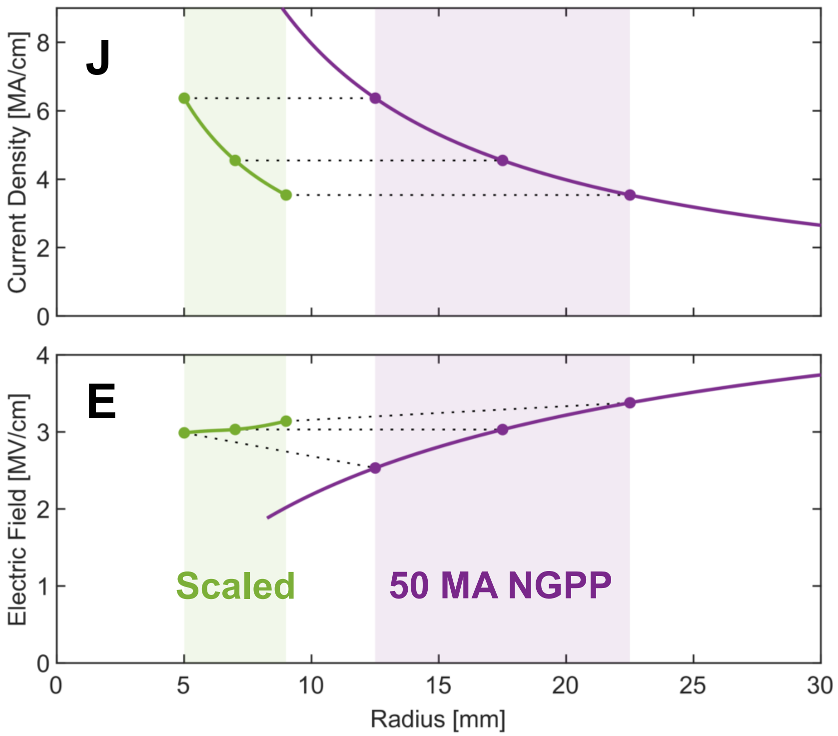


B-field, current density, and ohmic heating

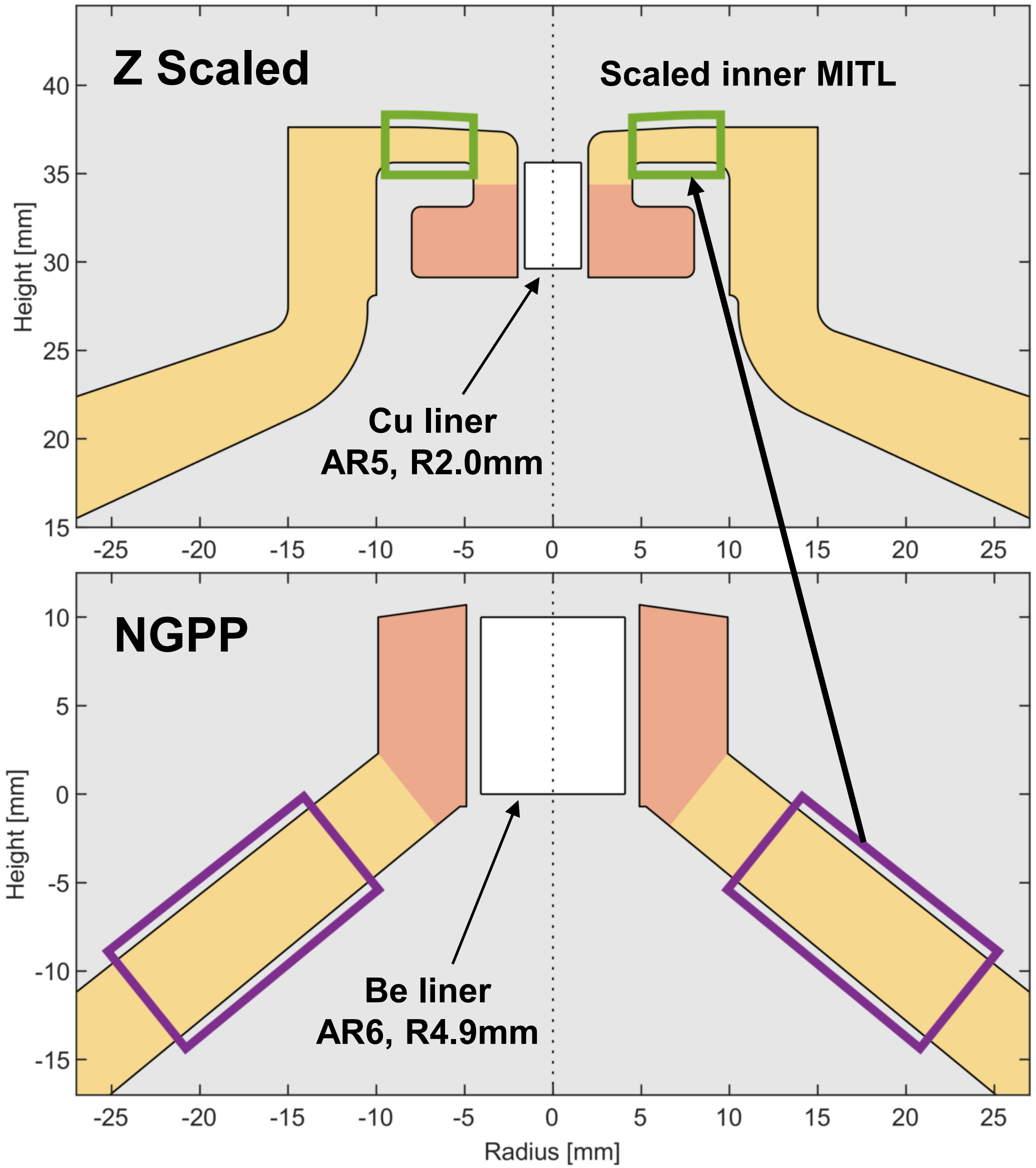
$$B \propto \frac{I_{\text{load}}}{R} \qquad J \propto \frac{I_{\text{load}}}{R} \qquad P_{\text{OH}} \propto \frac{I_{\text{load}}^2}{R^2}$$

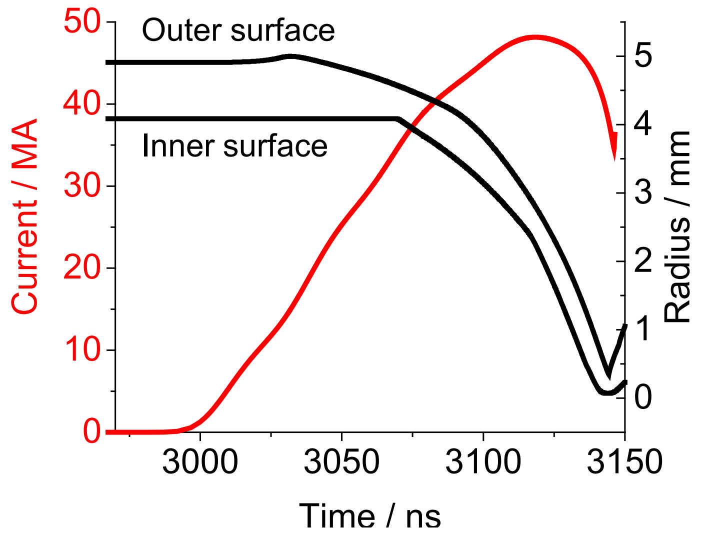
Electric field → static + ~~dynamic~~

$$E = \frac{V}{d} = -\frac{\dot{\Phi}}{d} \sim -\frac{I_{\text{load}}}{d}\left(i\omega L_{\text{load}} + \dot{L}_{\text{load}}\right)$$

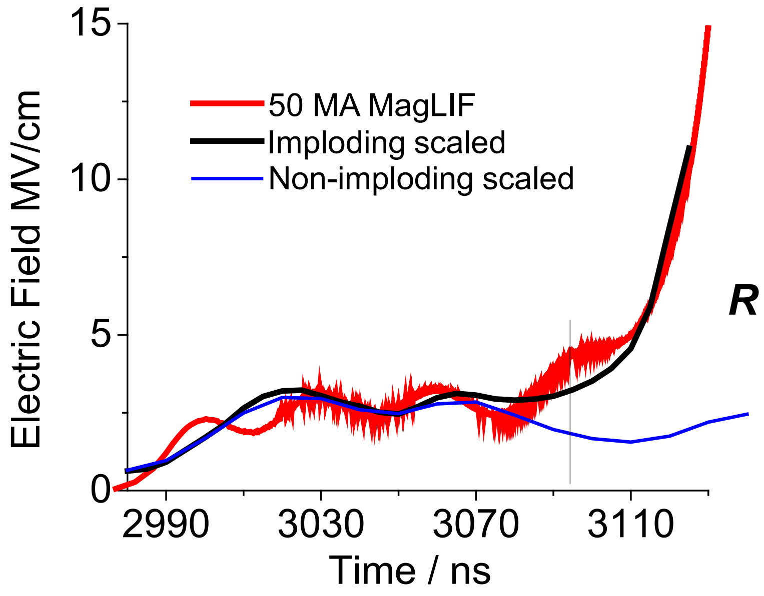


Adding a AR5 (2-mm radius, 400-µm thick) copper liner on-axis mimics the dynamic stress of a representative 50-MA NGPP MagLIF implosion.





This is just one possible NGPP MagLIF design.



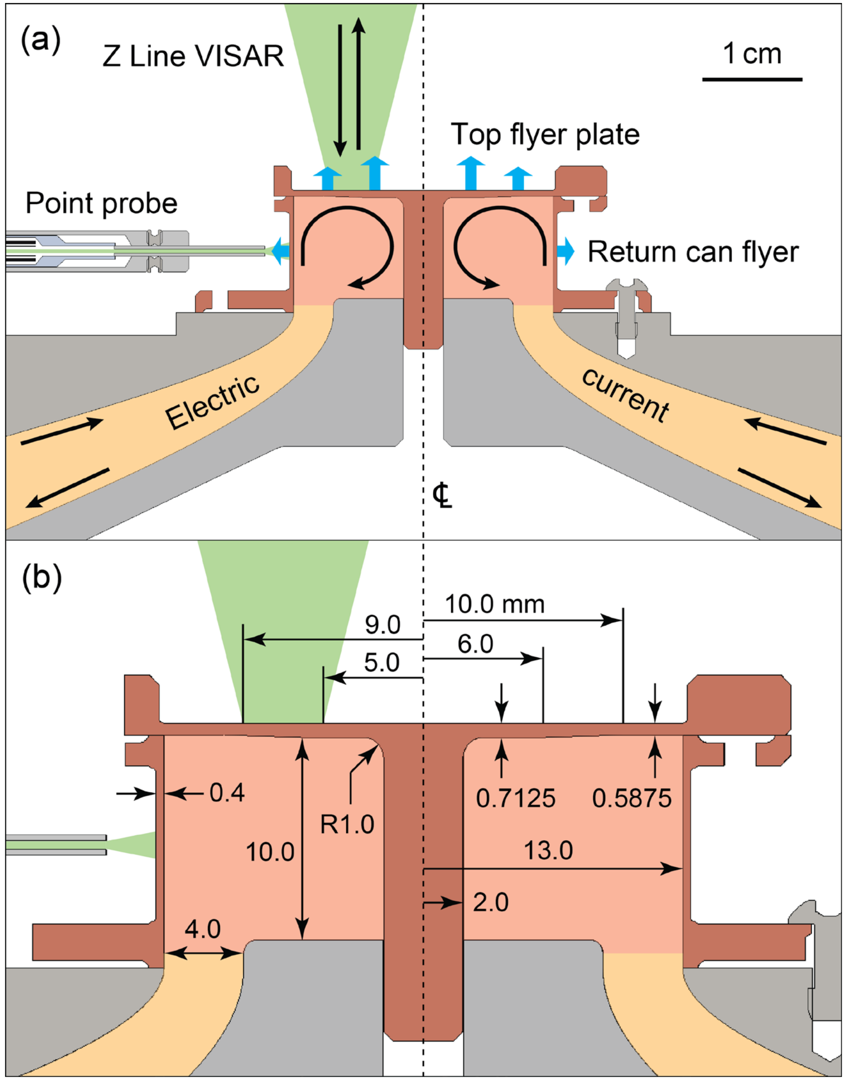
R = 9 mm

Scaled Power Flow Experiments on Z

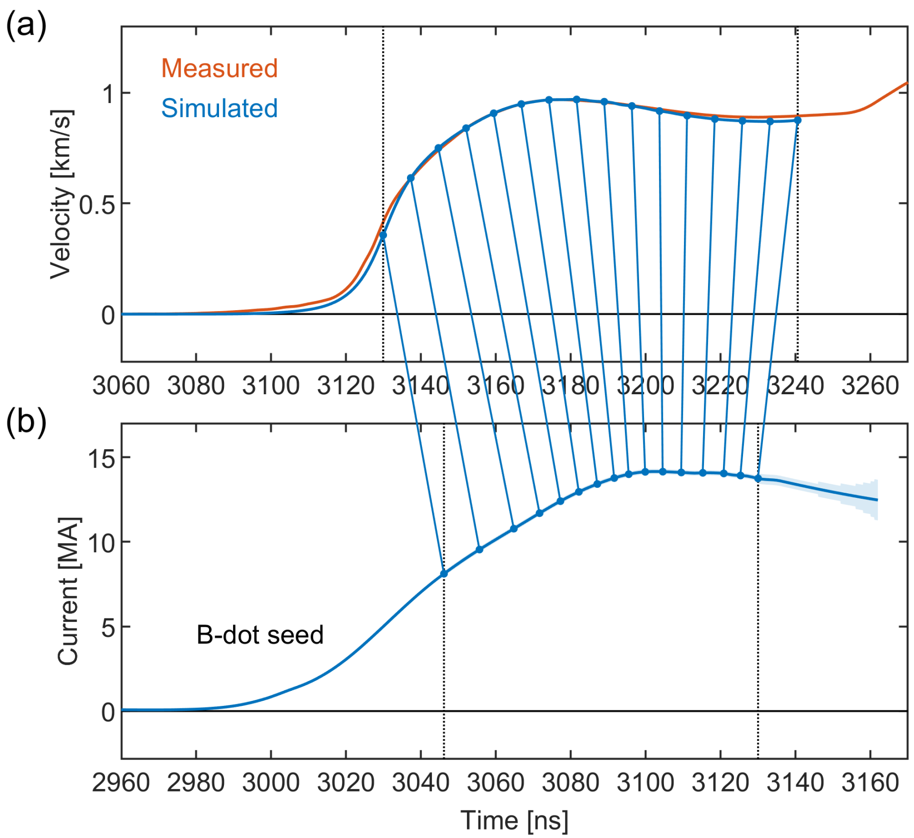
1. Motivation for a next-generation pulsed power (NGPP) facility.
2. Design of a 50-MA-equivalent power flow scaling platform at 20 MA on Z.
3. **Using velocimetry to diagnose the current delivered through scaled transmission lines.**
4. Results, analysis, and modeling of the first power flow scaling experiments.
5. Follow-on scaling experiments and future work.

The first power flow scaling experiments on Z indicate that the current coupling through a 50-MA-equivalent transmission line (R ~ 1–2 cm) is essentially lossless.

Load current velocimetry is a powerful technique that is routinely used to infer the current delivered to load region on Z.



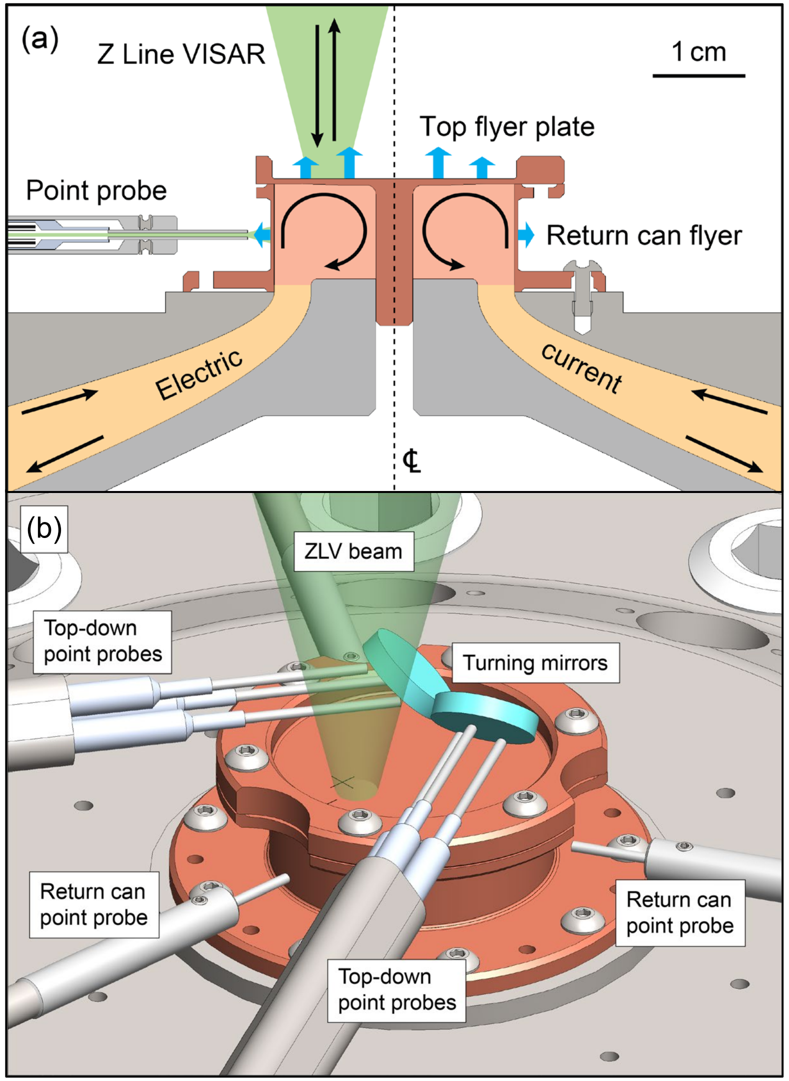
- Measure the explosion of the return can with fiber-coupled VISAR and PDV point probes.
- Use MHD simulations of the flyer to infer the load current waveform.

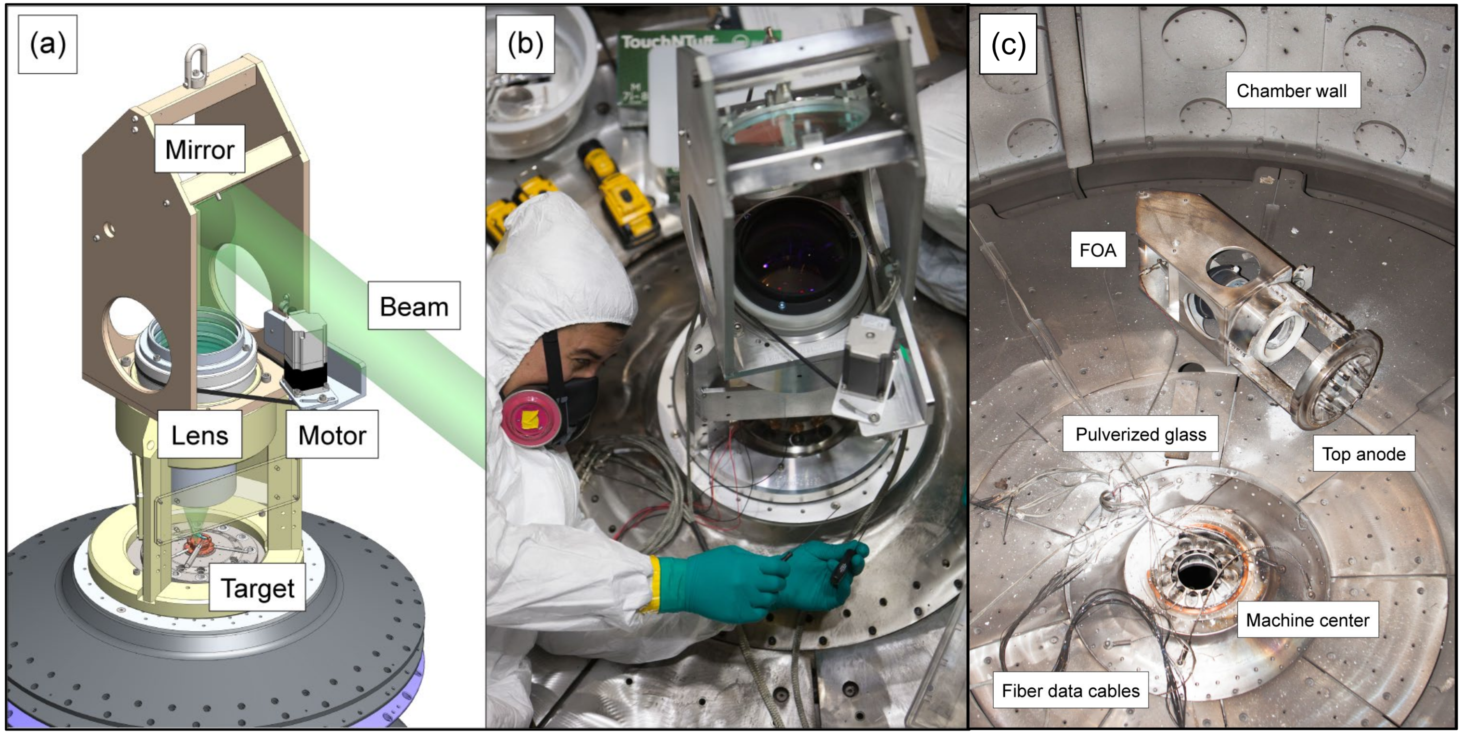


Myers et al. *PRAB*, to be submitted (2021)

Jennings et al. *PRAB*, in preparation.

Z Line VISAR (ZLV) is a new line-imaging velocity interferometer that provides radially resolved velocity measurements on the top flyer plate.



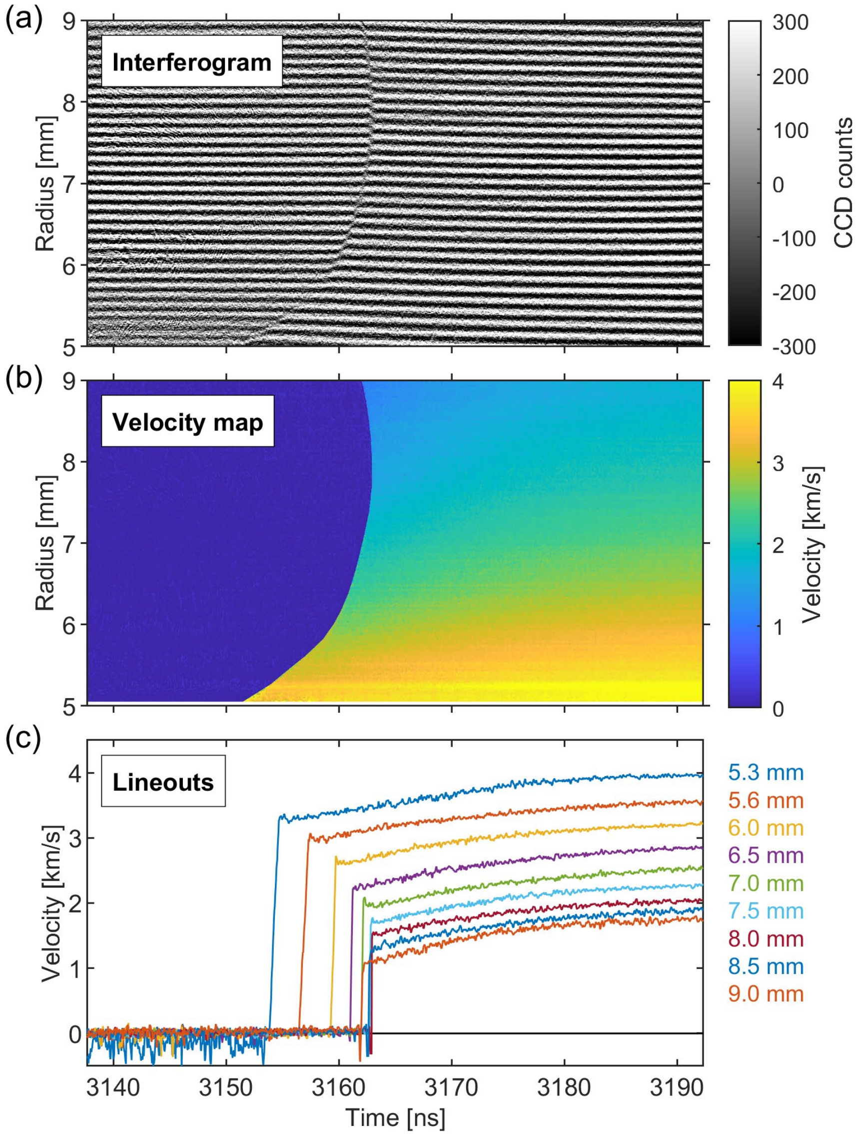


ZLV has become a workhorse diagnostic for understanding current drive on ICF, power flow, and materials experiments.

Myers et al. *PRAB*, to be submitted (2021)

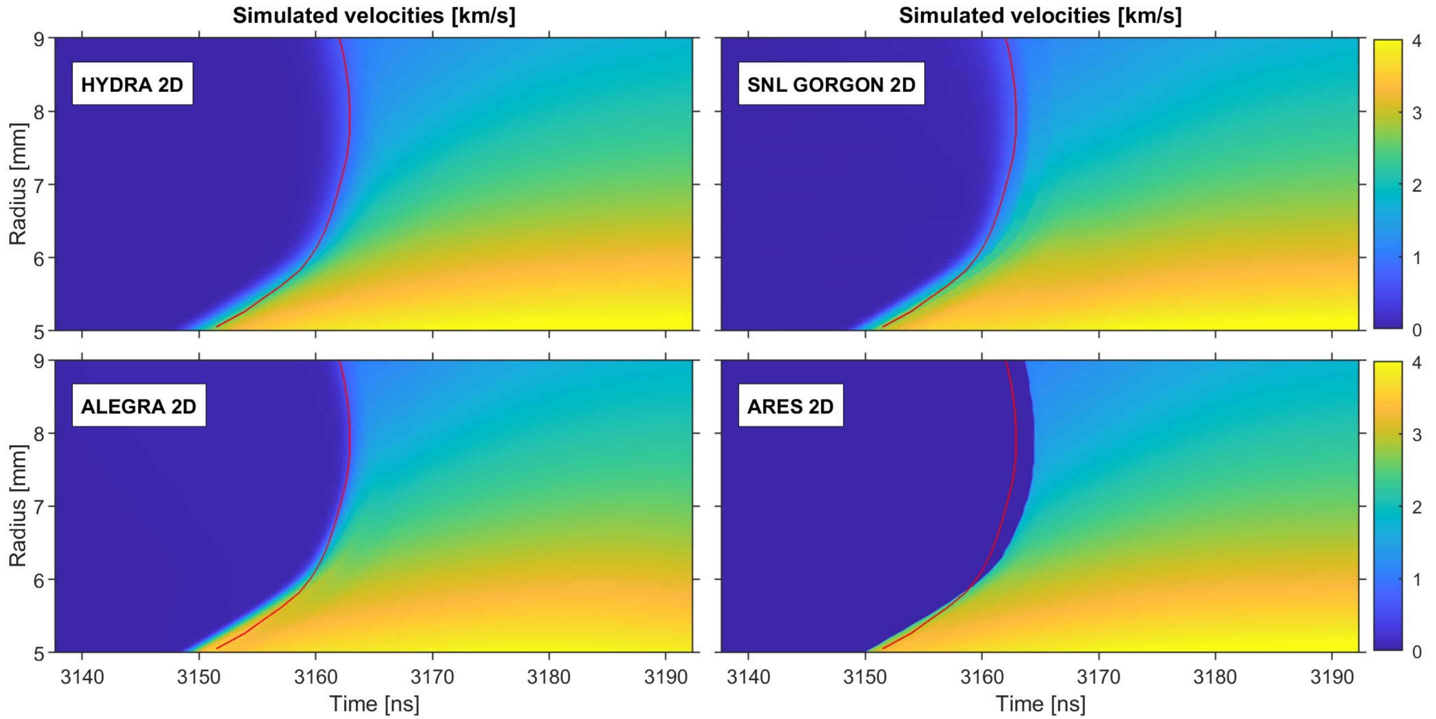
Datte et al. *RSI* **91**, 043508 (2020)

The velocities measured on the ZLV commissioning experiment agree with four MHD codes to ±5%. → ZLV and the codes work in this regime.



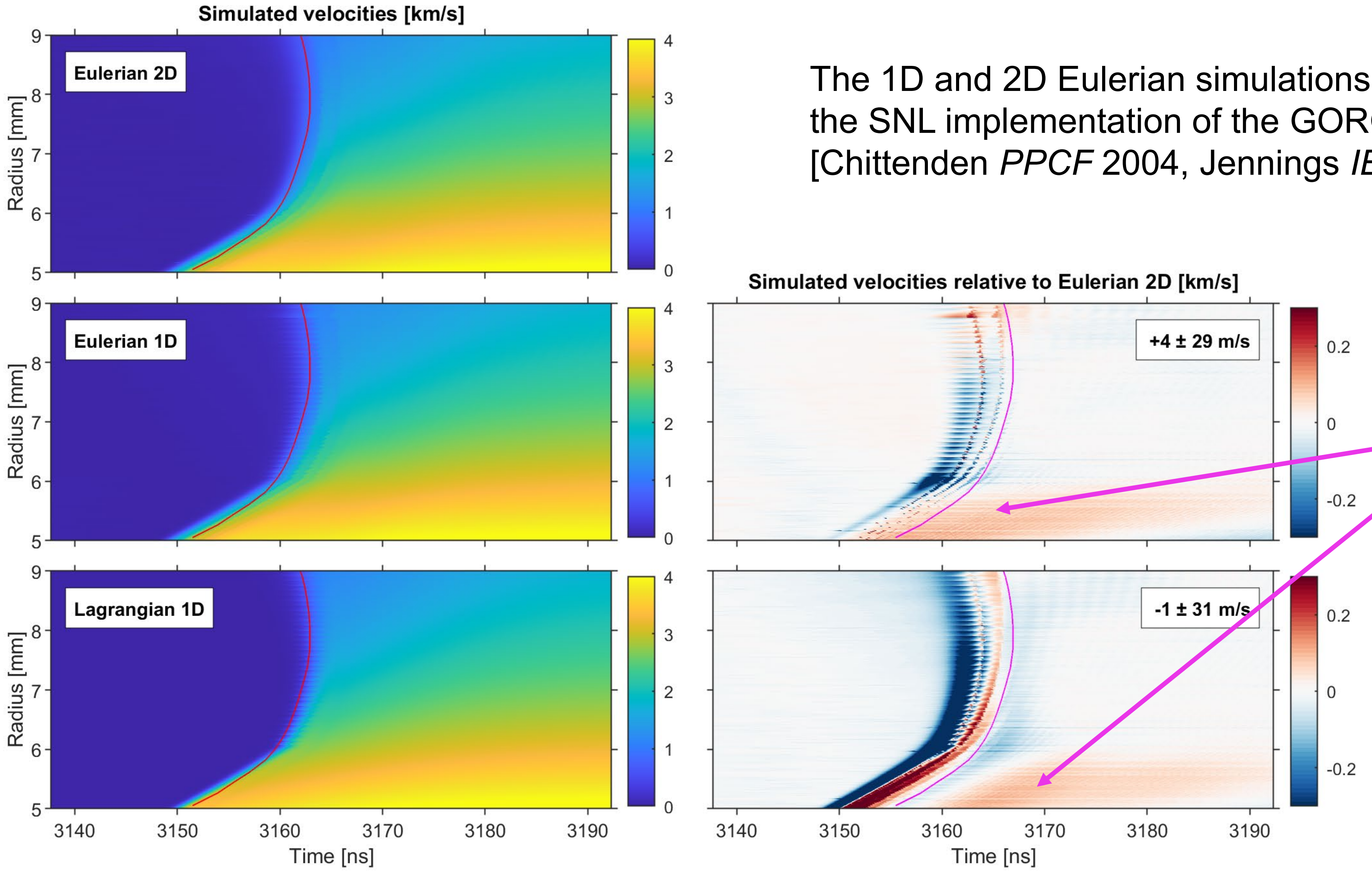
Myers et al. *PRAB*, to be submitted (2021)

- Velocities are extracted from the ZLV interferograms using the Fourier Transform Method of Celliers et al. [*RSI* 2004].
- 2D simulations are driven with the load current extracted from return can velocimetry. → "Lossless" current delivery.



Farmer et al. *PRAB*, to be submitted (2021)

Comparing 2D and 1D simulations indicates that the flyer behavior is decoupled radially so that 1D current unfold techniques can be used.



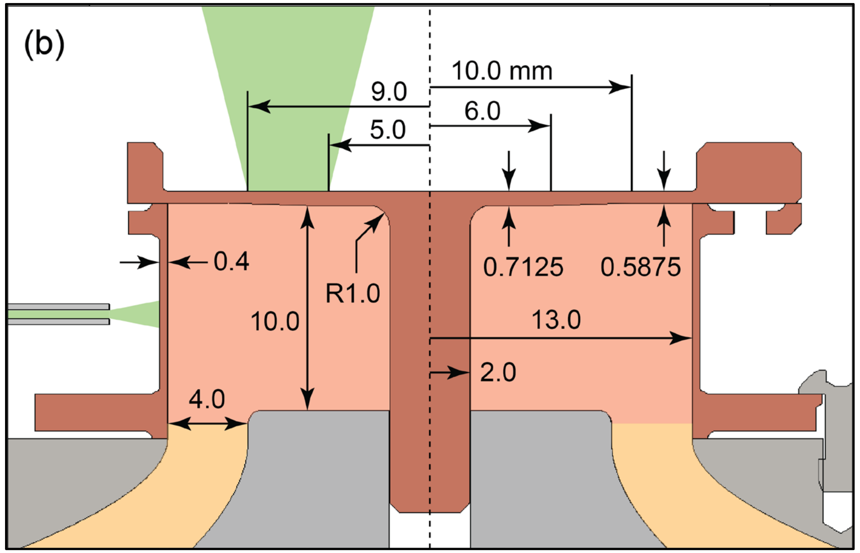
The 1D and 2D Eulerian simulations are generated by the SNL implementation of the GORGON MHD code [Chittenden *PPCF* 2004, Jennings *IEEE TPS* 2010].

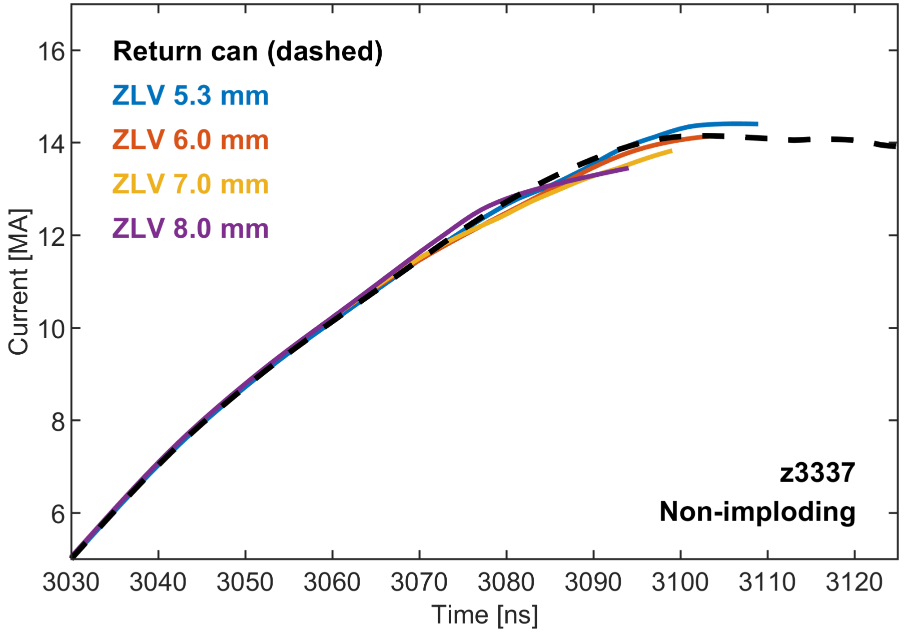
2D behavior due to steeper magnetic pressure gradients at the smallest radii.

Only a few-percent effect, which is comparable to the velocity uncertainties.

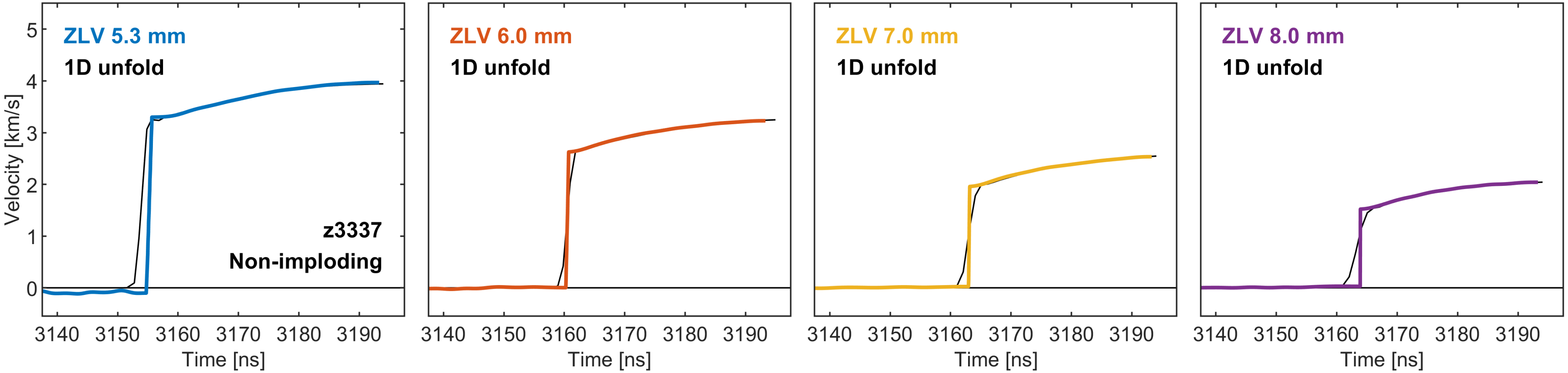
Myers et al. *PRAB*, to be submitted (2021)

1D current unfolds at four different radii indicate lossless current delivery across the top flyer plate. → Constrained to ~0.5 MA (~3%).





Velocities constrain the current.



Myers et al. *PRAB*, to be submitted (2021)

Scaled Power Flow Experiments on Z

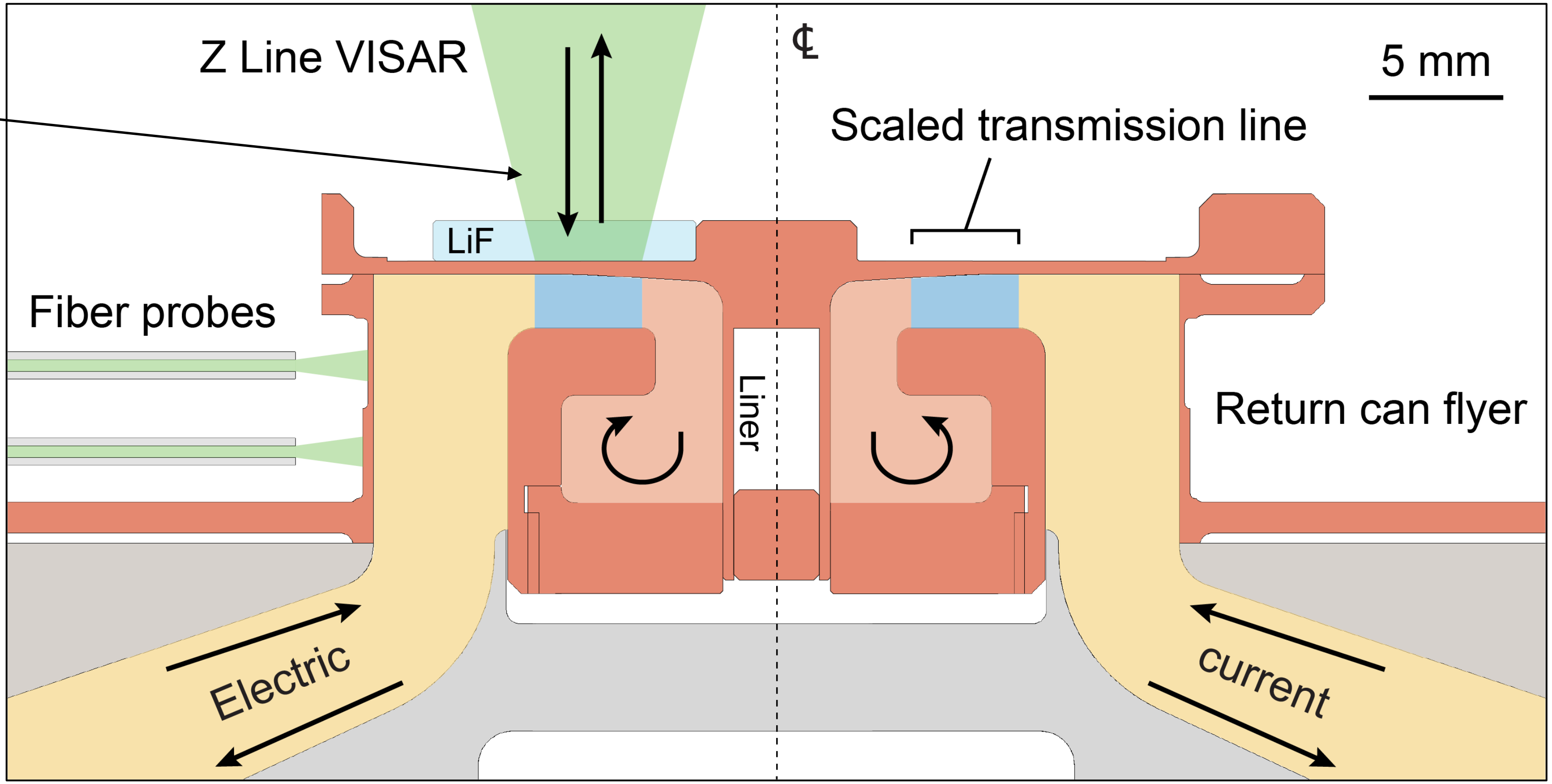
1. Motivation for a next-generation pulsed power (NGPP) facility.
2. Design of a 50-MA-equivalent power flow scaling platform at 20 MA on Z.
3. Using velocimetry to diagnose the current delivered through scaled transmission lines.
4. **Results, analysis, and modeling of the first power flow scaling experiments.**
5. Follow-on scaling experiments and future work.

The first power flow scaling experiments on Z indicate that the current coupling through a 50-MA-equivalent transmission line (R ~ 1–2 cm) is essentially lossless.

Use load current velocimetry to diagnose the current delivered to the return can and through the scaled transmission line.

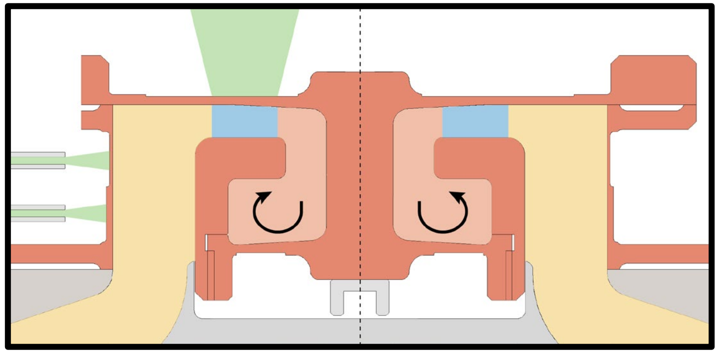
Spatially resolved current delivery along the scaled transmission line.

Input current to the scaled transmission line.

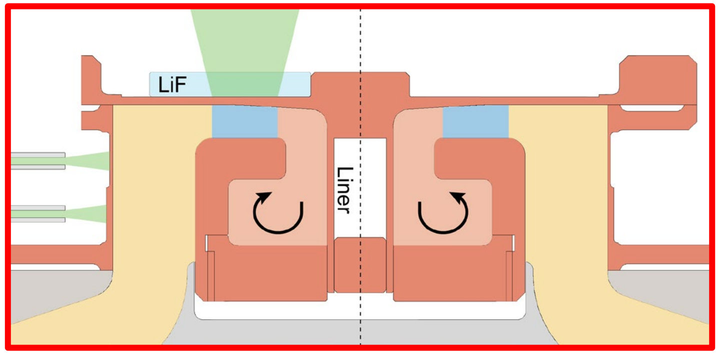


The load currents (return can) on the non-imploding and imploding Power Flow Scaling experiments agree with pre-shot circuit modeling.

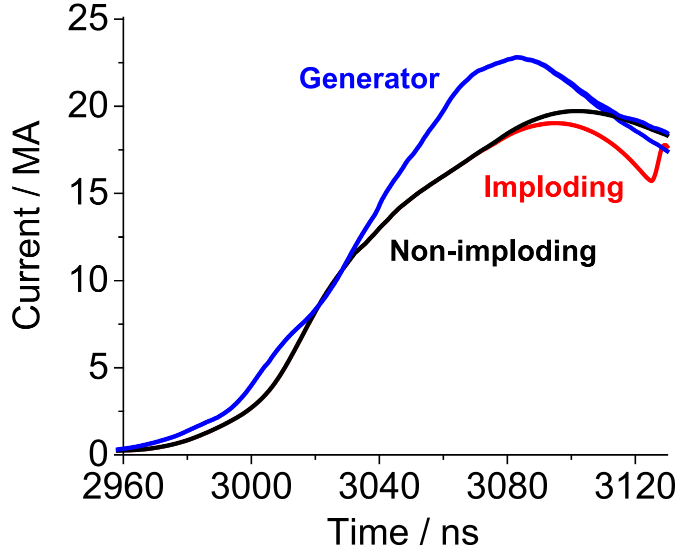
Non-imploding – z3537



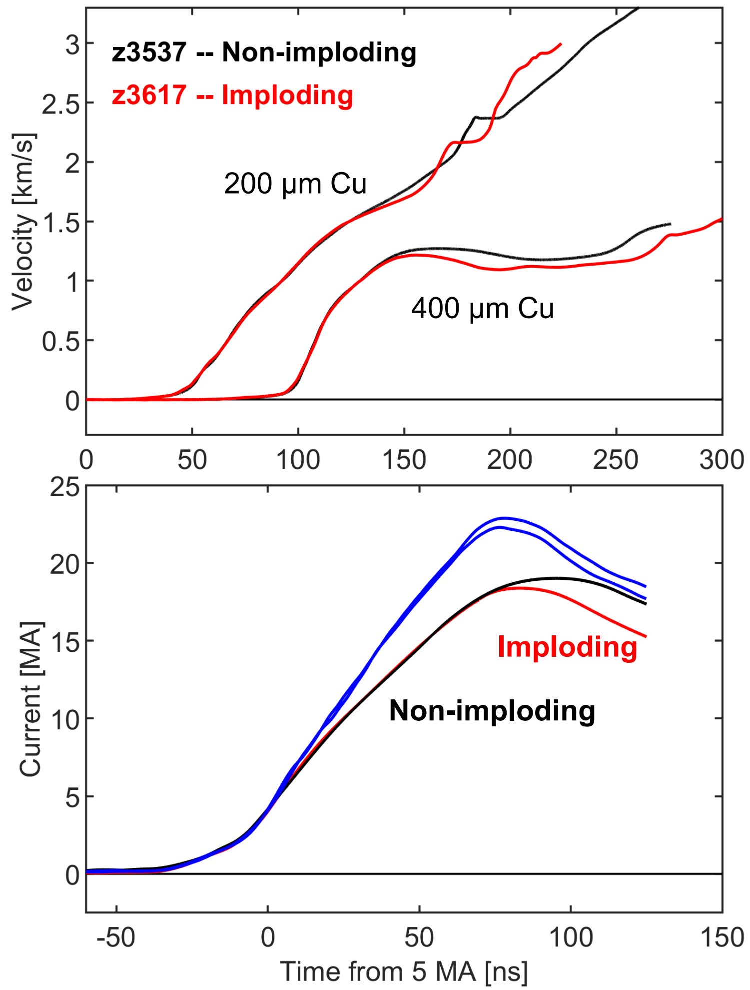
Imploding – z3617



Pre-shot circuit modeling

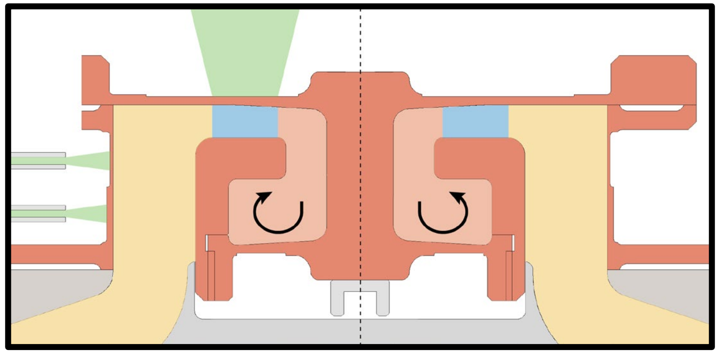


Measured return can currents

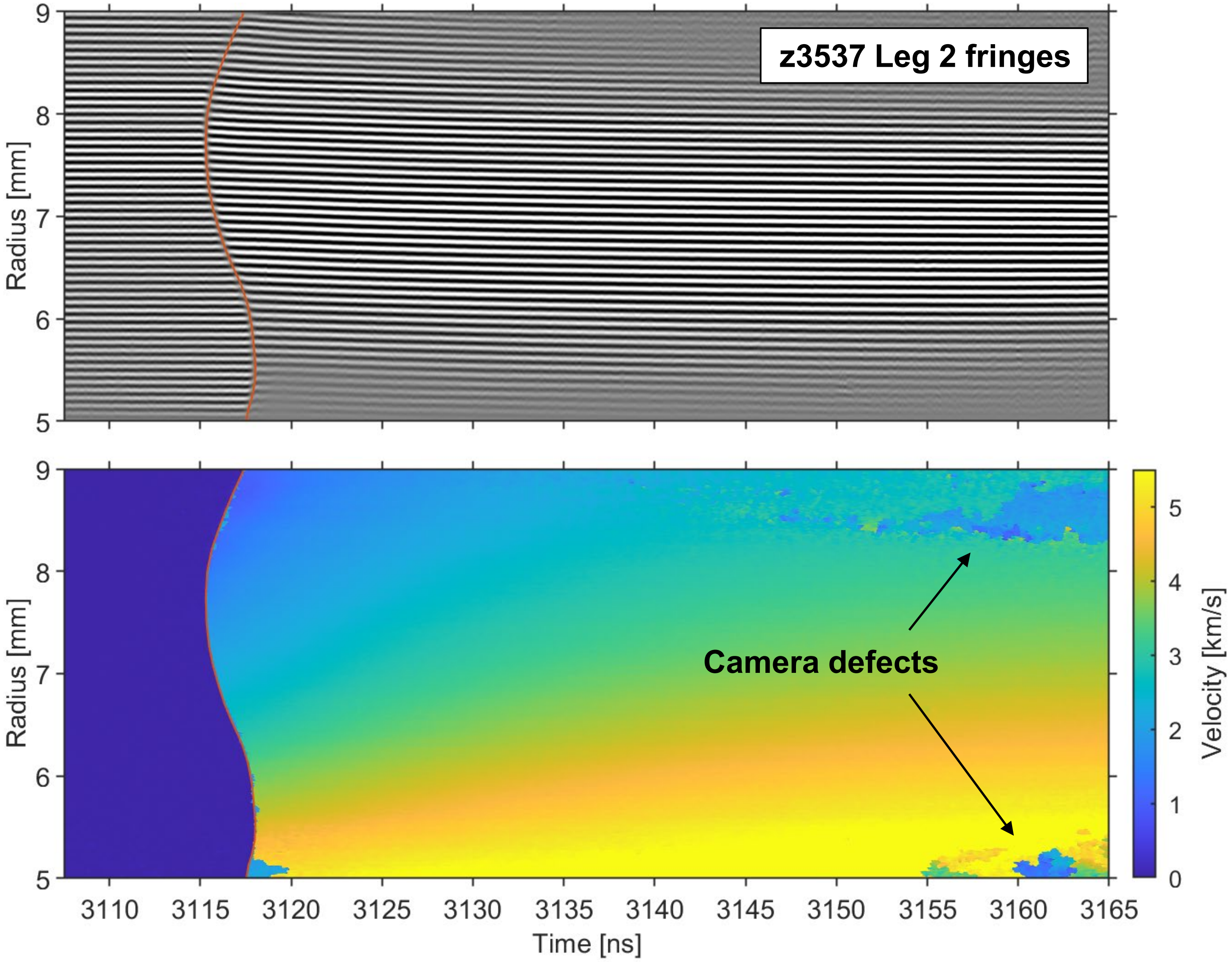


Z Line VISAR returned interferograms that provide spatially resolved shock breakout and flyer velocity information along the scaled transmission line.

Non-imploding – z3537



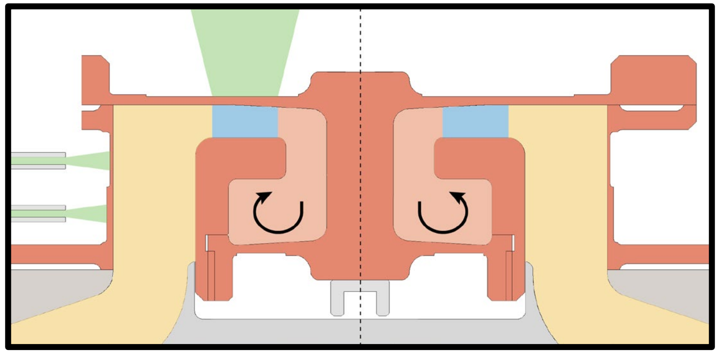
- Shock breakout and post-shock fringe motion observed on the first Power Flow Scaling experiment!
- Reduction in reflectivity at small radii (highest velocities/pressures).
- A velocity map was successfully extracted from the ZLV data.



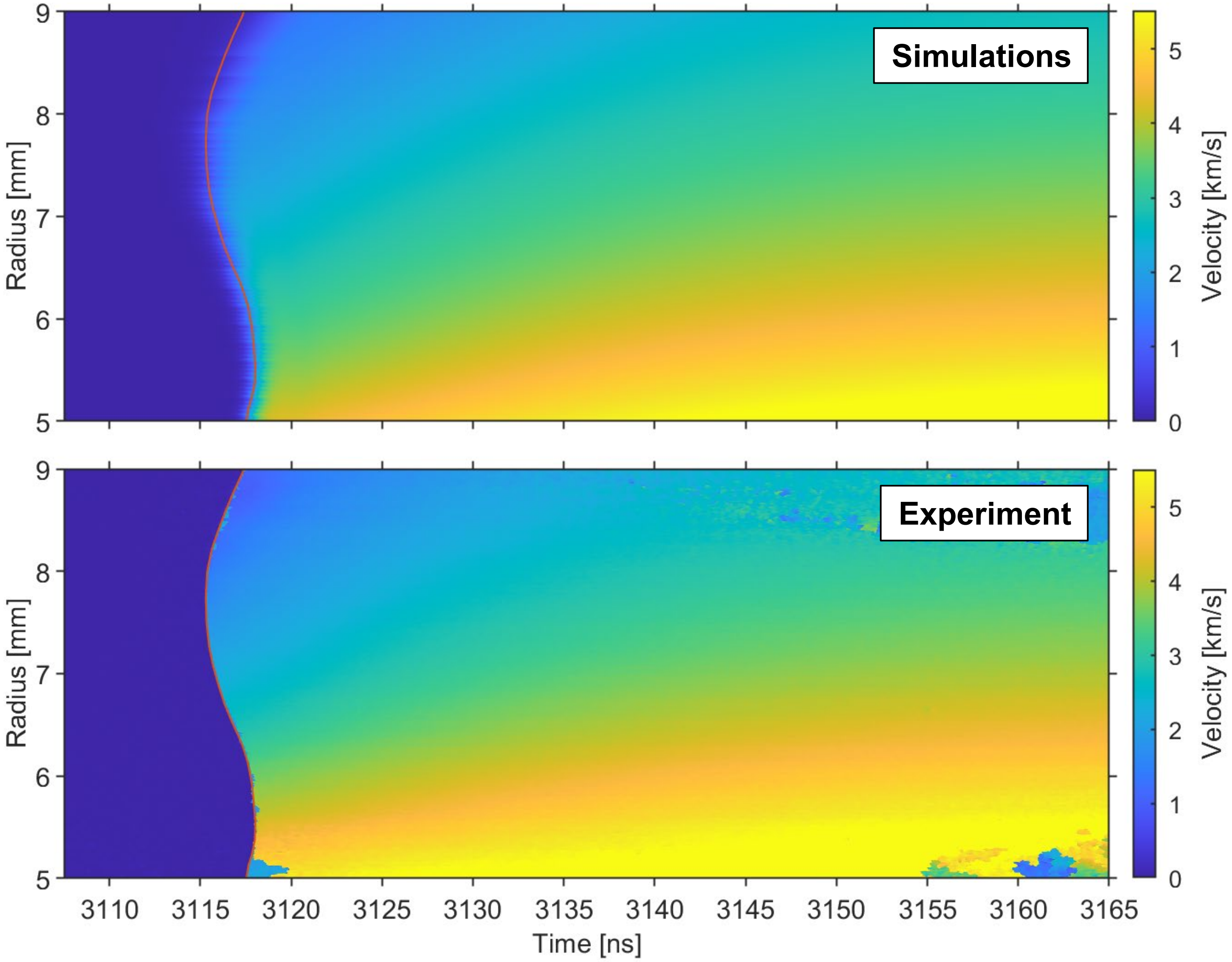
Celliers et al. *RSI* **75**, 4916 (2004)

The velocities measured on the non-imploding experiment agree with lossless post-shot simulations to better than 10%! → Minimal current loss.

Non-imploding – z3537

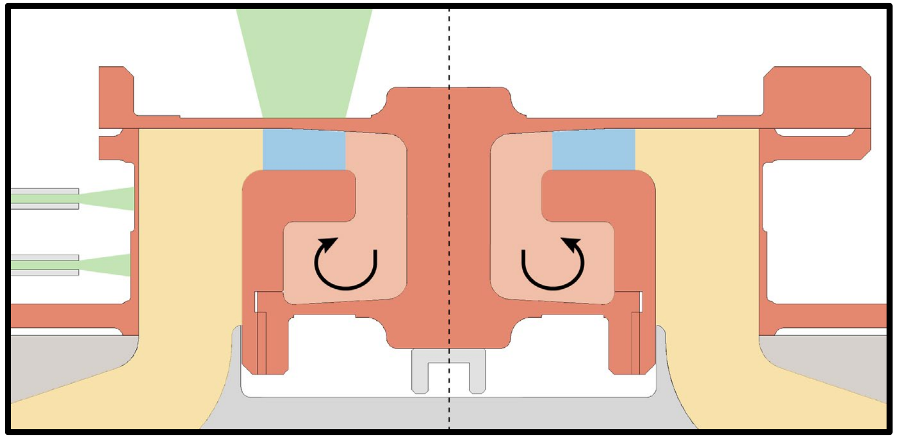


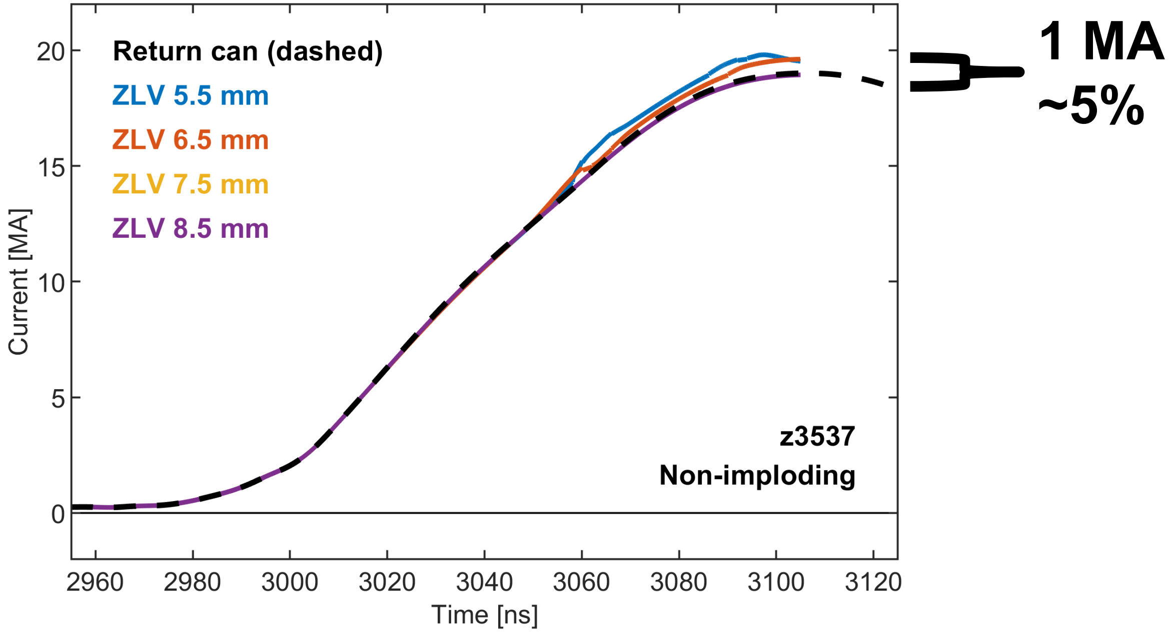
- Shock breakout and post-shock fringe motion observed on the first Power Flow Scaling experiment!
- Reduction in reflectivity at small radii (highest velocities/pressures).
- A velocity map was successfully extracted from the ZLV data.
- 1D Lagrangian flyer simulations are driven by the return can current.



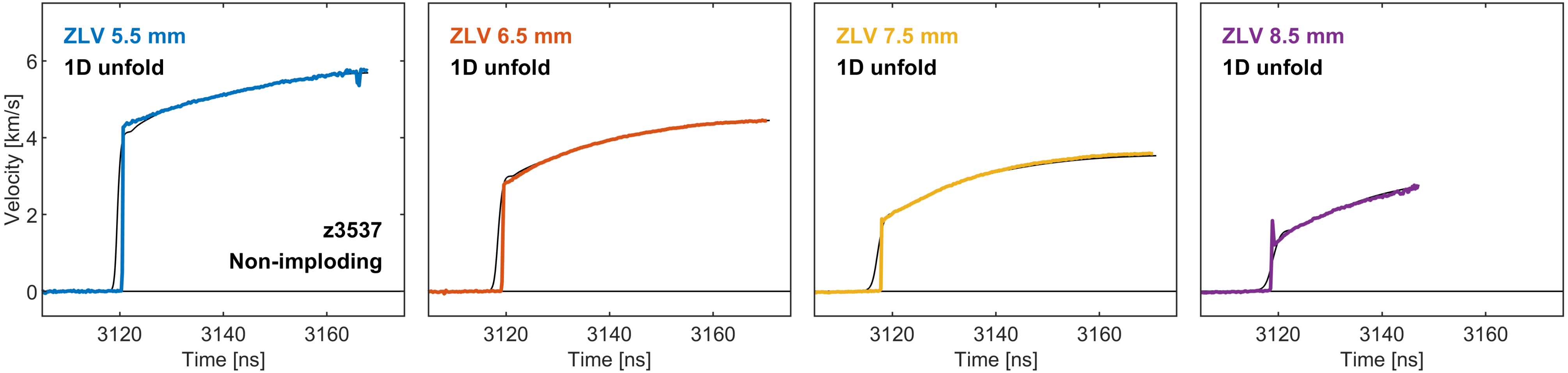
Current delivery through a 50-MA equivalent scaled transmission line that is **stressed by a static inductance** is essentially lossless!

Non-imploding – z3537

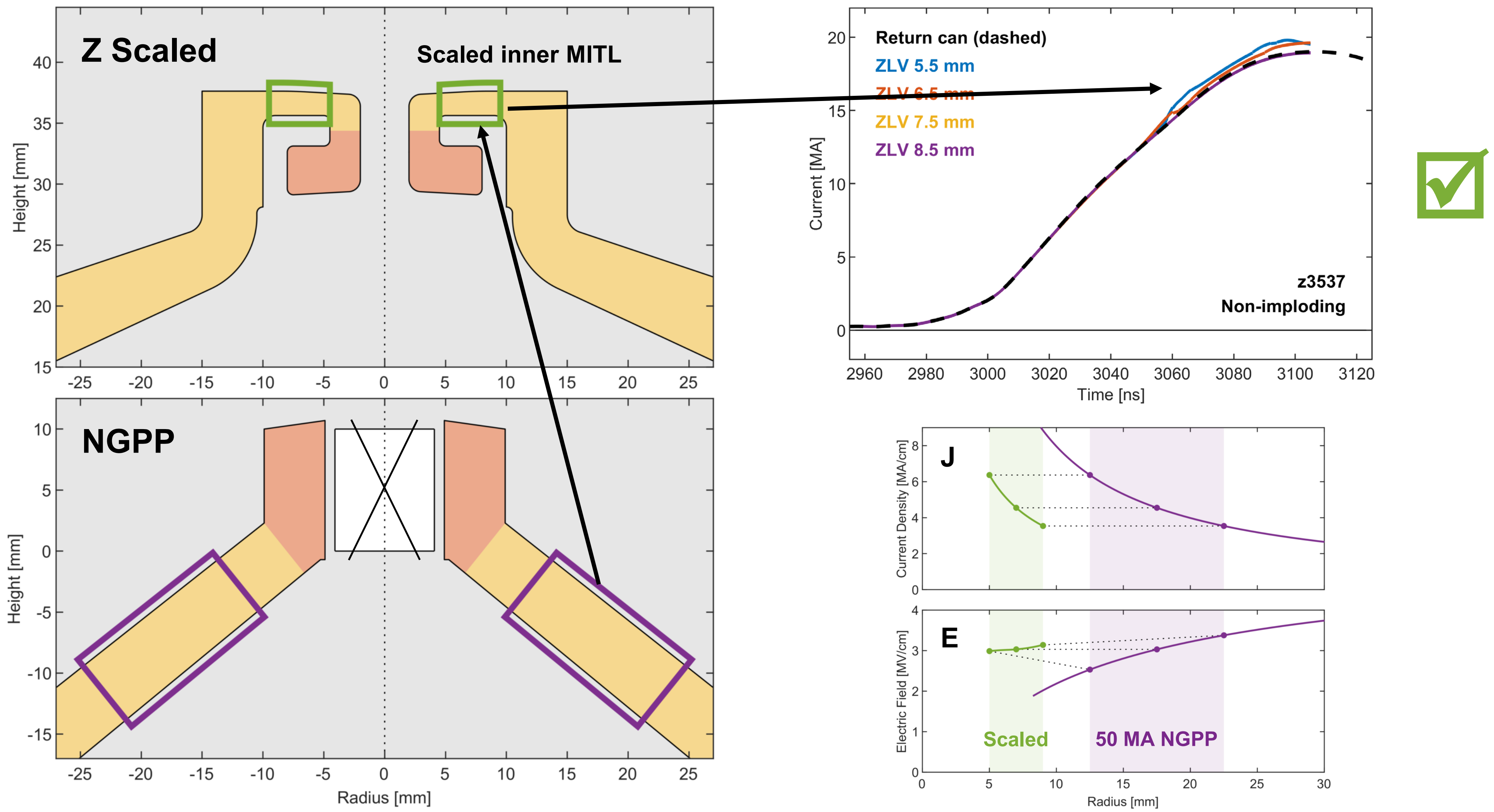




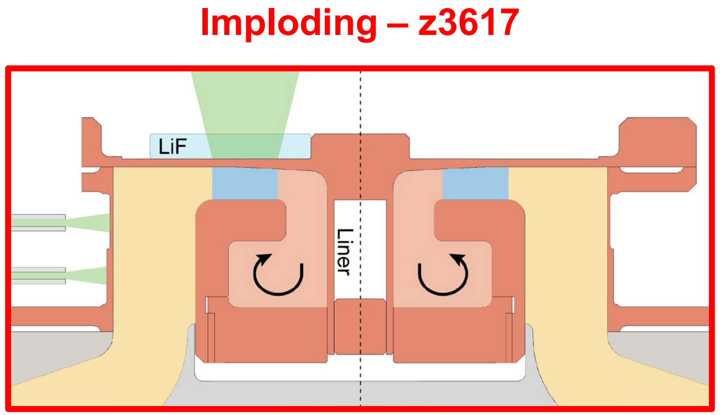
Velocities constrain the current.



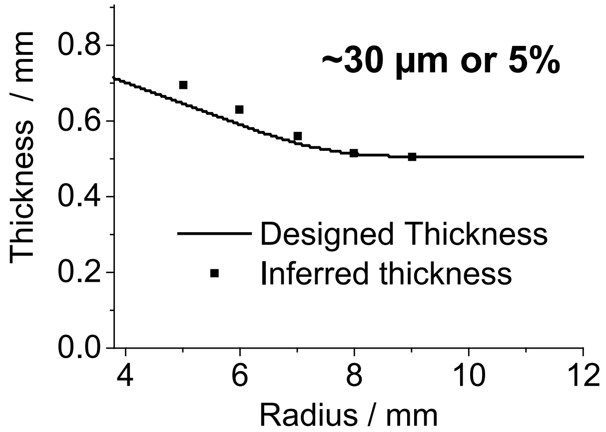
Current delivery through a 50-MA equivalent scaled transmission line that is **stressed by a static inductance** is essentially lossless!

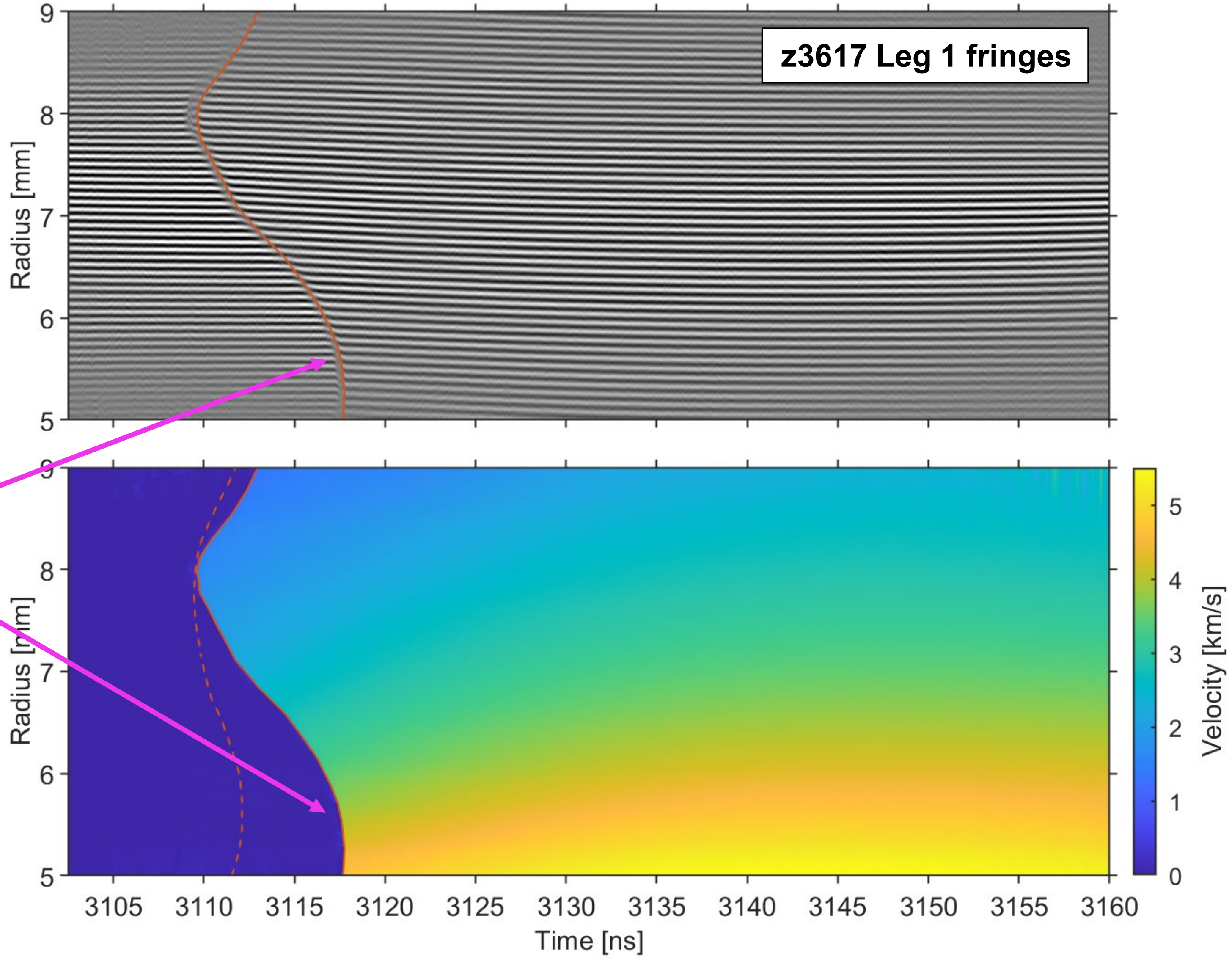


The imploding experiment with LiF windows generated a high-quality interferogram across the full ZLV field of view (R = 5–9 mm).



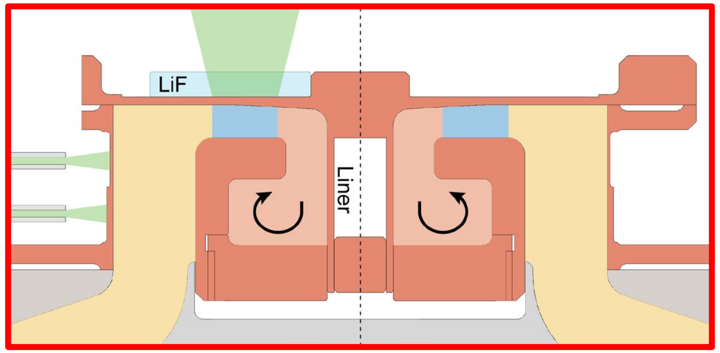
- Much cleaner interferograms obtained with LiF windows.
- Shock breakout profile is different due to out-of-spec flyer:



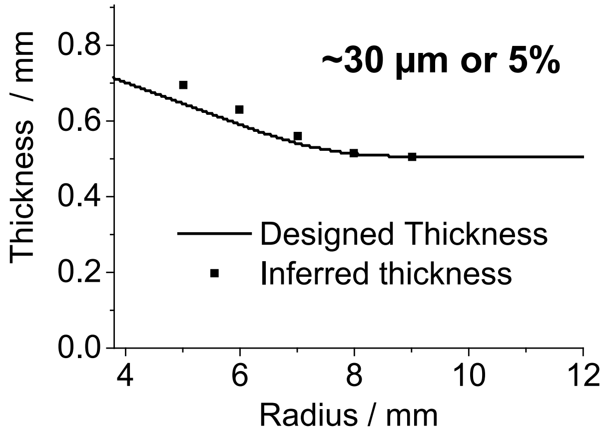


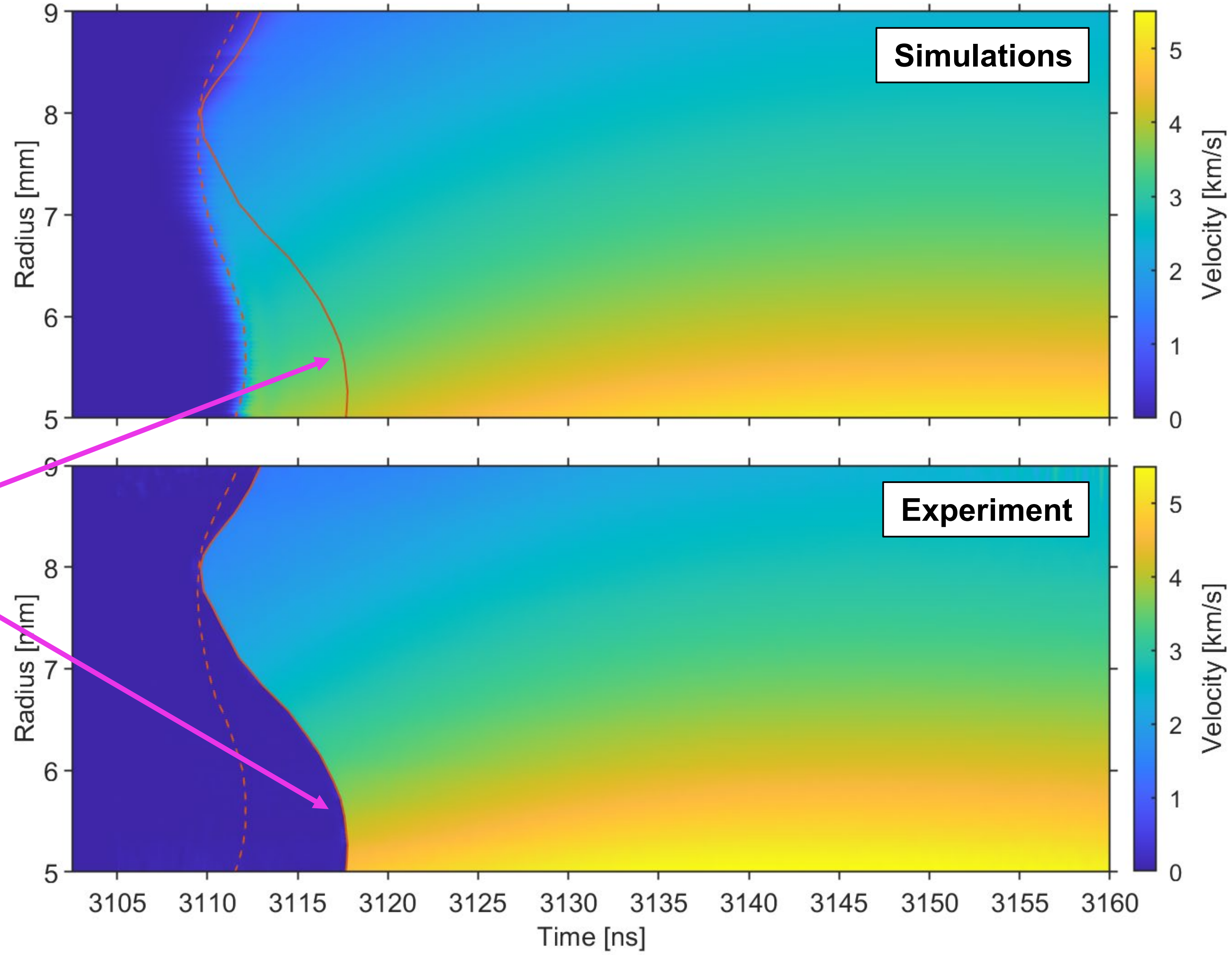
The velocities once again agree with post-shot lossless simulations to better than 10%. → Still minimal loss in spite of the imploding liner!

Imploding – z3617



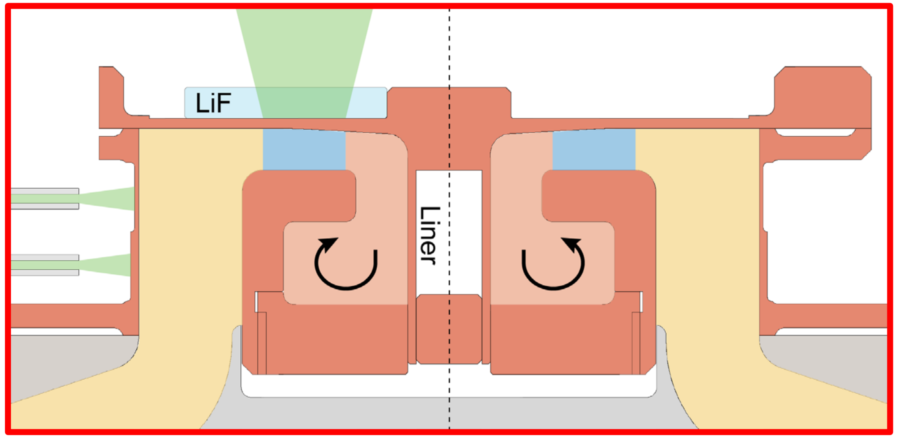
- Much cleaner interferograms obtained with LiF windows.
- Shock breakout profile is different due to out-of-spec flyer:

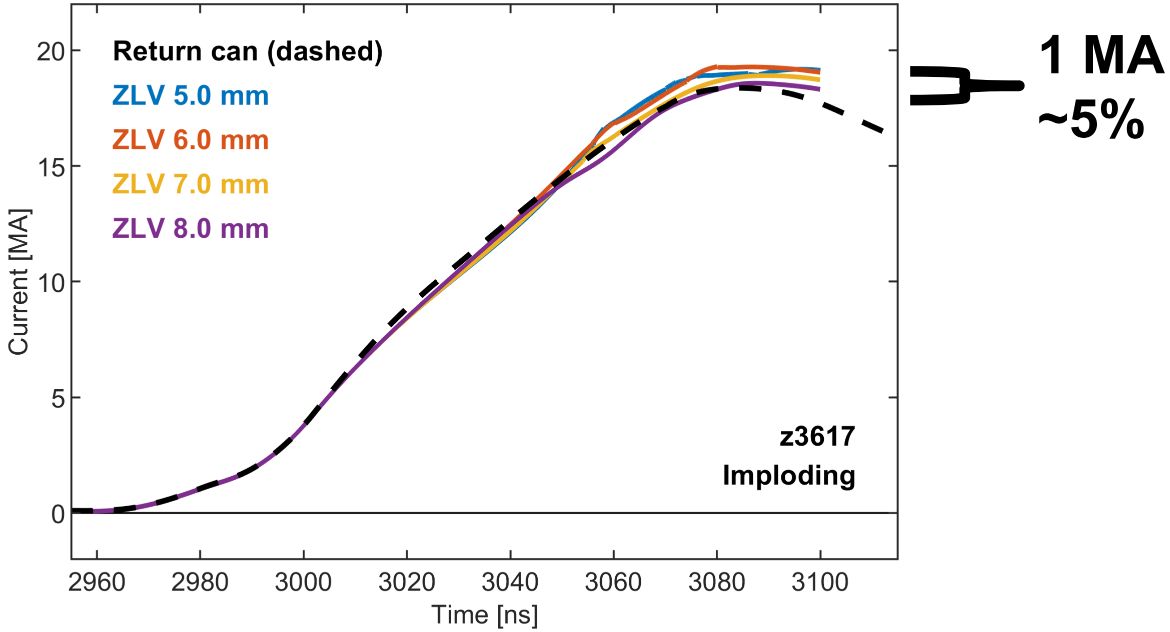




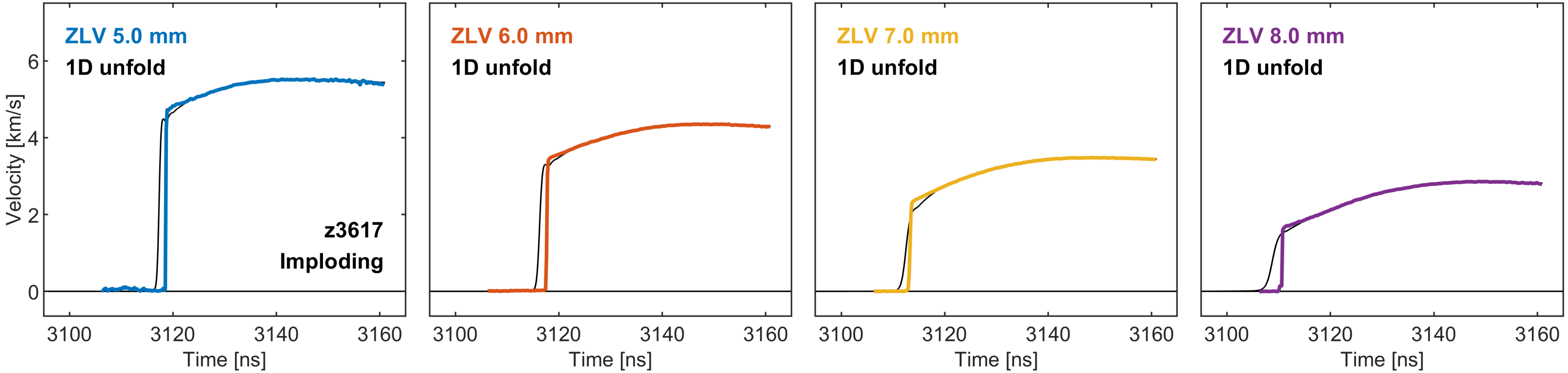
Current delivery through a 50-MA equivalent scaled transmission line that is **stressed by an imploding liner** is essentially lossless!

Imploding – z3617

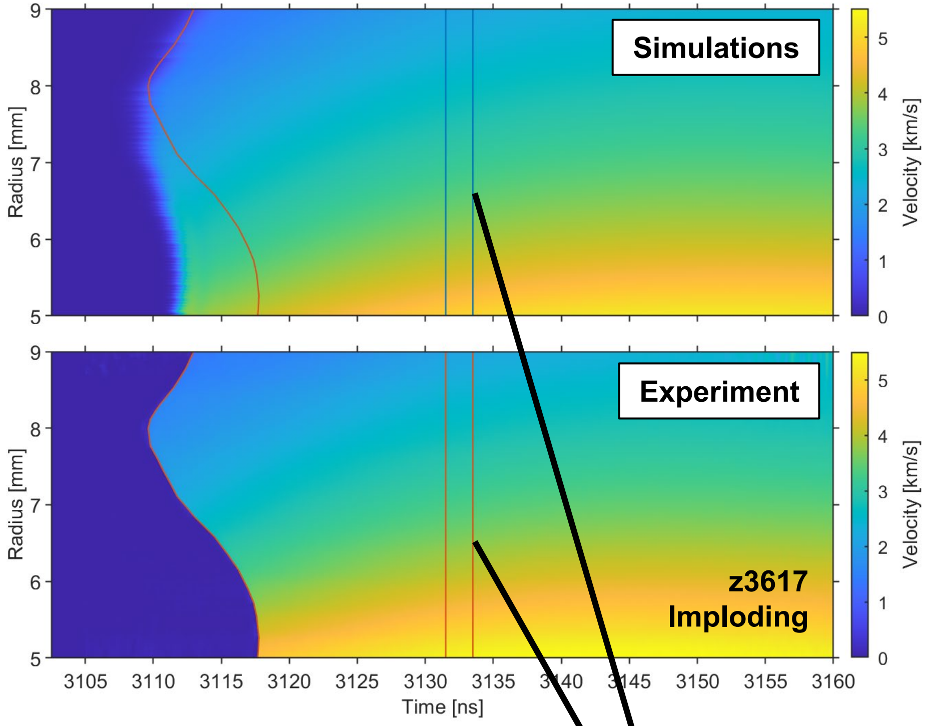




Velocities constrain the current.
Shock timings constrain the flyer thickness.



Excess velocity in both experiments indicates that a larger-than-expected pressure is driving the flyer at smaller radii. → ~5% effect on the current.

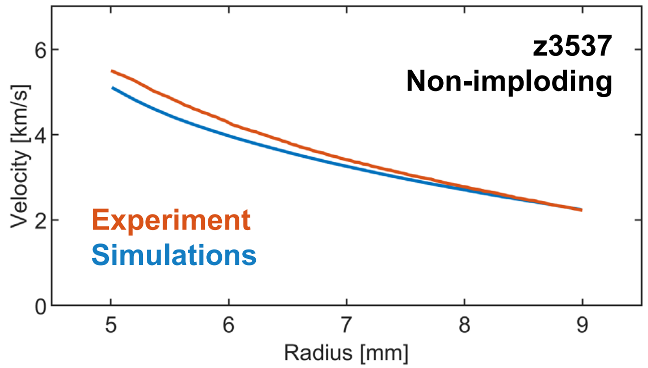


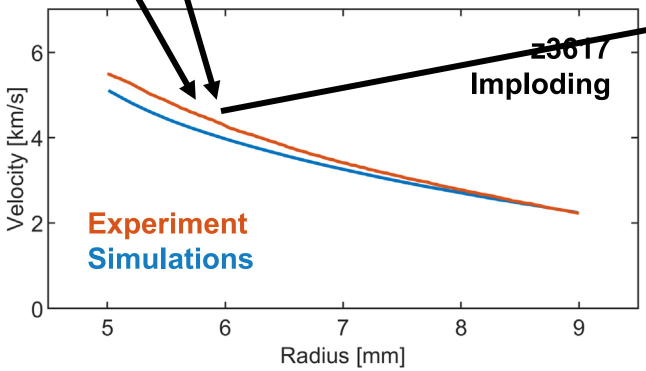
We have ruled out many possible causes:

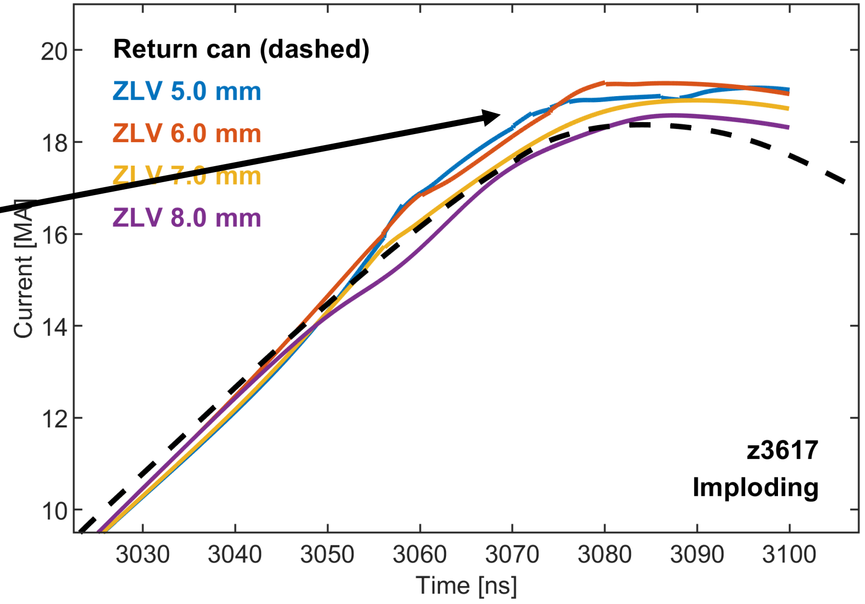
- Temporal or spatial shifts of the ZLV data.
- Nonlinear LiF window index of refraction.
- Larger-than-expected early time current.

This leaves two candidate effects:

- Particle/plasma bombardment of the flyer.
- Radially varying current asymmetries.

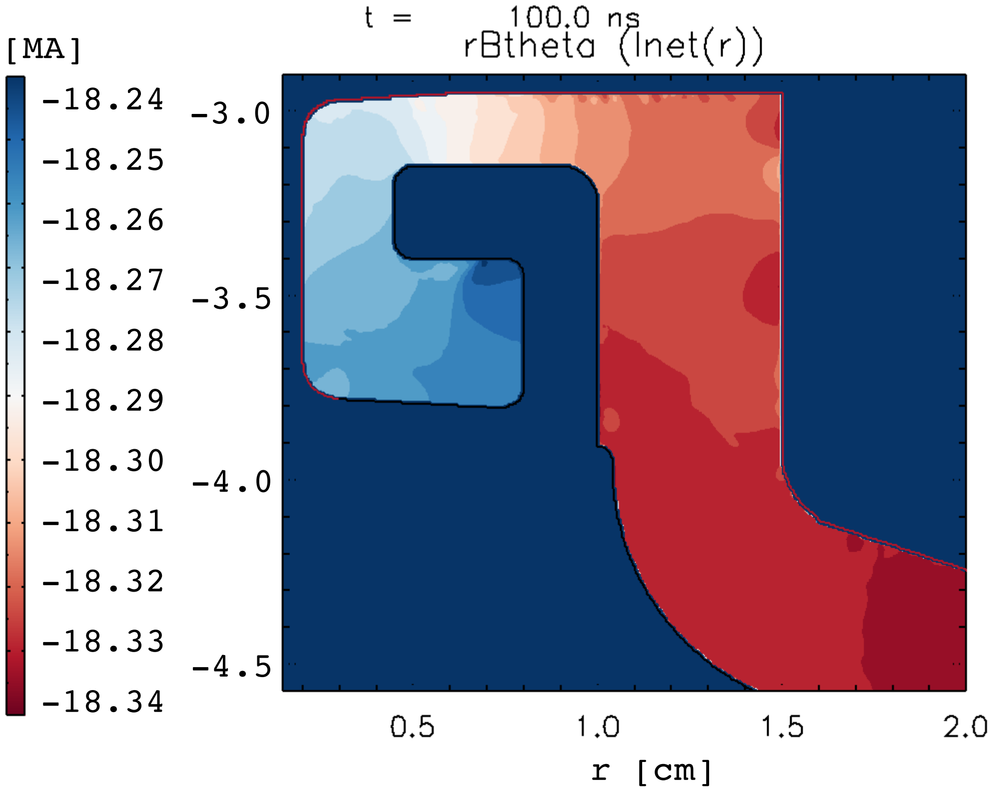






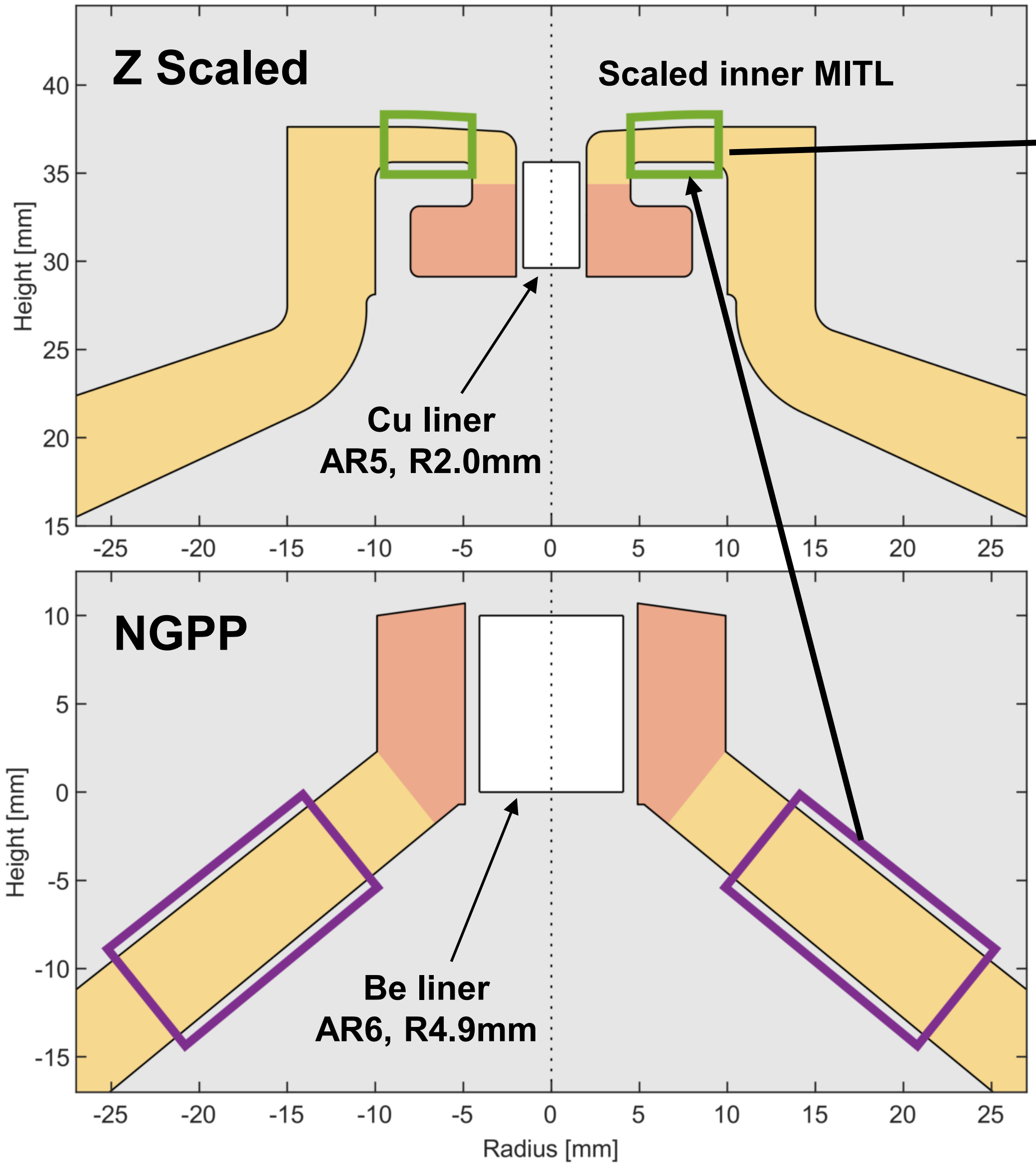
State-of-the-art multi-fluid and kinetic modeling of the non-imploding experiment shows extensive plasma formation but little loss.

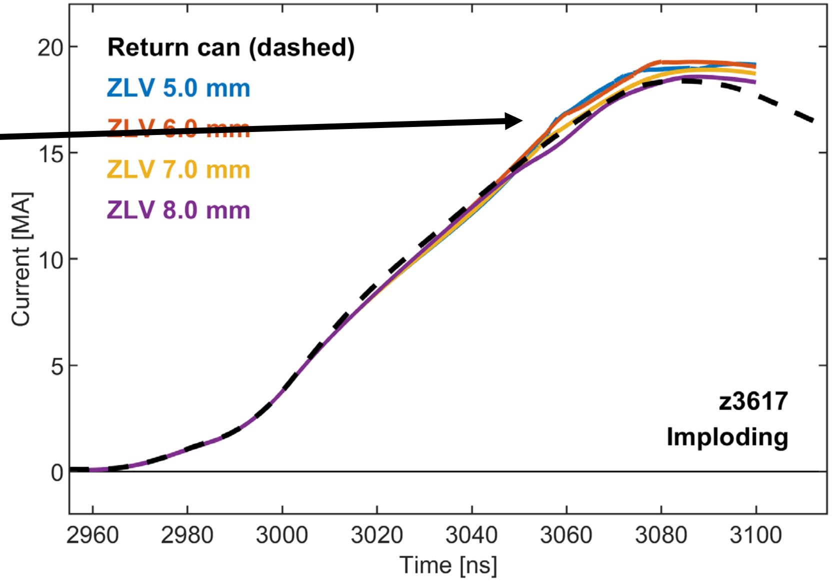
- Analytic calculations of magnetic insulation indicate that all species are insulated in the gap.
- Multi-fluid and kinetic simulations show negligible loss (~100 kA) in spite of 10^{17}/cc plasmas.
- **Ongoing work:** Calculate particle/plasma energy deposition in flyer. → Feed to current unfolds.

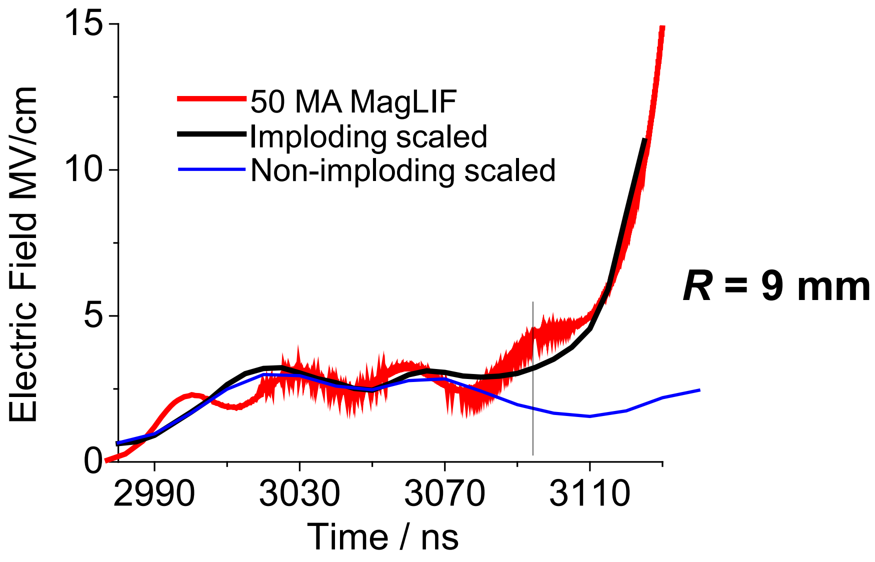


Modeling by Nichelle Bennett

Current delivery through a 50-MA equivalent scaled transmission line that is **stressed by an imploding liner** is essentially lossless!







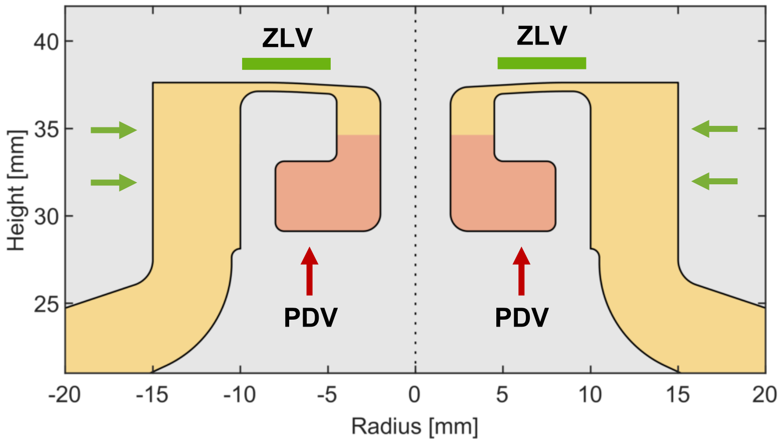
Scaled Power Flow Experiments on Z

1. Motivation for a next-generation pulsed power (NGPP) facility.
2. Design of a 50-MA-equivalent power flow scaling platform at 20 MA on Z.
3. Using velocimetry to diagnose the current delivered through scaled transmission lines.
4. Results, analysis, and modeling of the first power flow scaling experiments.
5. **Follow-on scaling experiments and future work.**

The first power flow scaling experiments on Z indicate that the current coupling through a 50-MA-equivalent transmission line (R ~ 1–2 cm) is essentially lossless.

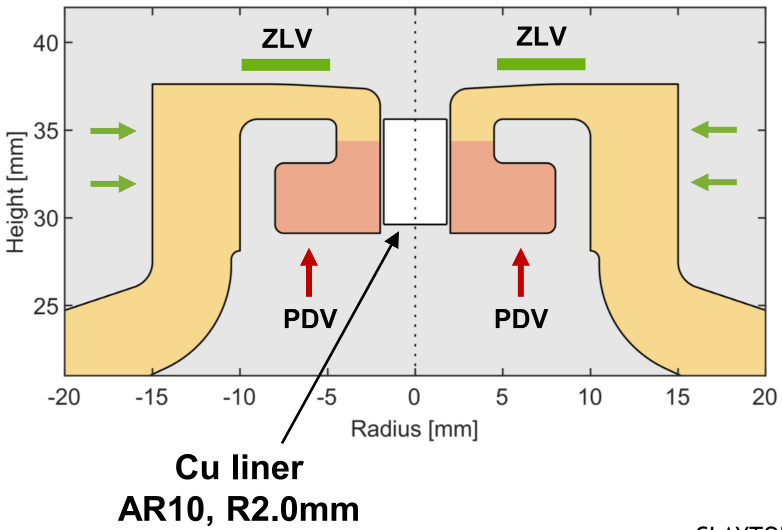
Future work: Four additional experiments are planned for Q1 of CY22. Further increase the electric field stress and test reproducibility.

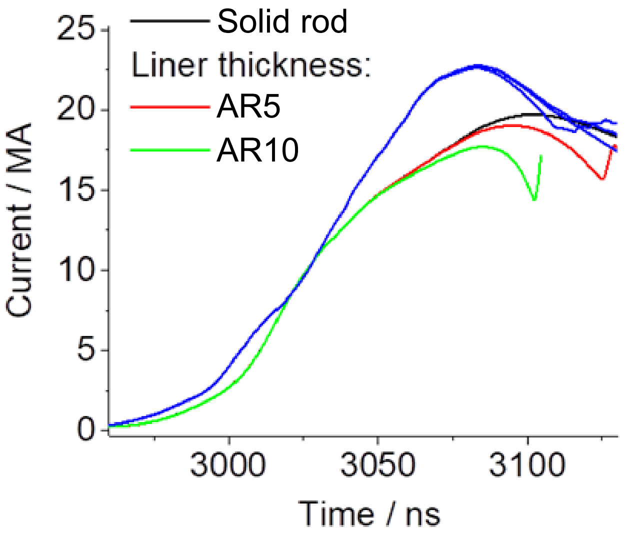
Increase static stress – 500 µm gap

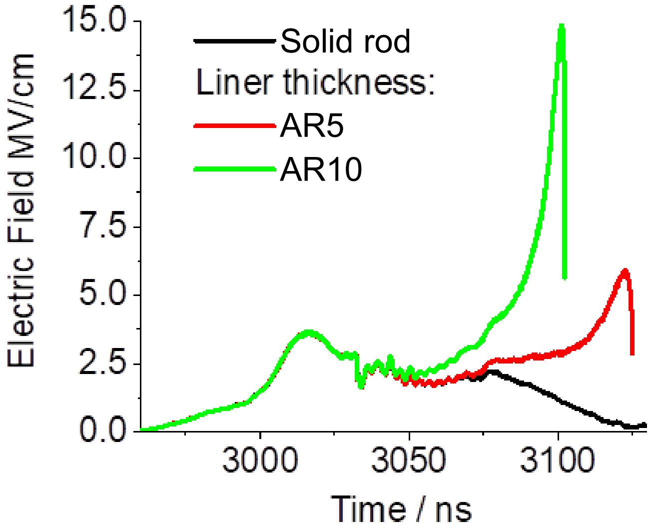


- Increase the static stress by reducing the A/K gap from 2 mm to 500 µm. → Study gap closure effects.
- Increase the dynamic stress by decreasing the liner wall thickness from 400 µm to 200 µm. → AR5 to AR10.
- Make bottom-side velocimetry measurements to quantify the current delivered to the inner target volume.
- Implement higher-precision machining methods and conduct detailed as-built flyer metrology.

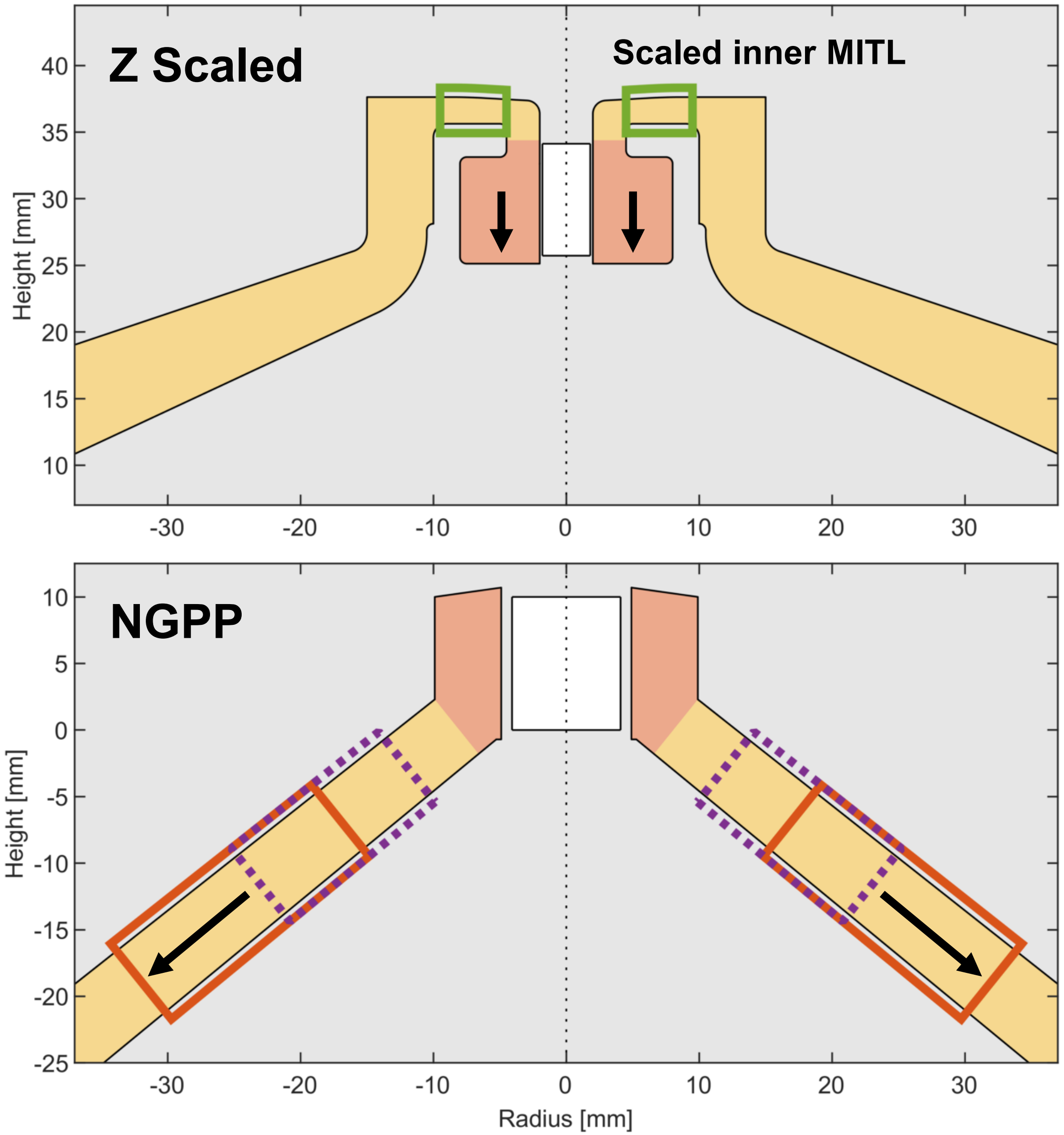
Increase dynamic stress – AR10 Cu liner







Future work: Increasing the load volume increases the electric field stress to match the **J** and **E** of a 70 MA MagLIF inner MITL over *R* ~ 2–3 cm.

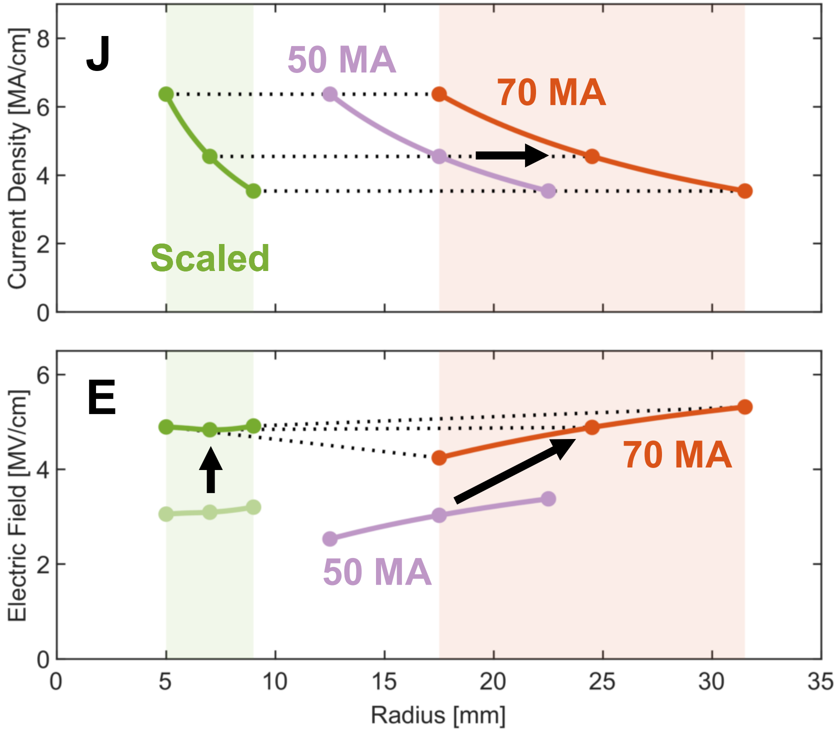


B-field, current density, and ohmic heating

$$B \propto \frac{I_{\mathrm{load}}}{R} \qquad J \propto \frac{I_{\mathrm{load}}}{R} \qquad P_{\mathrm{OH}} \propto \frac{I_{\mathrm{load}}^2}{R^2}$$

Electric field → static + dynamic

$$E = \frac{V}{d} = -\frac{\dot{\Phi}}{d} \sim -\frac{I_{\mathrm{load}}}{d}\left(i\omega L_{\mathrm{load}} + \dot{L}_{\mathrm{load}}\right)$$



Key result: Scaled experiments show that a transmission line operating at 50 MA conditions can efficiently deliver current to within 1 cm of the load!