Magnetically-driven High Energy Density Physics: Fundamentals, successes and building on collaborations

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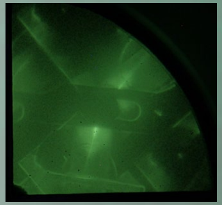
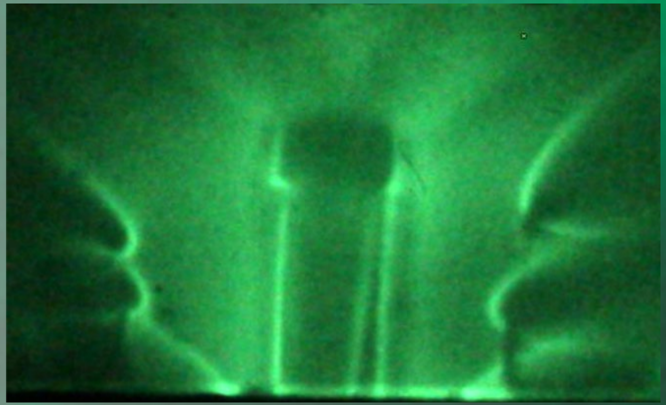
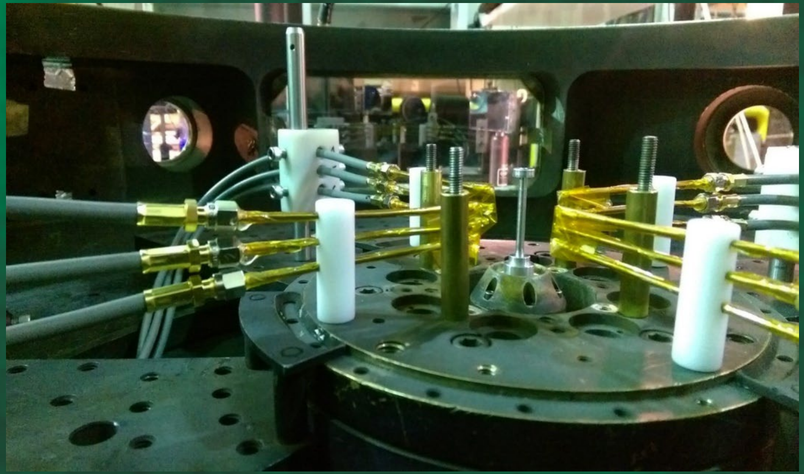
National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY





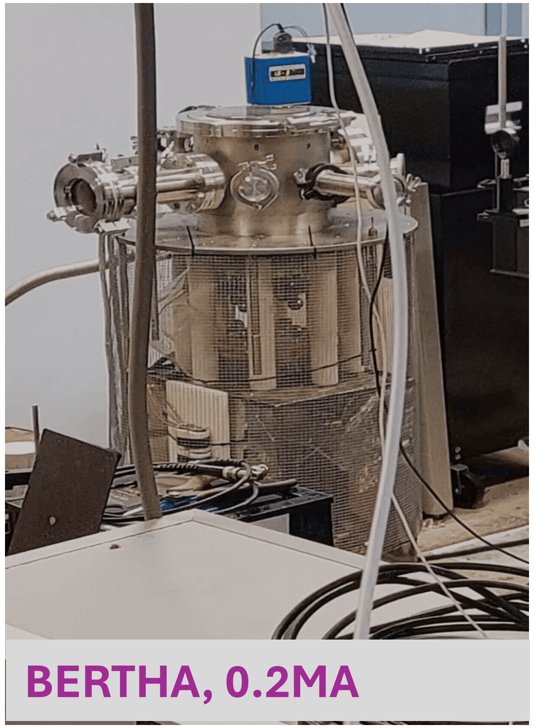


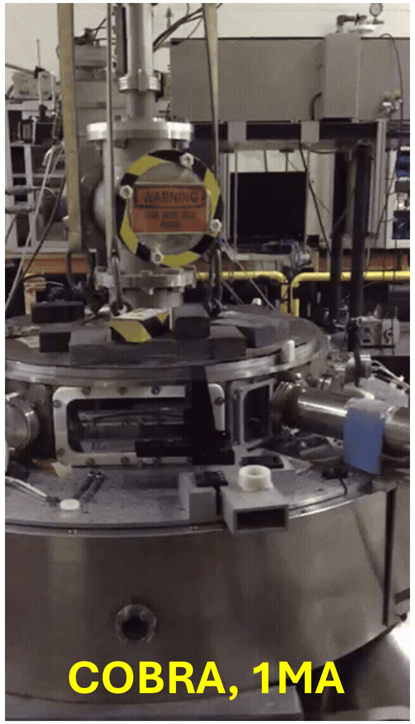
P³ Pulsed Power Plasmas Group

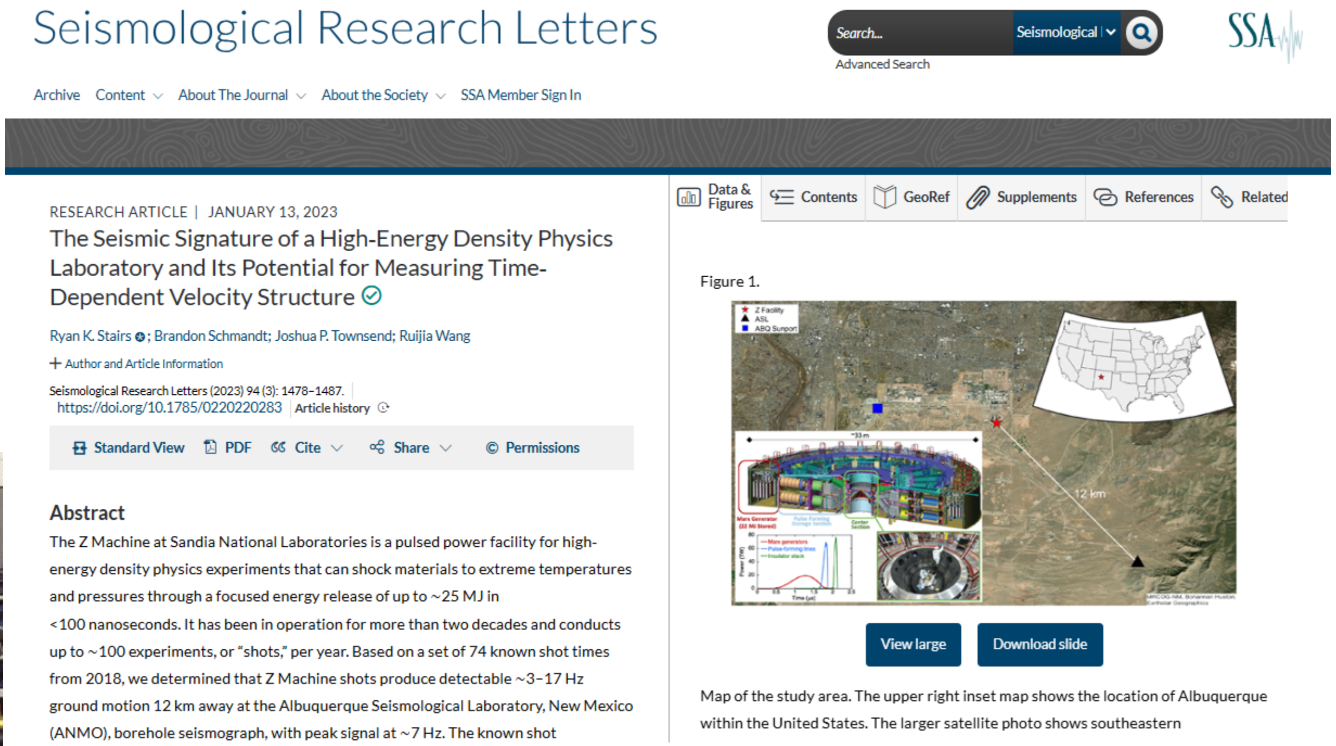
www.p3ucsd.com

Or; “From fun bangs to seismology”

- Pulsed power devices cover a very wide range of applications
- HEDP drivers are primarily of interest here



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RESEARCH ARTICLE | JANUARY 13, 2023

The Seismic Signature of a High-Energy Density Physics Laboratory and Its Potential for Measuring Time-Dependent Velocity Structure

Ryan K. Stairs; Brandon Schmandt; Joshua P. Townsend; Ruijia Wang

+ Author and Article Information

Seismological Research Letters (2023) 94 (3): 1478–1487.
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Abstract

The Z Machine at Sandia National Laboratories is a pulsed power facility for high-energy density physics experiments that can shock materials to extreme temperatures and pressures through a focused energy release of up to ~25 MJ in <100 nanoseconds. It has been in operation for more than two decades and conducts up to ~100 experiments, or “shots,” per year. Based on a set of 74 known shot times from 2018, we determined that Z Machine shots produce detectable ~3–17 Hz ground motion 12 km away at the Albuquerque Seismological Laboratory, New Mexico (ANMO), borehole seismograph, with peak signal at ~7 Hz. The known shot

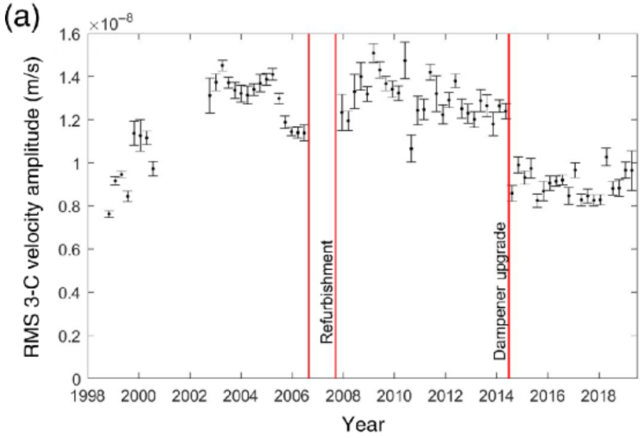
Data & Figures | Contents | GeoRef | Supplements | References | Related

Figure 1.

View large | Download slide

Map of the study area. The upper right inset map shows the location of Albuquerque within the United States. The larger satellite photo shows southeastern

Z Machine →



- Thanks to everyone

Imperial College London

Cornell University

University of Michigan

University of Rochester

Sandia National Laboratories

Lawrence Livermore National Laboratory

National Nuclear Security Administration

U.S. Department of Energy

- Special thanks to

Prof. Sergey Lebedev
Prof. Jerry Chittenden

Imperial College London

Prof. David Hammer
Prof. Bruce Kusse

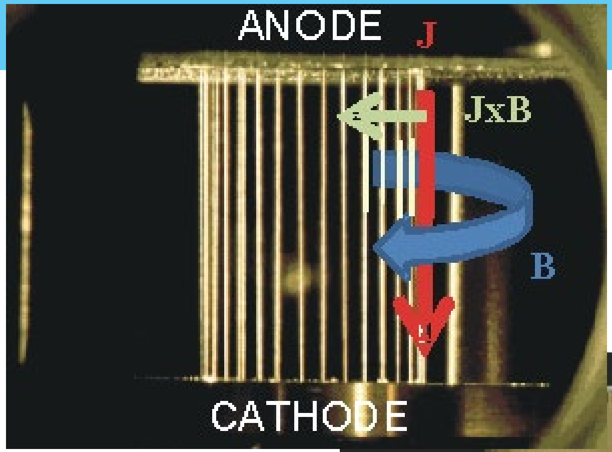
Cornell University

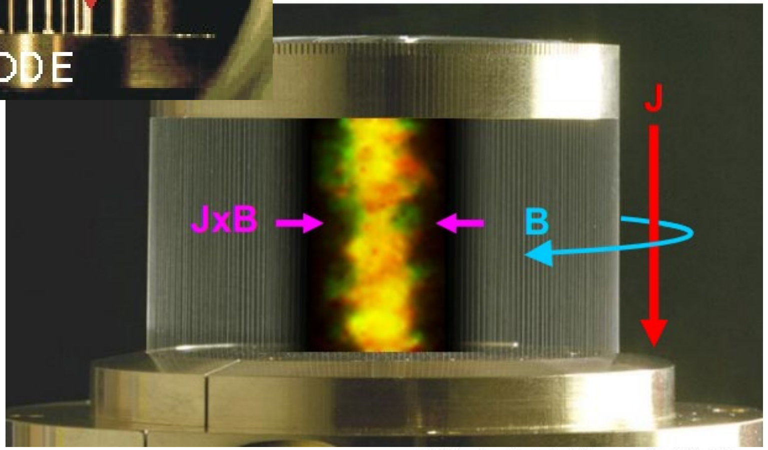
Dr. Dan Sinars
Dr. Mike Cuneo

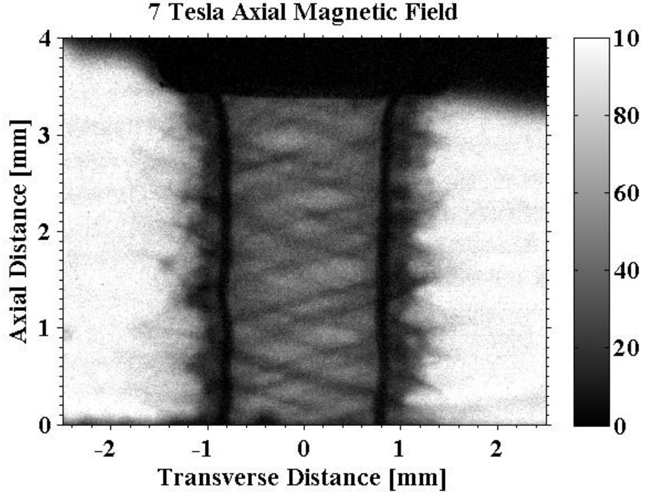
Sandia National Laboratories

Talk Outline

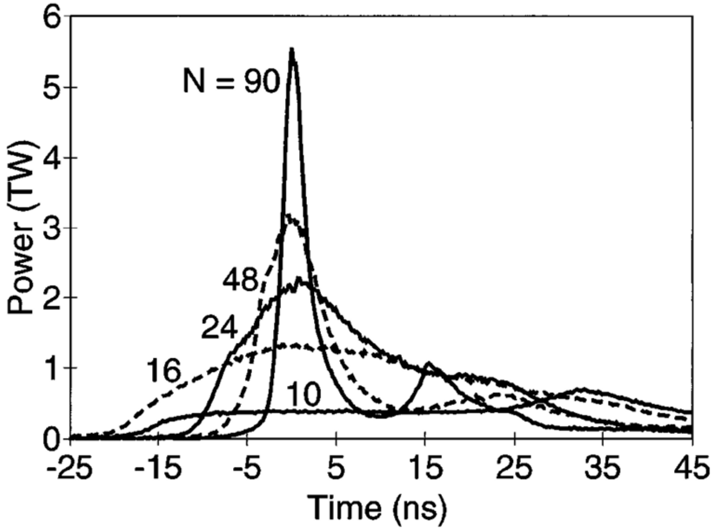
- Historical perspective of z-pinch performance
- Wire arrays – driving innovation and HEDP facilities
- University programs and Building on collaborations
- The transition to Liners
- Liner Fusion Energy







In the 1990s, the SATURN pulsed power machine driving arrays of fine wires produced interesting x-ray power outputs



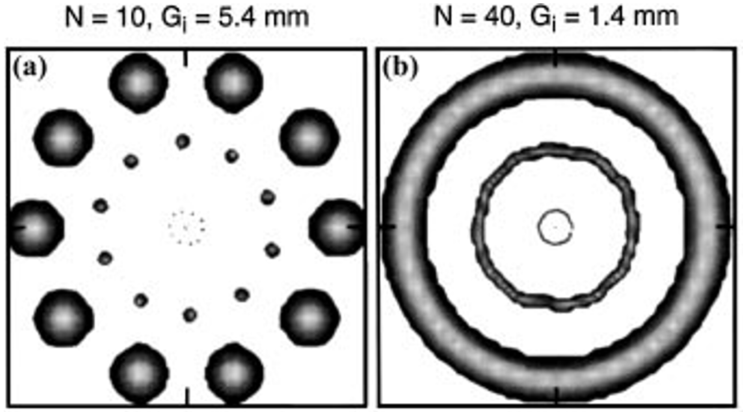
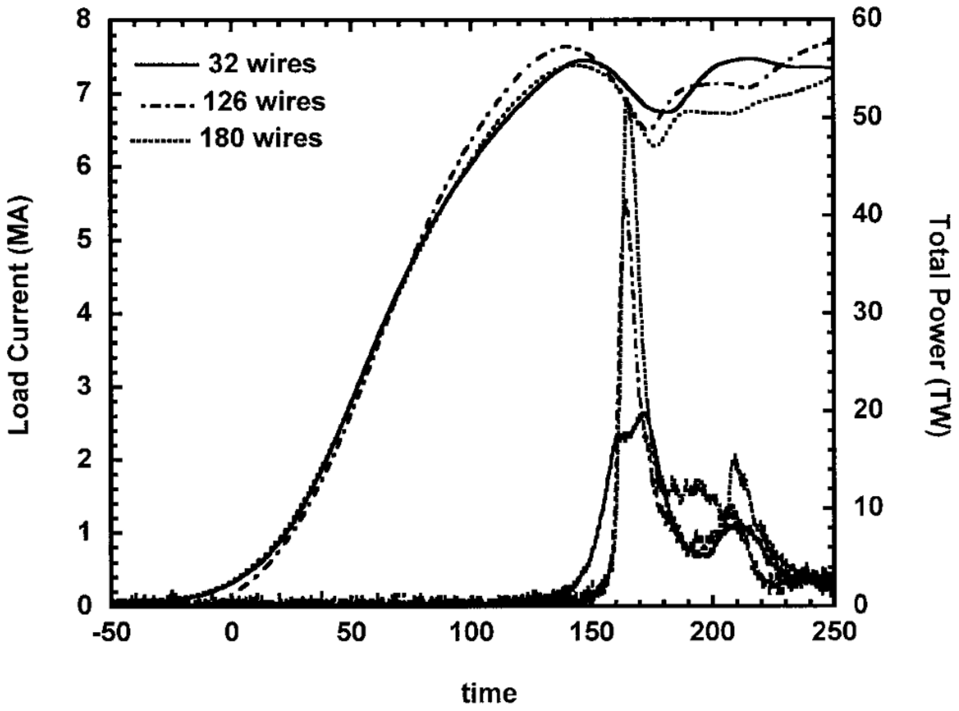


FIG. 6. *xy*-RMHC simulations for (a) 10- and (b) 40-wire, 8.6-mm implosions at 86, 11, 3, and 0 ns before stagnation. Azimuthal orientations at different times are not correlated.



- The success of these experiments in generating high power x-rays drove the conversion of PBFA-II (high voltage for ion beams) to Z (high current for wire arrays) in 1996
- Much of the trends for wire array configuration were noted in this work, but a more complete physics explanation was desirable

T.W.L. Sanford et al, Phys Rev Lett., **77**, 5063 (1996)
C. Deeney, Phys Rev E, **56**, 5945 (1997)
C. A. Coverdale Phys. Rev. Lett, **88**, 065001 (2002)

It's not the size........

- While Sandia worked of increasing absolute powers, university groups looked at how wire explode, ablate and implode

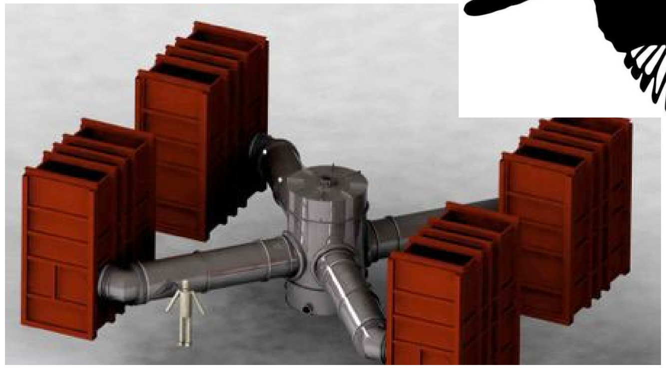
- Seemed like a challenge to continue to much large drivers with 1MA or less, but innovative experiments and simulation approaches were very successful

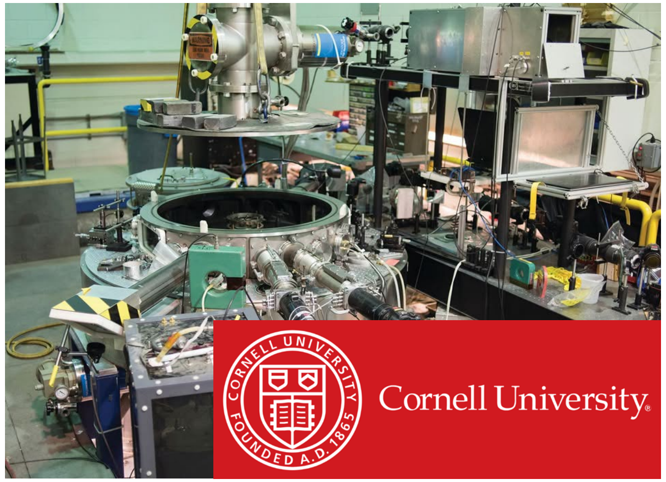
- Part of this was the ability to design experiments, chambers and drivers with more extensive diagnostic access

  Time resolved imaging was particularly insightful and difficult on Sandia drivers in early work

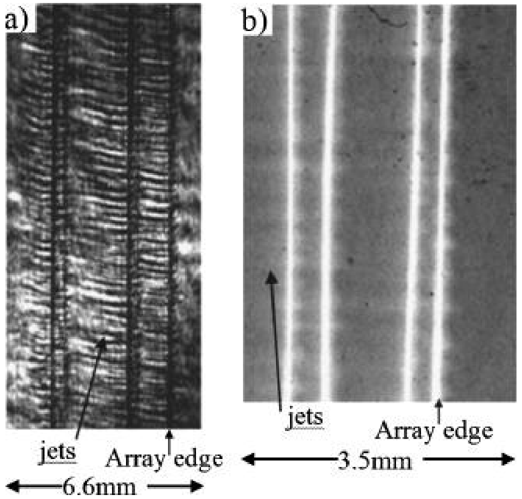
- Don't need to optimize power for mission needs, but can follow similar trends to elucidate the physics

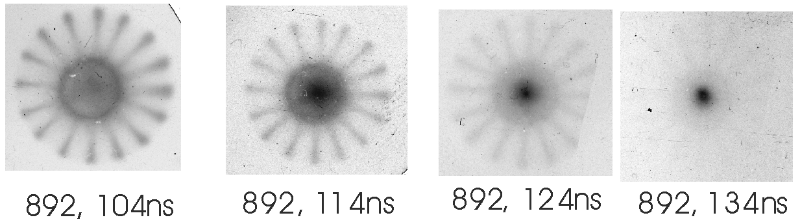
Imperial College London

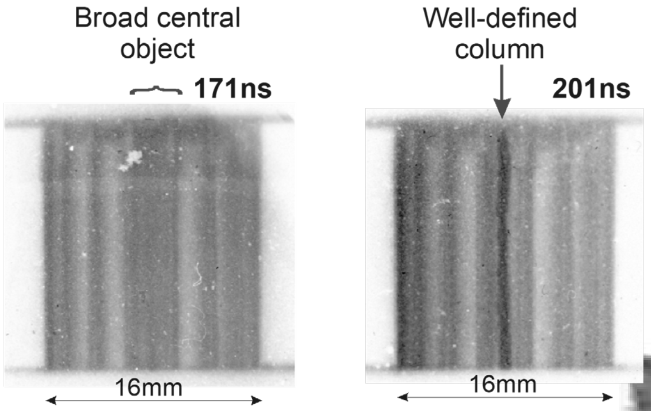


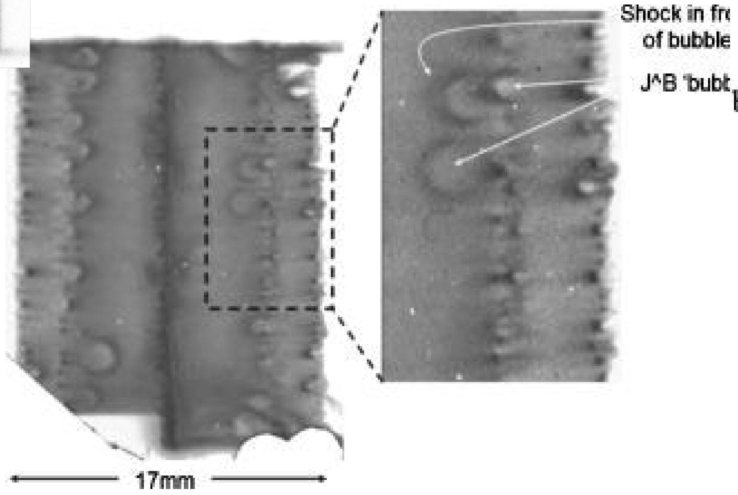


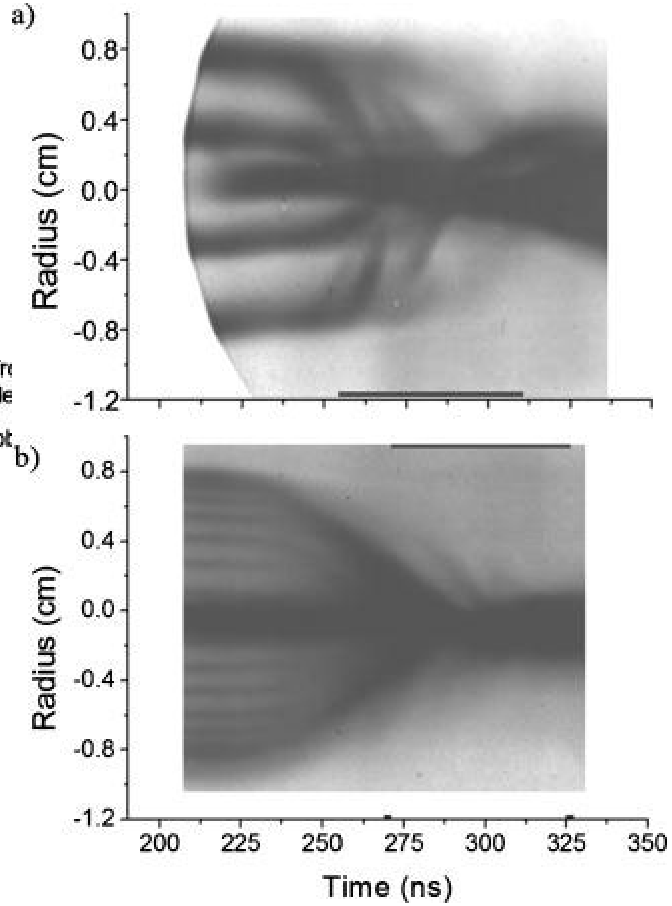
Exploding wires turned out to be complicated











Bland *et al, Phys. Plasmas* 14, 056315 (2007)
Bott *et al*, Phys. Rev. E, 74, 046403 (2006)

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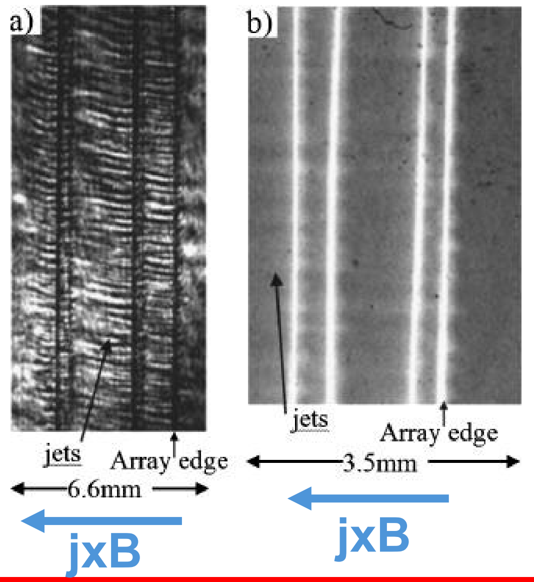
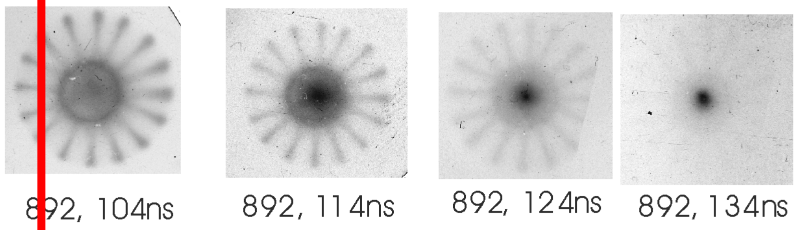
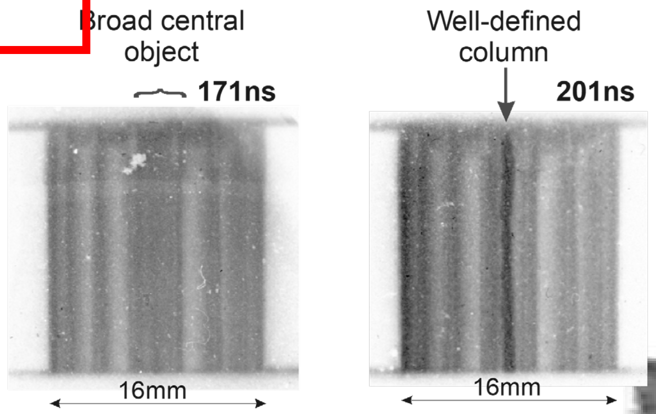
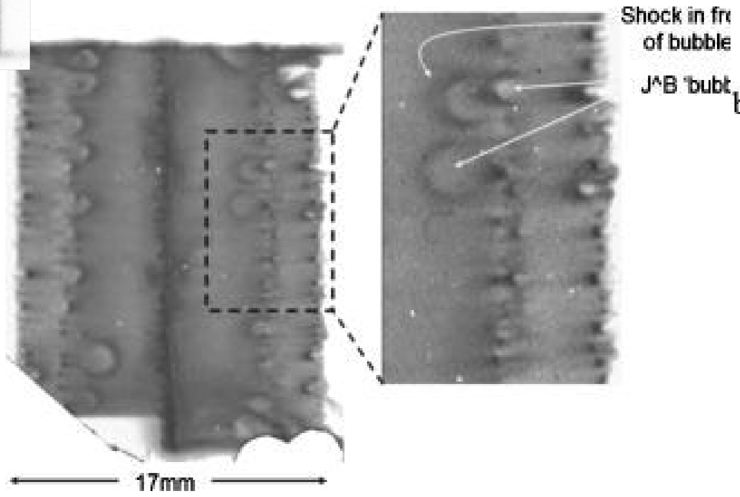
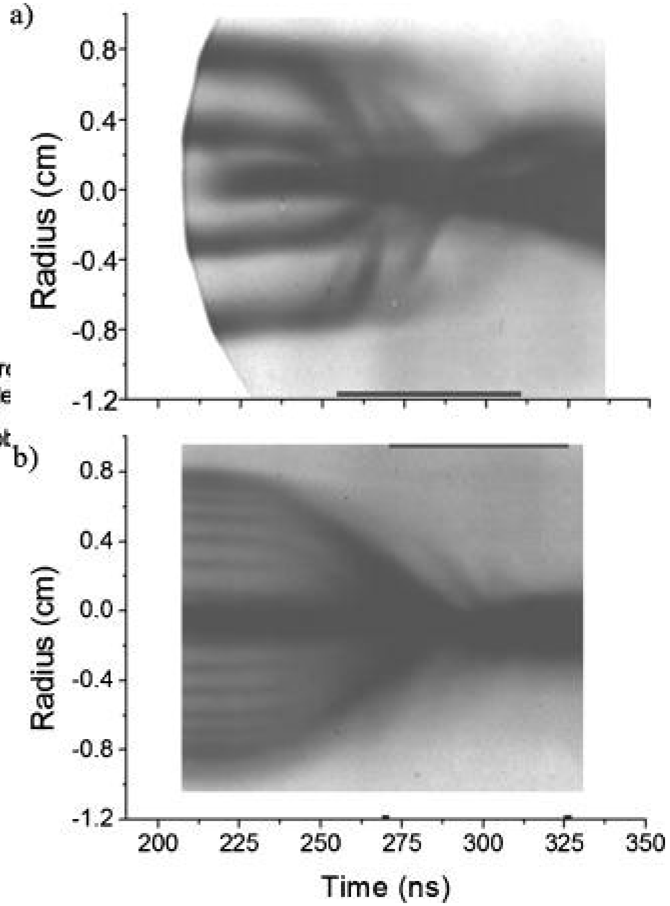


Wires ablate non-uniformly over a long time









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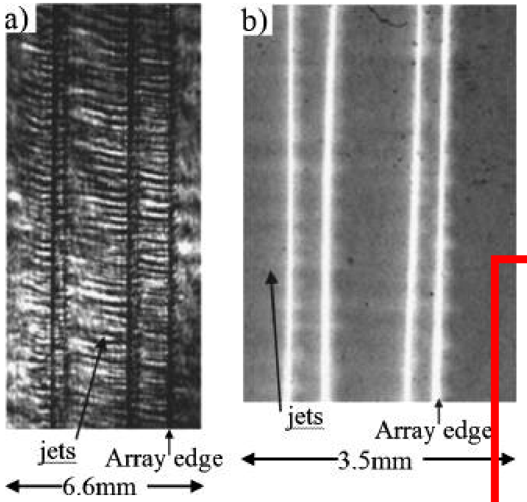

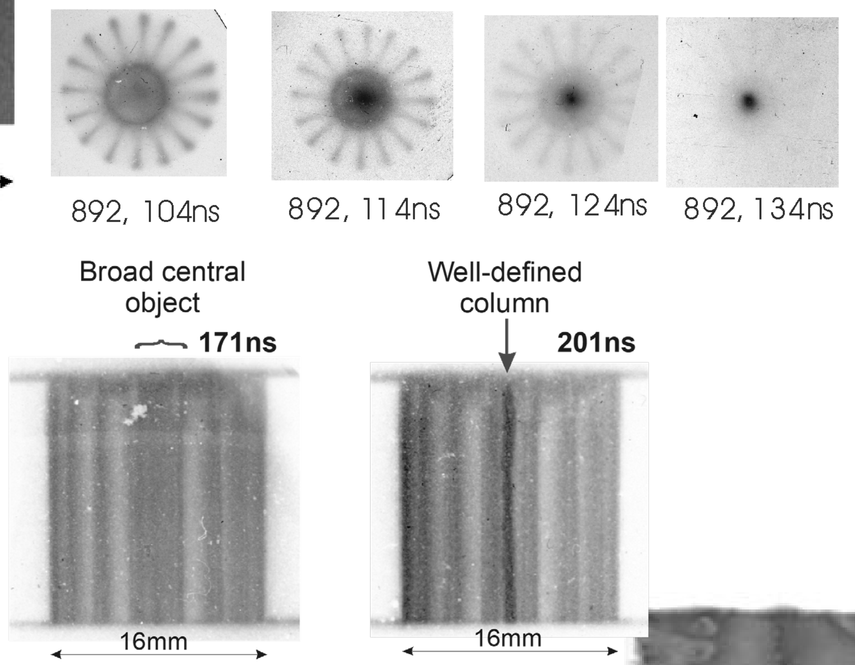

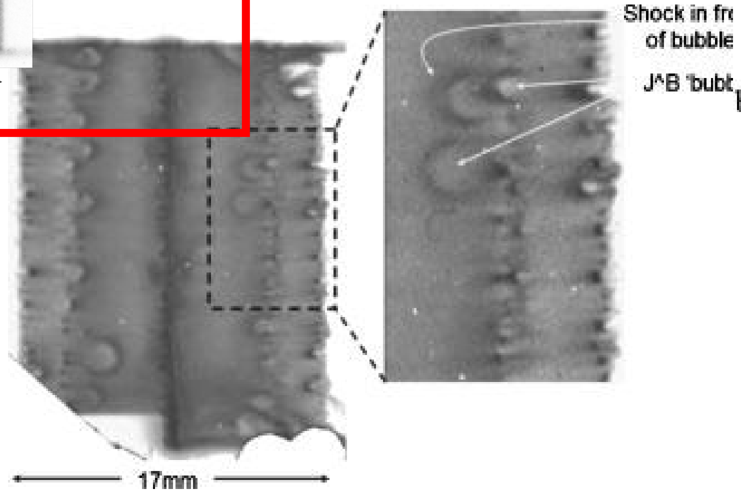

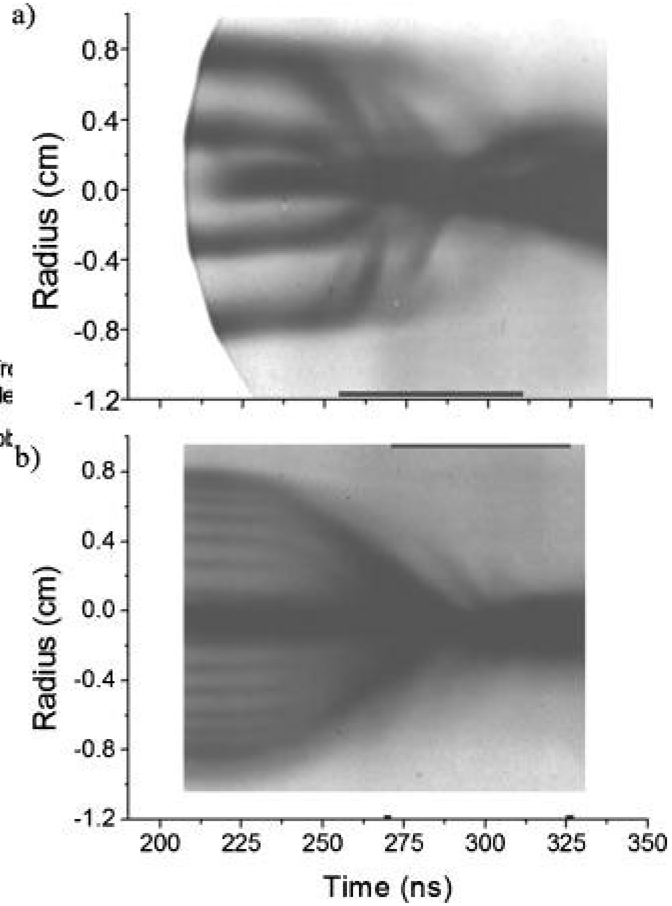

Leads to a mass distribution profile ahead of an implosion…..

Bland *et al, Phys. Plasmas* 14, 056315 (2007)
Bott *et al*, Phys. Rev. E, 74, 046403 (2006)

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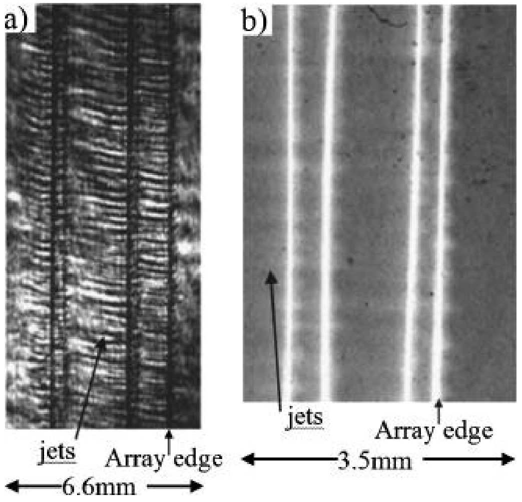
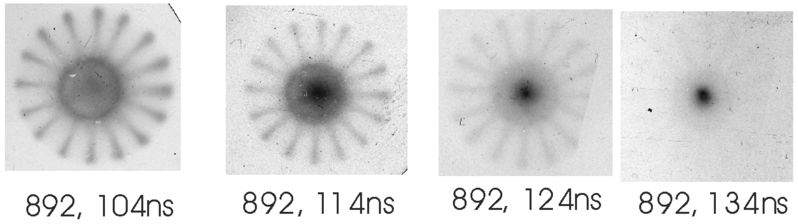
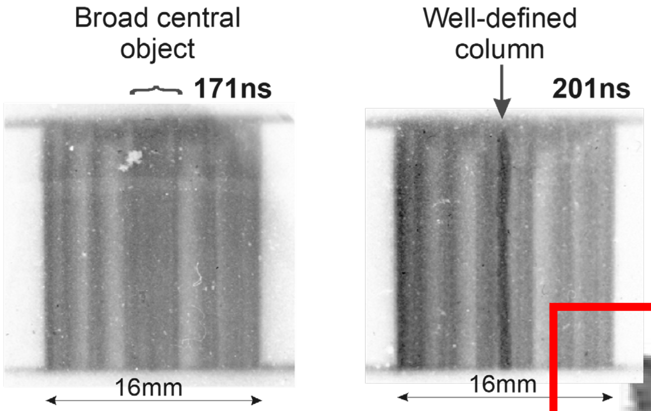
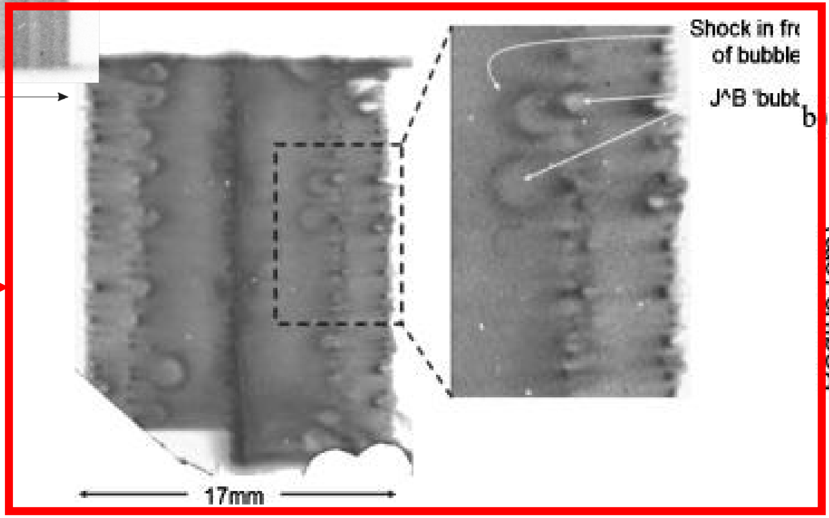
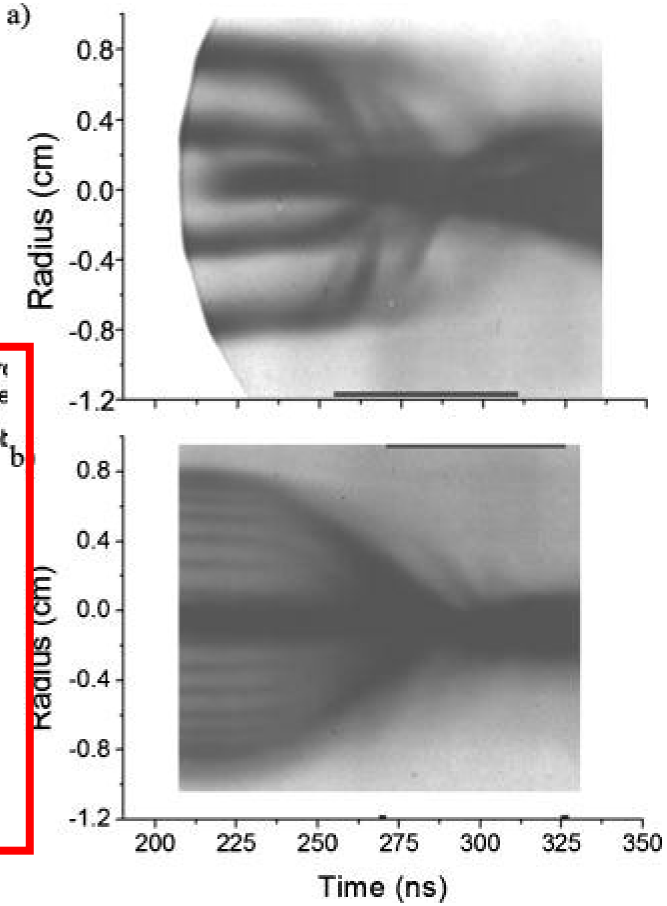






...and localized wire breakage which is different for adjacent wires





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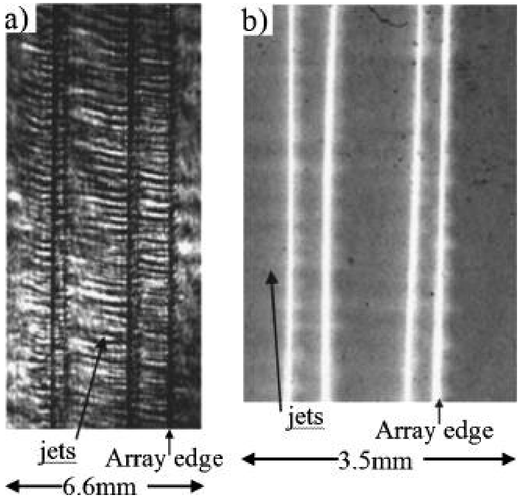
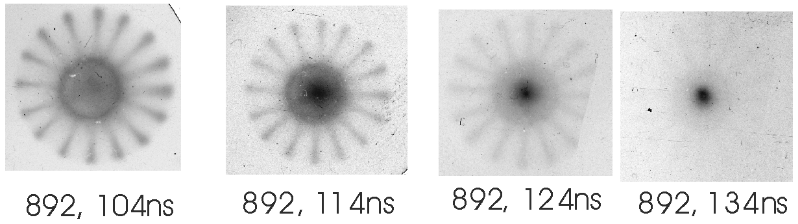
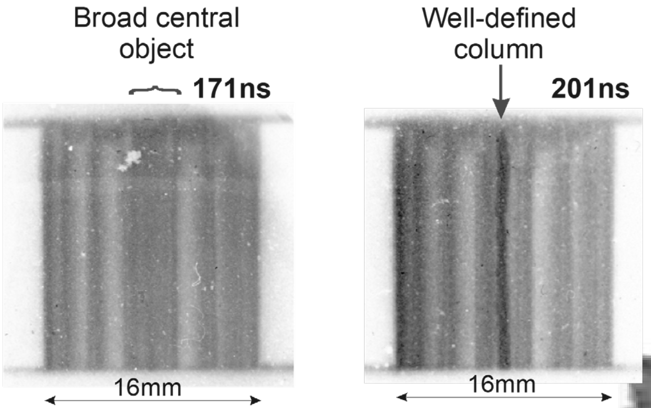
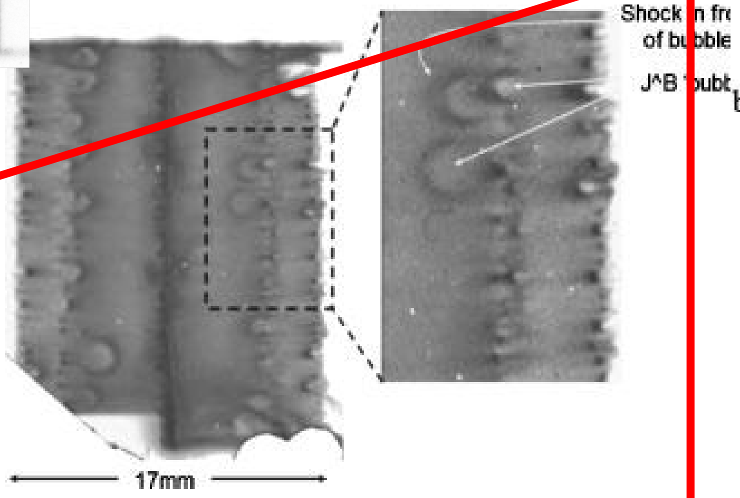
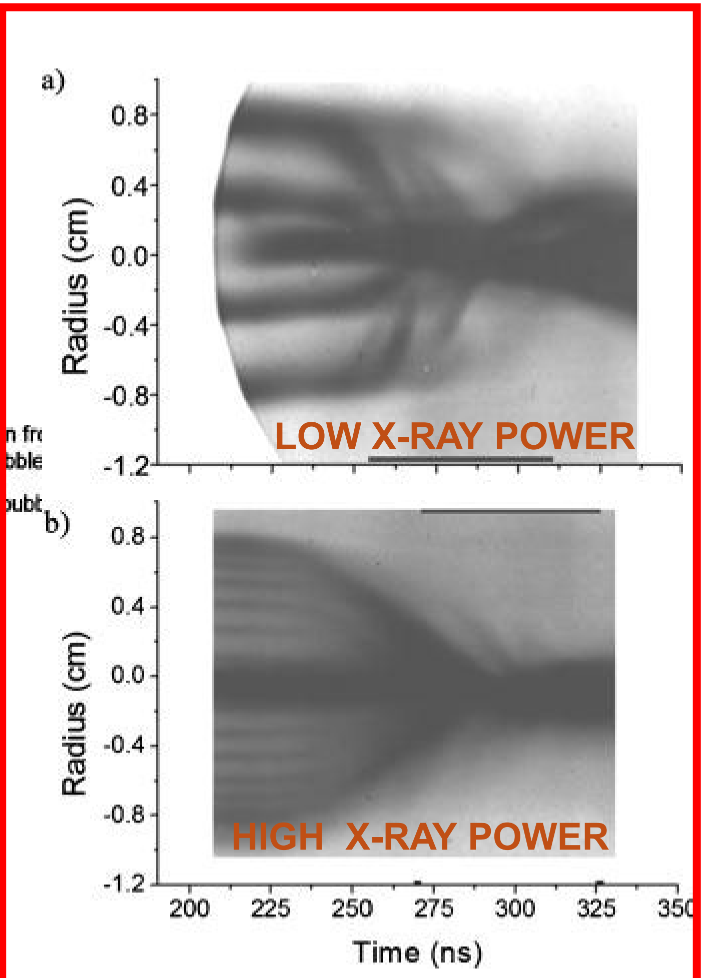








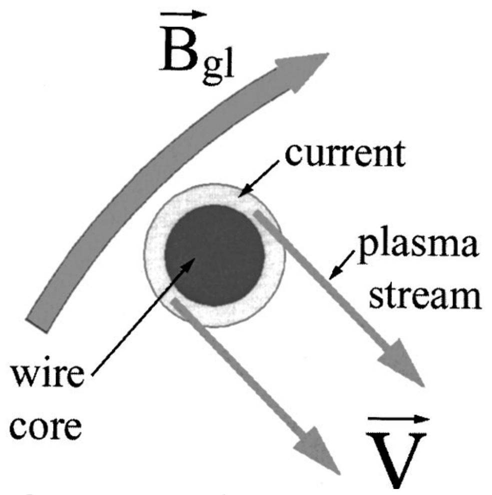


Closing the space between wires allow some MHD modes to correlate, leading to more synchronized implsion phase

Bland *et al, Phys. Plasmas* 14, 056315 (2007)
Bott *et al*, Phys. Rev. E, 74, 046403 (2006)

Many observables explained by the Core –corona Model

- Once the wire is driven into plasma by the current pulse, a central high mass core is surrounded by a low-density corona which carries most of the current
- Rocket Model proved a remarkably accurate, quantitative guide for experimental design and analysis



For the configuration with stationary wire cores and the flow of coronal plasma, the rate of the mass removal from the cores (per unit length) could be written as a condition of the momentum balance,

$$V\frac{dm}{dt} = -\frac{\mu_0 I^2}{4\pi R_0}. \qquad (1)$$

This replaces the standard 0D equation of motion used to describe the Z-pinch implosion (radius r vs time t) of a thin shell (see, e.g., Ref. 25),

Lebedev et al, Phys. Plasmas 8, 3734–3747 (2001)

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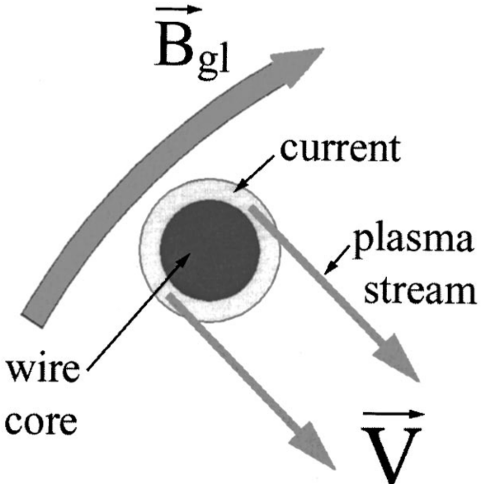

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"ablation velocity" *Measured from laser imaging*

"mass ablation rate" *Measured from laser imaging*

Wire array Radius *known*

Generator current *measured*

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Many observables explained by the Core –corona Model

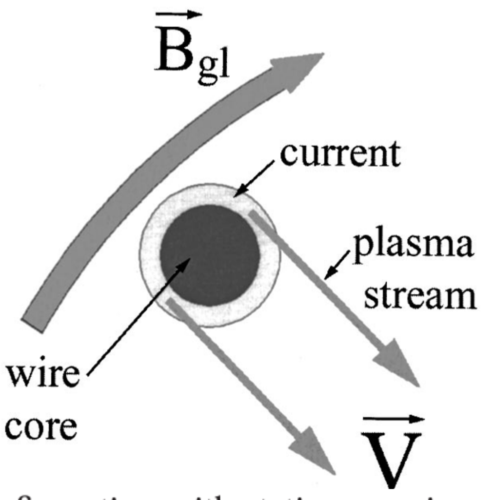
- Once the wire is driven into plasma by the current pulse, a central high mass core is surrounded by a low-density corona which carries most of the current
- Rocket Model proved a remarkably accurate, quantitative guide for experimental design and analysis
  - Allowed scaling to other configurations and drivers

$$\delta m(t) = \frac{\mu_0}{4\pi V R_0}\int_0^t I^2 dt.$$

  - Allows derivation of radial density profiles

$$\rho(r,t_0) = \frac{\mu_0}{8\pi^2 R_0 r V^2}\left[I\left(t_0 - \frac{R_0 - r}{V}\right)\right]^2$$

Lebedev et al, Phys. Plasmas 8, 3734–3747 (2001)



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“ablation velocity” *Measured from laser imaging*

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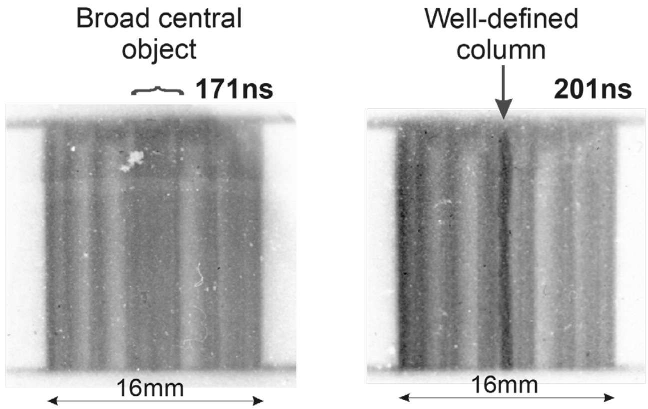
Wire array Radius *known*

Generator current *measured*

Lebedev Rocket model was a very enabling step forward

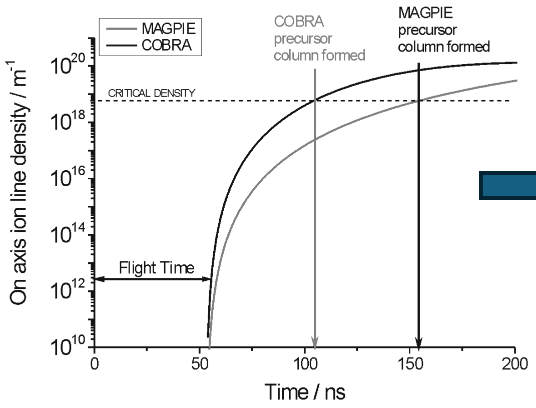
- Demonstration of a good understanding of dominant processes



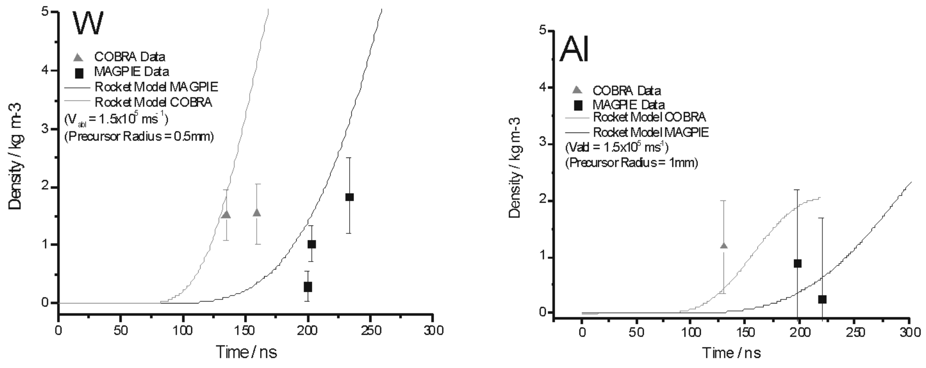
INITIAL DATA
(MAGPIE, 1MA 240ns)

COBRA

1MA, 1000ns



SCALING PREDICTION



QUATITATIVE COMPARISON

- Recreated trends for array performance observed at Sandia

- Provided a useful reference point for simulation initial conditions

Chittenden *at al, Phys. Plasmas* 11, 1118–1127 (2004)
E. Yu *et al, Phys. Plasmas* 14, 022705 (2007)

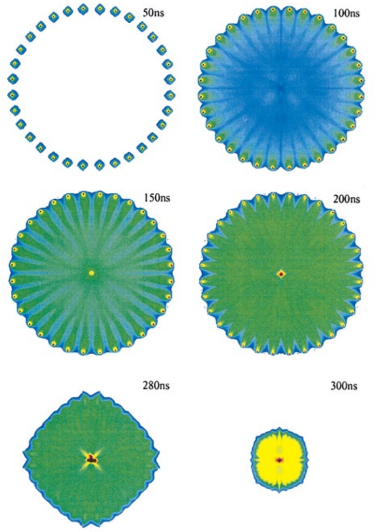


FIG. 1. (Color) Logarithmic mass density contours from a 2D simulation of 32 15-μm aluminum wires on MAGPIE.

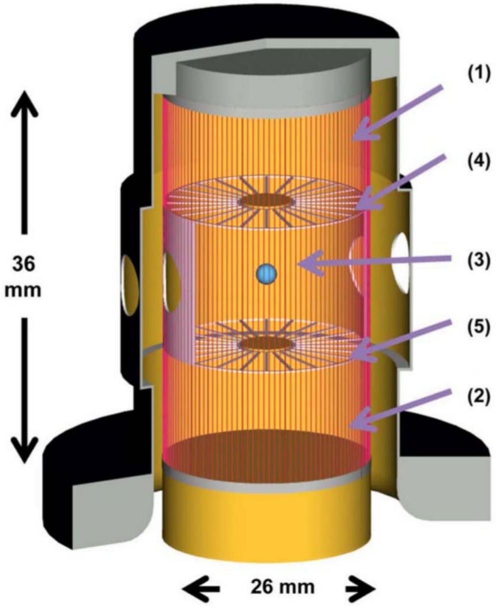
S.N.Bland *et al, Phys. Plasmas* 10, 1100–1112 (2003)

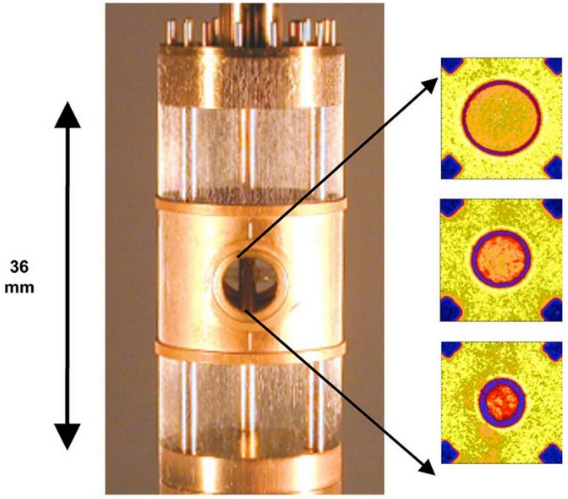
Wire array systems for Inertial Confinement Fusion

Much of this understanding and increasing ability to simulate wire array performance led to application in several ICF designs based on hohlraum indirect drive schemes

Deeney et al, Phys. Rev. Lett. **81**, 4883 (**1998)**

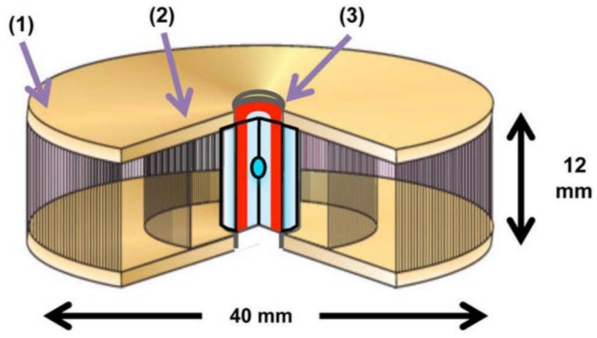
DOUBLE-ENDED HOHLRAUM





- Time-averaged capsule radiation symmetry of 2% was demonstrated with 2-mm diameter capsules
- Additional optimization with 4.7mm capsules led to a point design with a yield of 460MJ for 70MA driver

DYNAMIC HOHLRAUM



- More compact system with potentially higher efficiency
- Still used very effectively for radiation and EOS studies

Cuneo *et al, IEEE Trans*. Plasma Sci., **40**, 3222 (2012)

Wire array systems for Inertial Confinement Fusion

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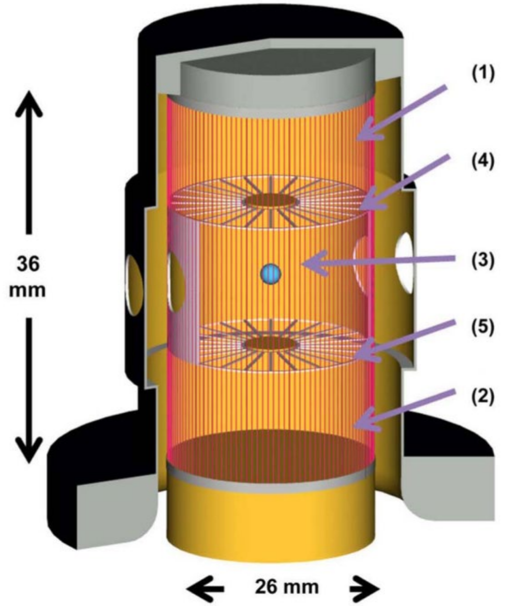
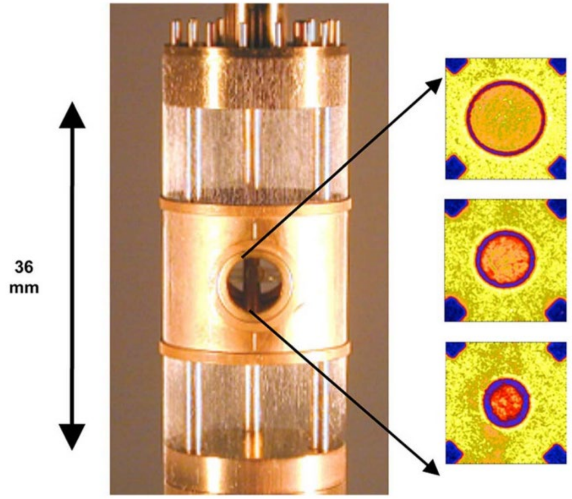
280 TW, 1.8 MJ in 1998 (from 11MJ stored energy = 16% eff.) Deeney et al, Phys. Rev. Lett. **81**, 4883 (**1998**)

DOUBLE-ENDED HOHLRAUM





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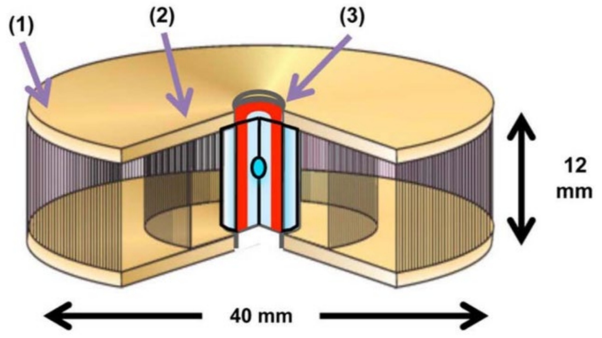

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Cuneo *et al, IEEE Trans*. Plasma Sci., **40**, 3222 (2012)

The NNSA Center of Excellence in pulsed power (2003 – present)

NNSA
National Nuclear Security Administration

- The ability of a collaborative university effort to support, influence and extend national lab programs led to the establishment of "The Center" in 2003

- Led by Dave Hammer and Bruce Kusse (2002-2022), and now Ryan McBride

Cornell University

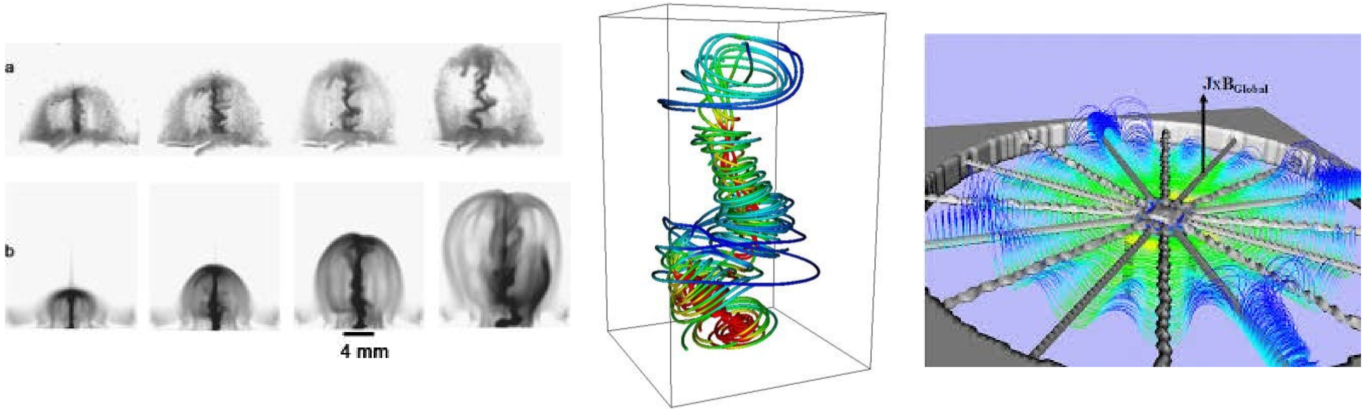
University of Michigan

- Provide foundational support for a wide range of pulsed power activities, both mission focused and blue-skies research

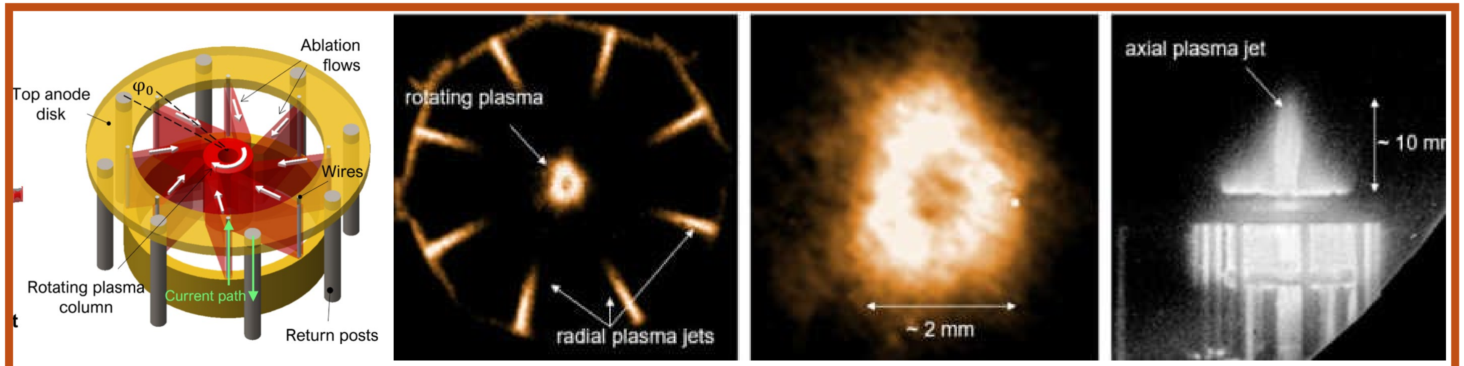
- An engine of productivity, and an effective workforce supply chain in HEDP

Wire arrays are a remarkably flexible platform for physics studies

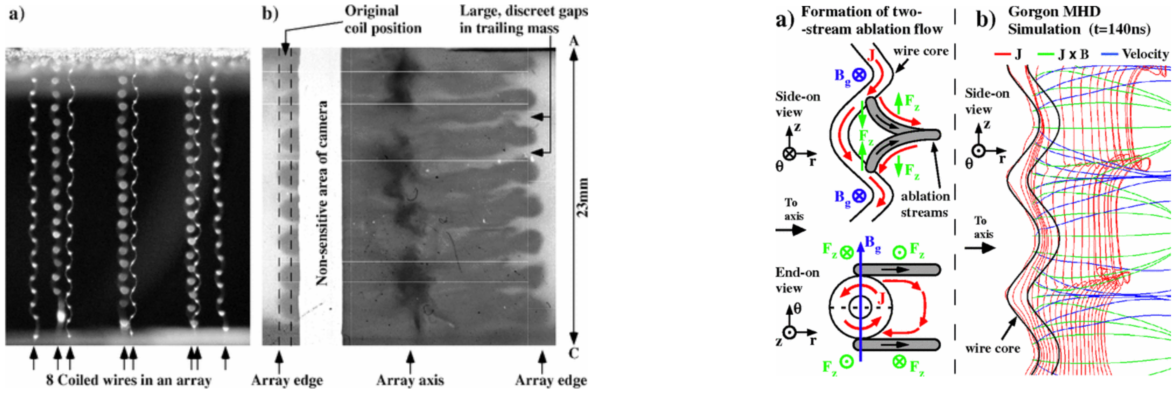
- Direct, close collaboration of simulation and experiments has been key in all these developments



MAGNETICALLY-DRIVEN JETS A. Ciardi et al, Phys. Plasmas 14, 056501 (2007)



DIFFERENTIALLY ROTATING FLOWS V. Valenzuela-Villaseca, PRL. 130, 195101 (2023)



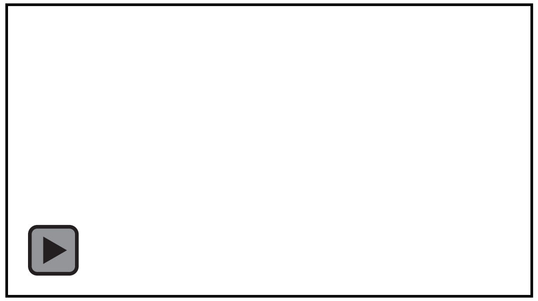
COILED WIRE ARRAYS G.N. Hall *et al, Phys. Rev. Lett.* 100, 065003 (2008)

- Strong shocks and the effect of radiation

- Magnetic Reconnection using wires

Wire arrays are a remarkably flexible platform for physics studies

- Direct, close collaboration of simulation and experiments has been key in all these developments



S.N.Bland *et al*

- Strong shocks and the effect of radiation

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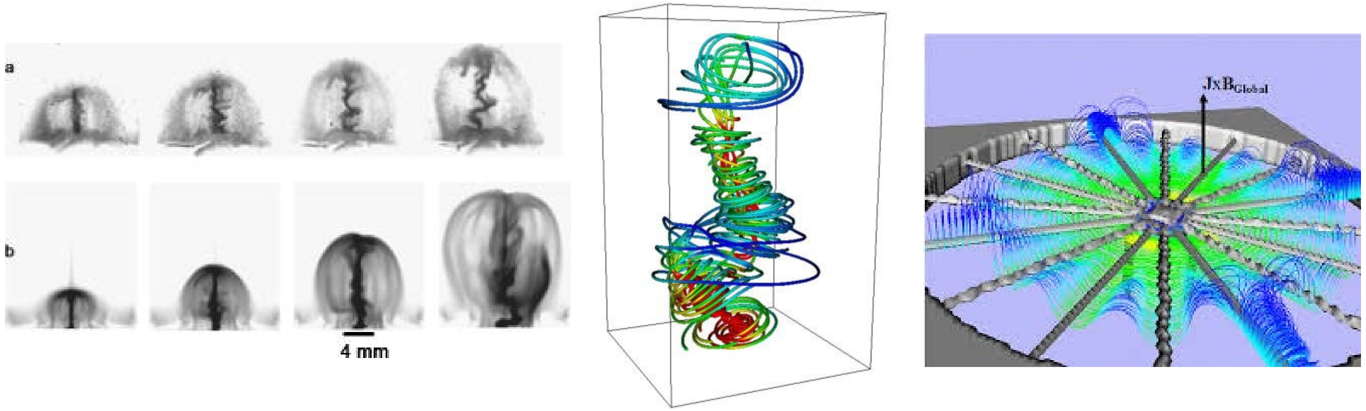
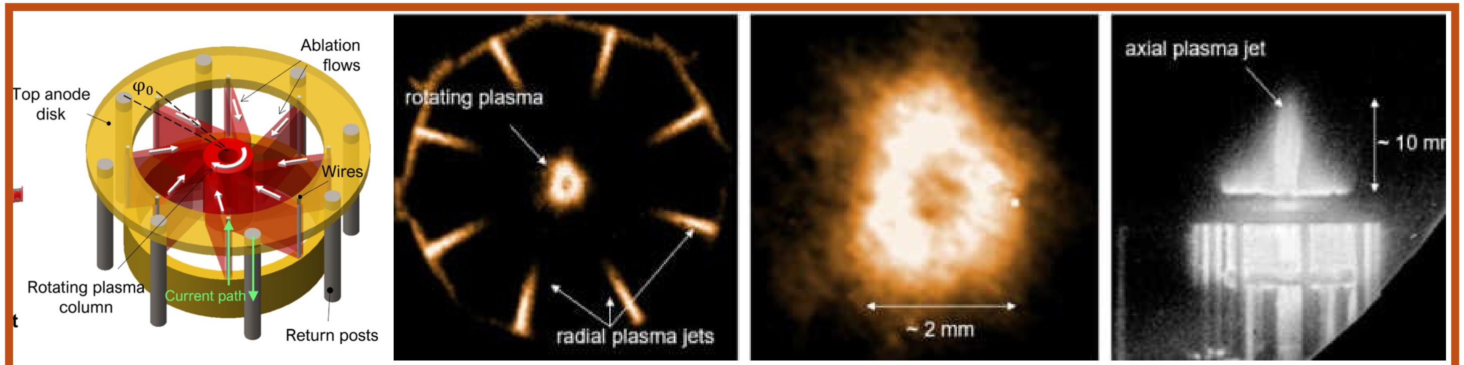
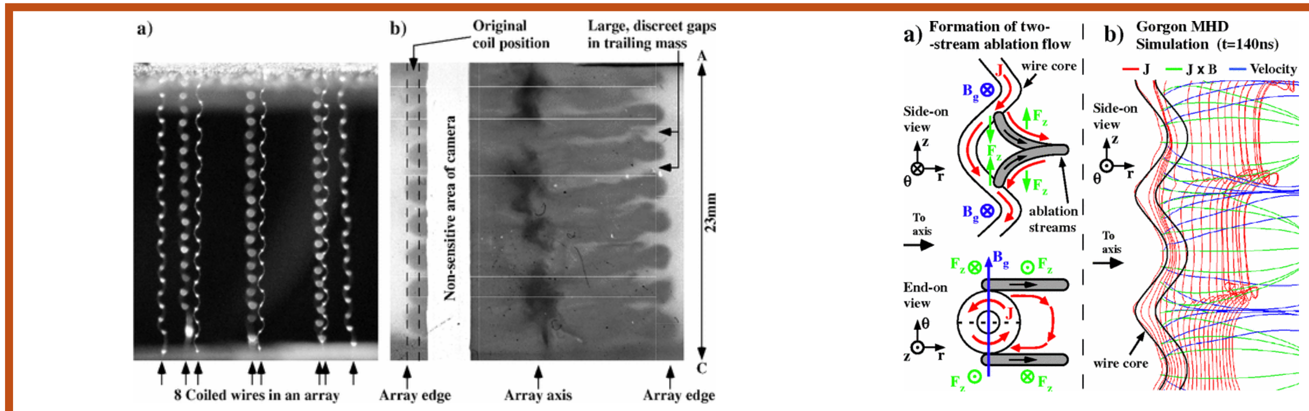


MAGNETICALLY-DRIVEN JETS A. Ciardi et al, Phys. Plasmas 14, 056501 (2007)



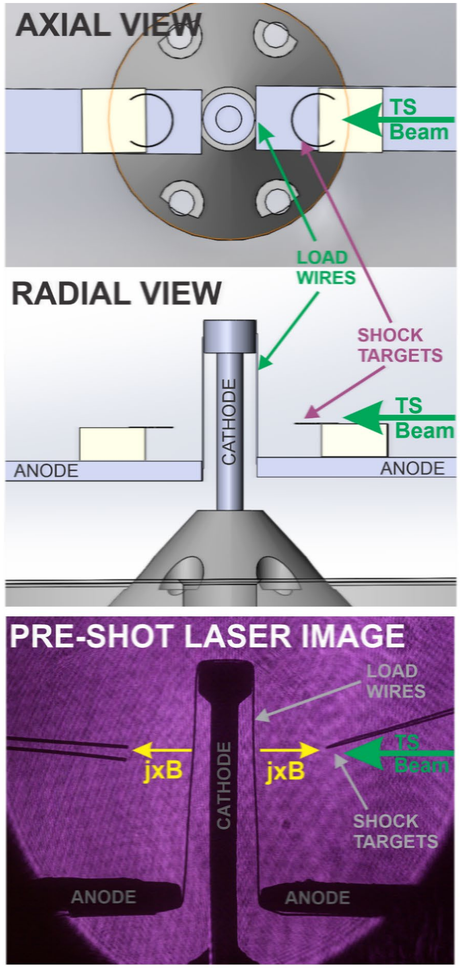
DIFFERENTIALLY ROTATING FLOWS V. Valenzuela-Villaseca, PRL. 130, 195101 (2023)

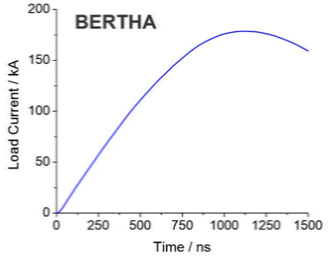


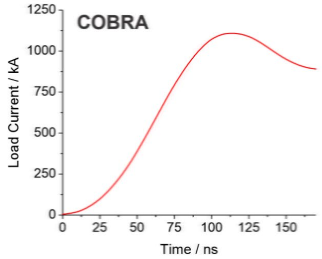
COILED WIRE ARRAYS G.N. Hall *et al, Phys. Rev. Lett.* 100, 065003 (2008)

Plasma flow parameters in inverse wire arrays

UC San Diego · Cornell University · Imperial College London

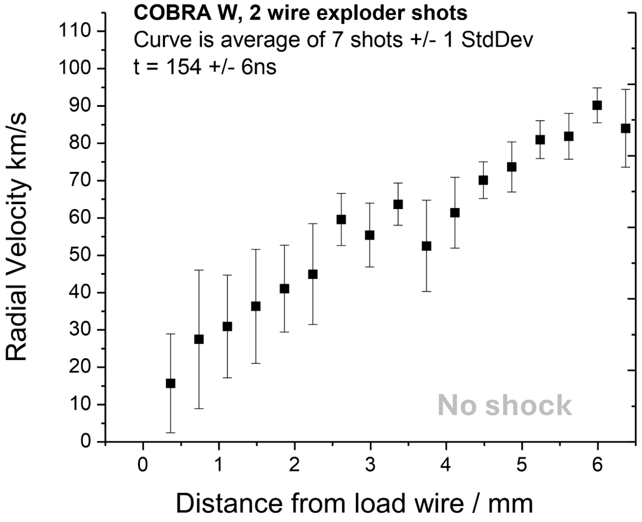


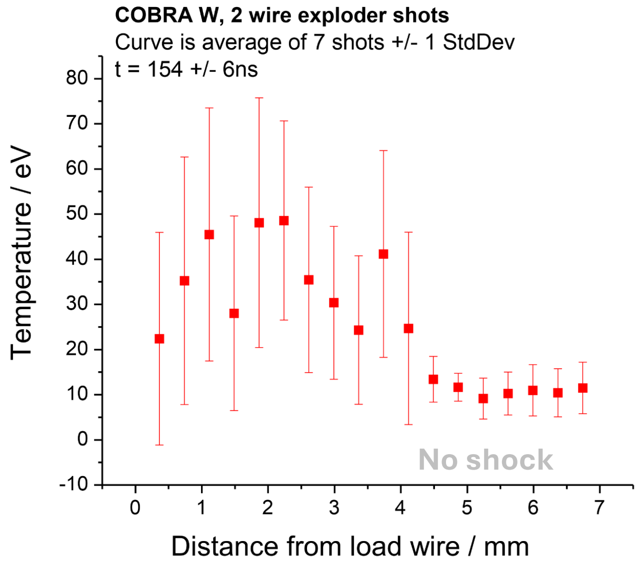




Directly measured parameters

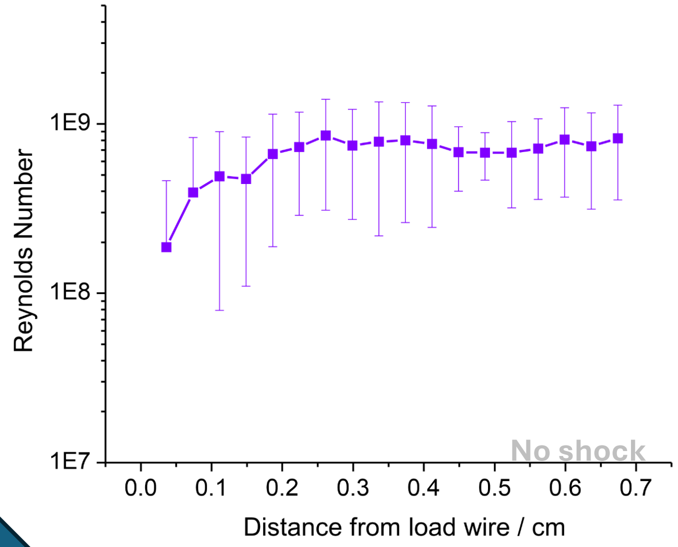
Thomson Scattering (n_e, V_r)

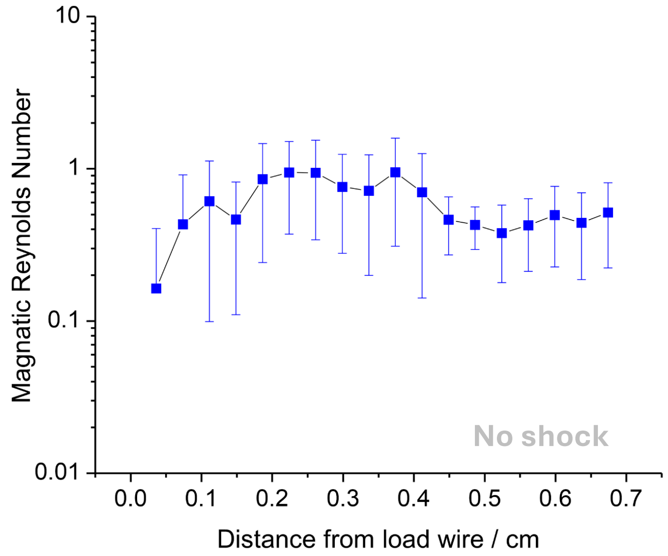




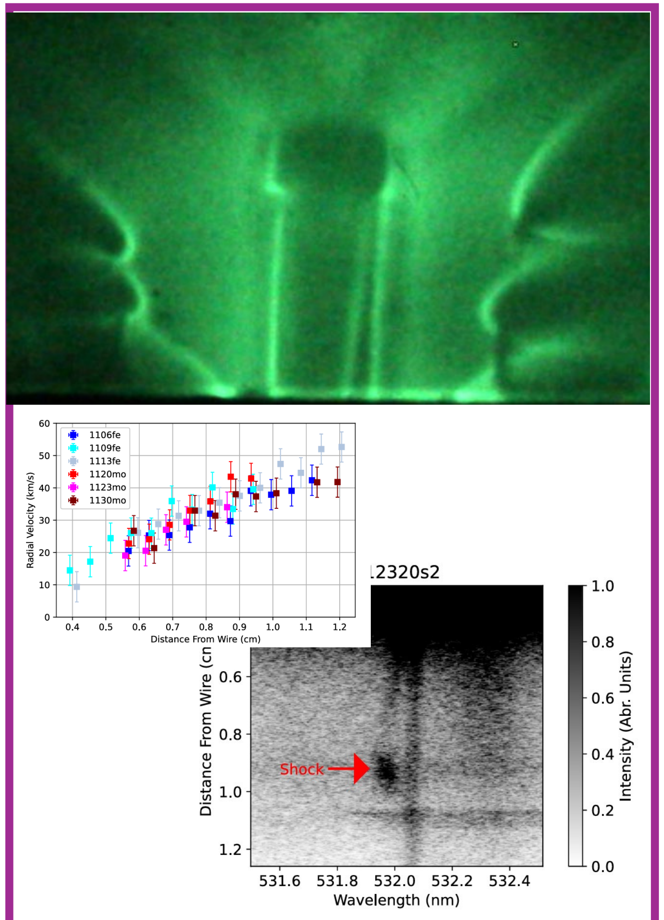
Calculated parameters

(R_e, $R_{e,M}$)

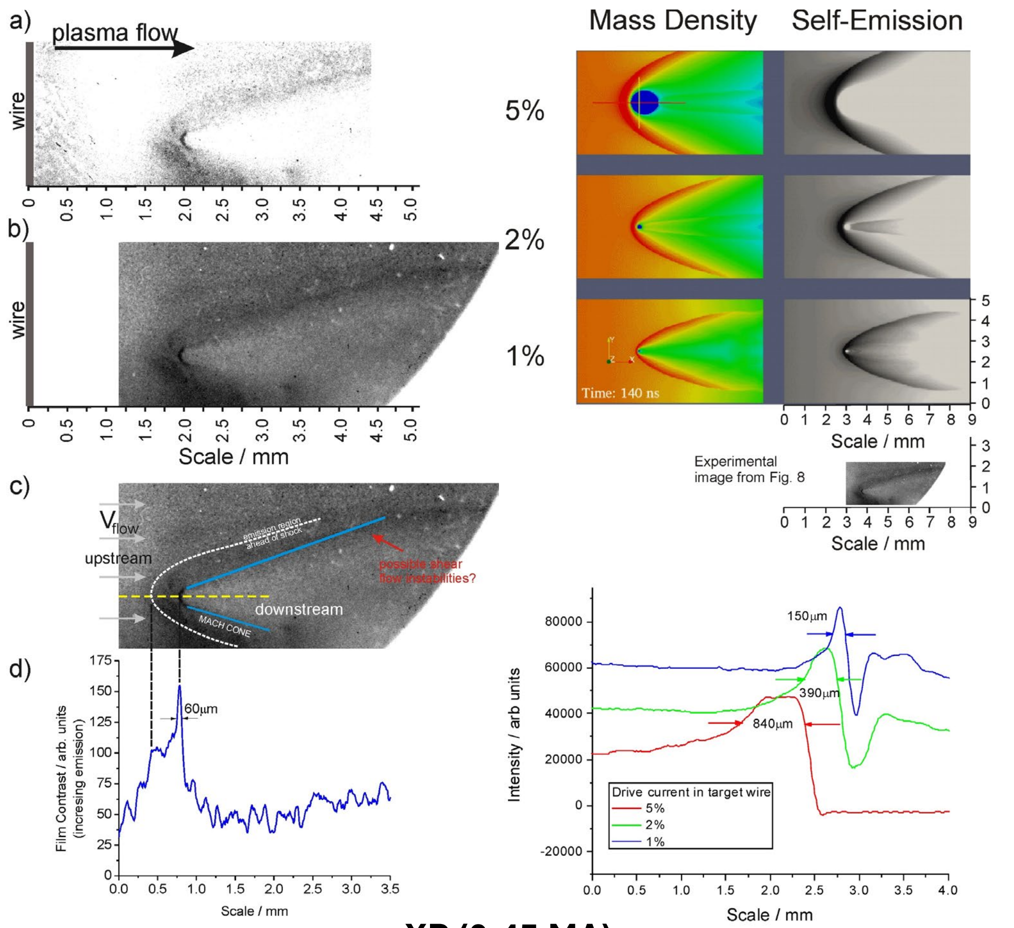




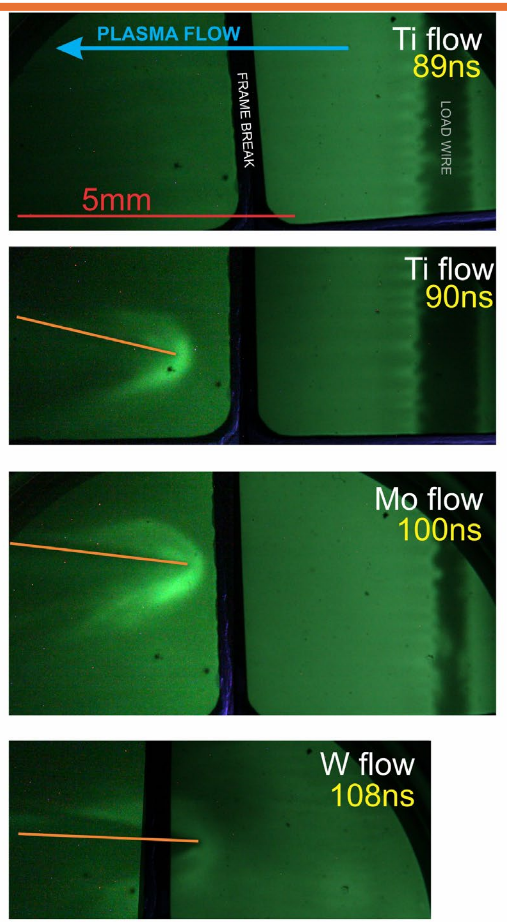
Stationary Targets in the plasma flow generate bow-shocks



BERTHA (0.2 MA)



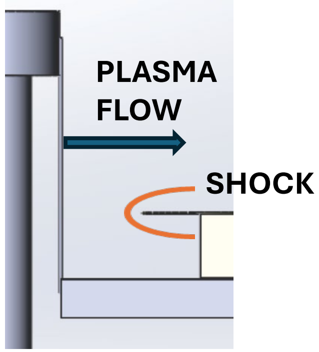
XP (0.45 MA)



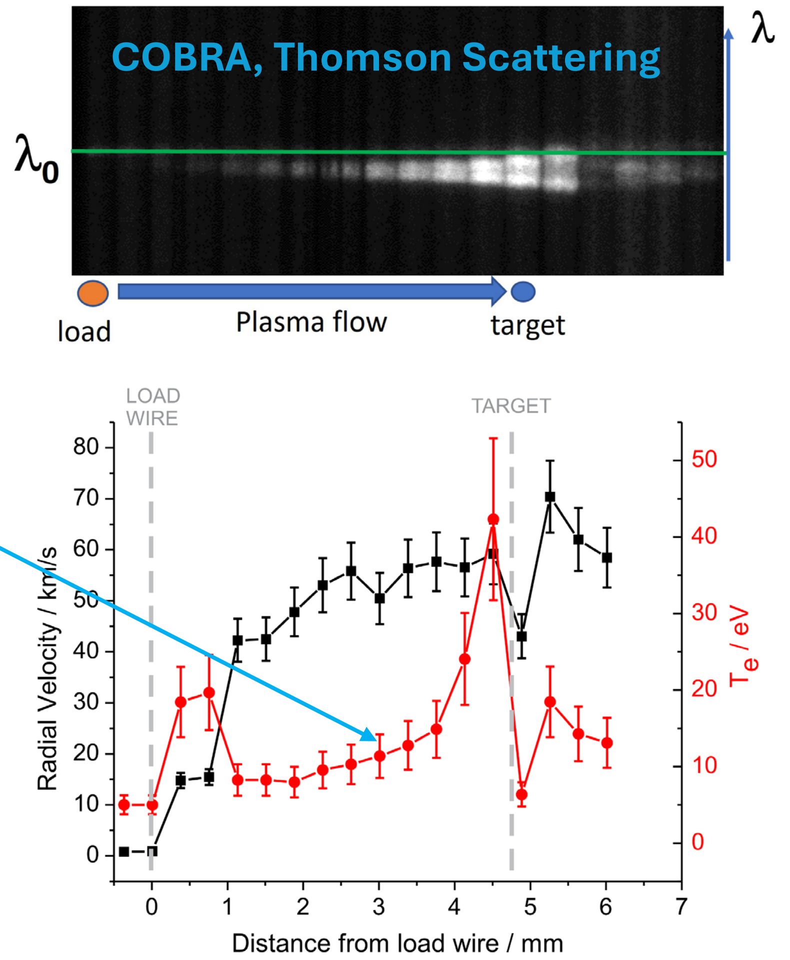
COBRA (1MA)

INCREASING DRIVER CURRENT

- Emission features ahead of shock only observed in higher density experiments

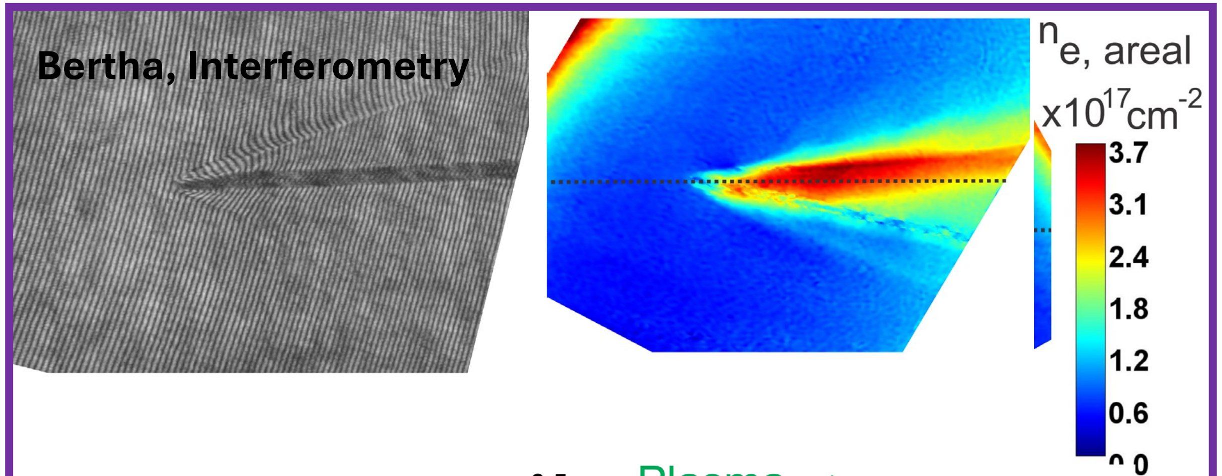


Quantitative upstream plasma heating in COBRA data is not observed in Bertha data

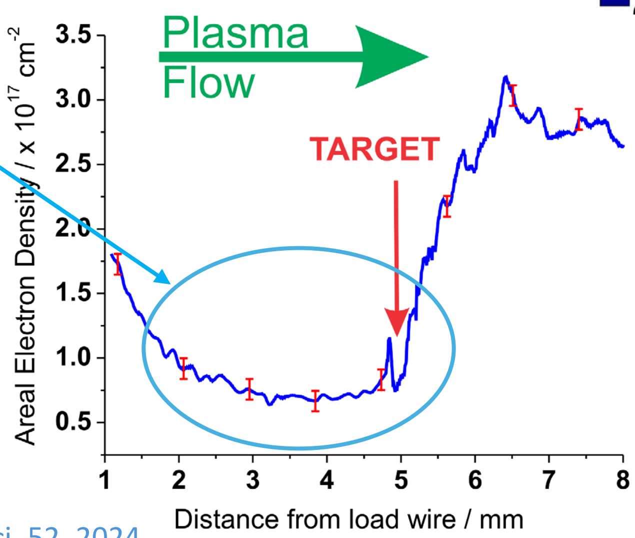


T_e increase upstream of shock

Bott-Suzuki et al., IEEE Trans. Plasma Sci, 52, 2024



No change in n_e (ionization ~ T_e) upstream of shock



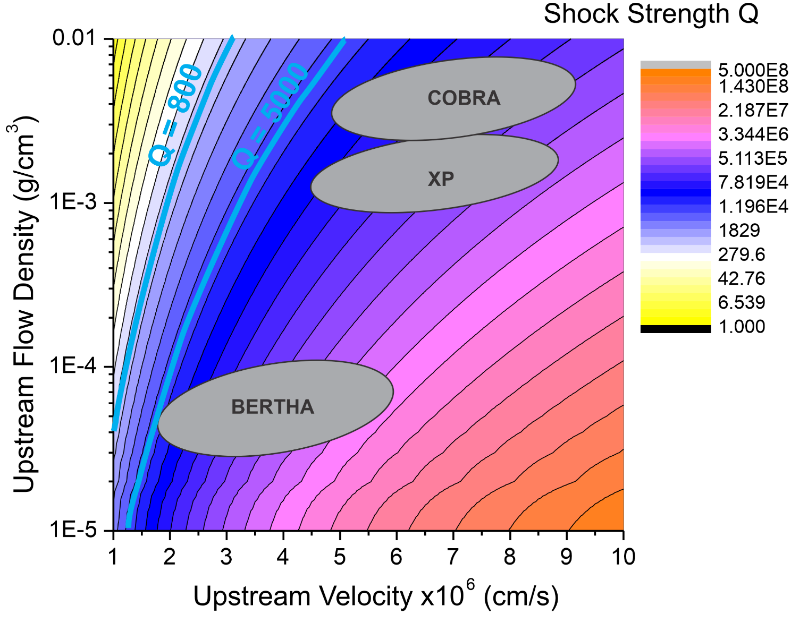
Valdivia et al., IEEE Trans Plasma Sci, 52, 2024

The effect of radiation on the upstream flow is determined by plasma density

SHOCK STRENGTH

$$Q = \frac{2\sigma u_s^5}{R^4 \rho_0}$$

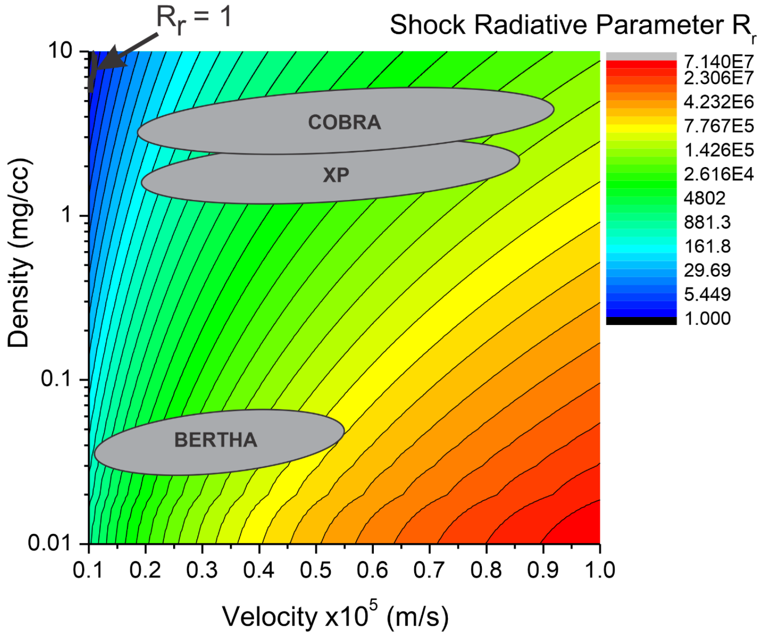
Require: $Q > 5000$ for $\gamma = 5/3$
$Q > 800$ for $\gamma = 4/3$



RADIATIVE PARAMETER

$$R_r = \frac{64}{\gamma(\gamma+1)} \frac{\sigma}{c_v^4} \frac{u_s}{\rho_0}$$

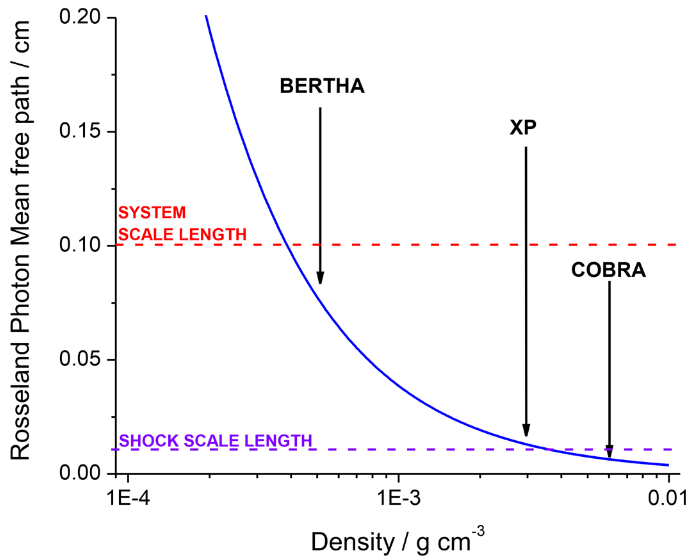
Require $R_r > 1$



PHOTON MEAN FREE PATH

$$l_{\text{photon}} = \frac{1}{K\rho}$$

Require l_{photon} < system



S. C . Bott-Suzuki et al, IEEE Trans Plasma Sci, 52, 4866 (2024)

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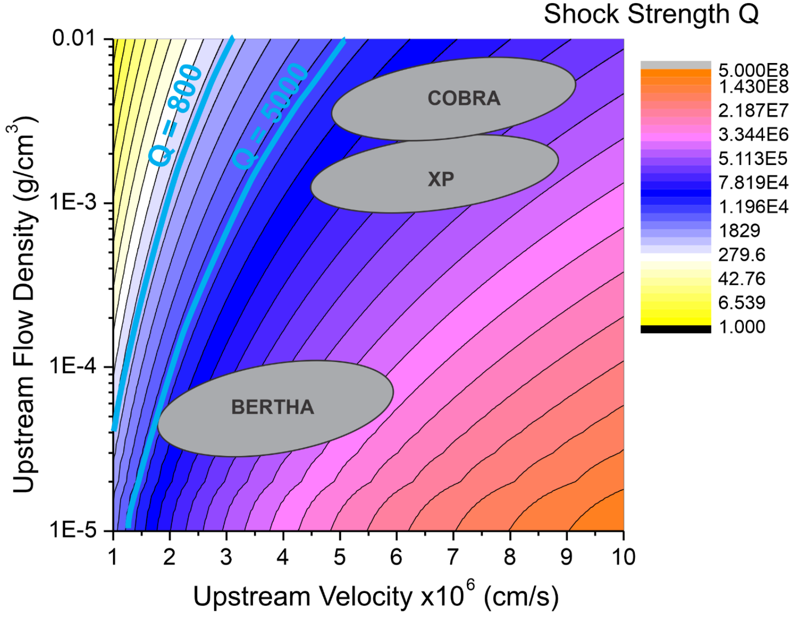

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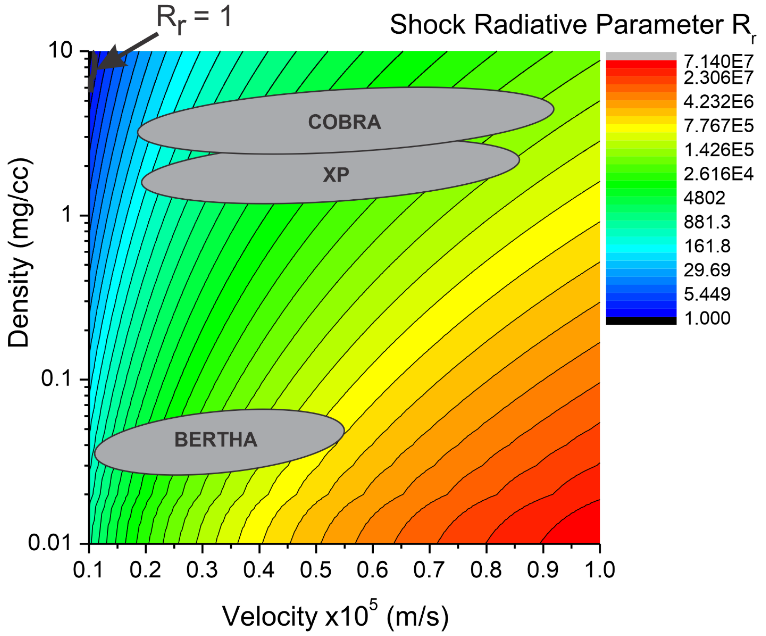

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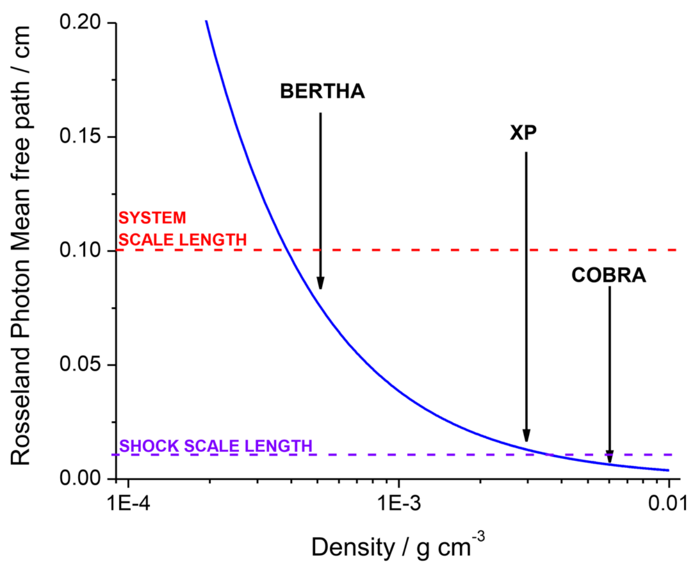
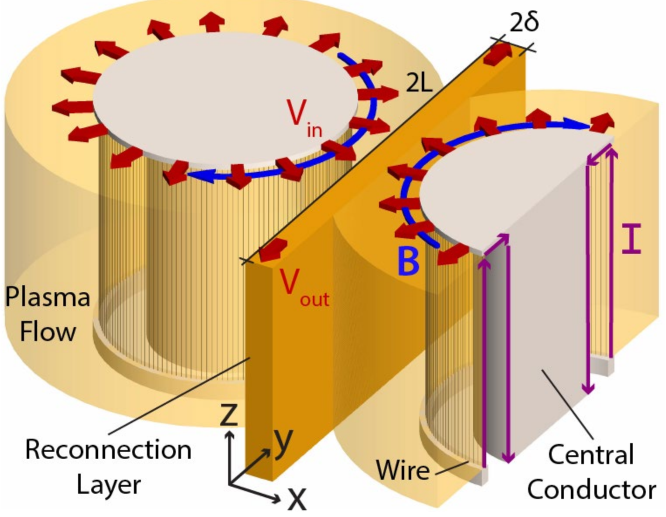
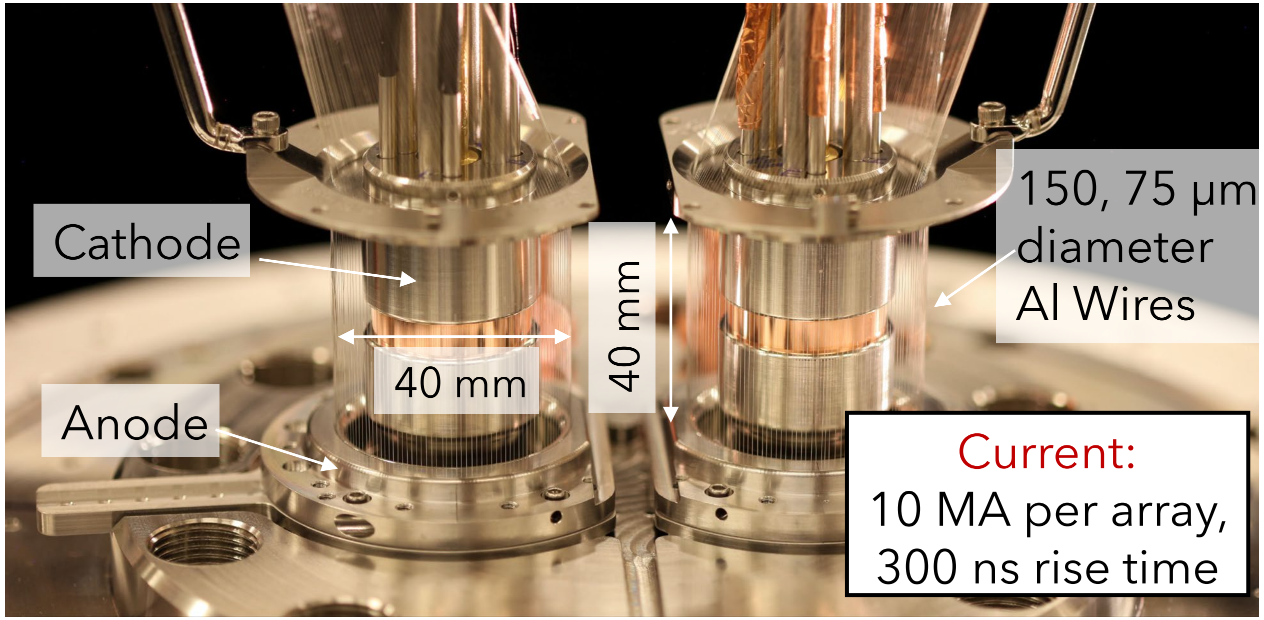


S. C . Bott-Suzuki et al, IEEE Trans Plasma Sci, 52, 4866 (2024)

The Magnetic Reconnection on Z (MARZ) Platform





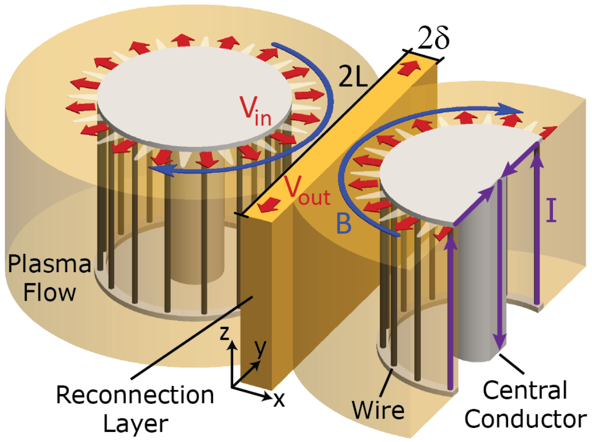
- Platform tested at 1 MA on MAGPIE, scaled to Z: important role for University scale experiments at labs
- Reconnection experiment with coupled strong radiative cooling (Al K-shell) and MHD instabilities
- PI: Prof. Hare, involves Center members Profs. Lebedev and Chittenden

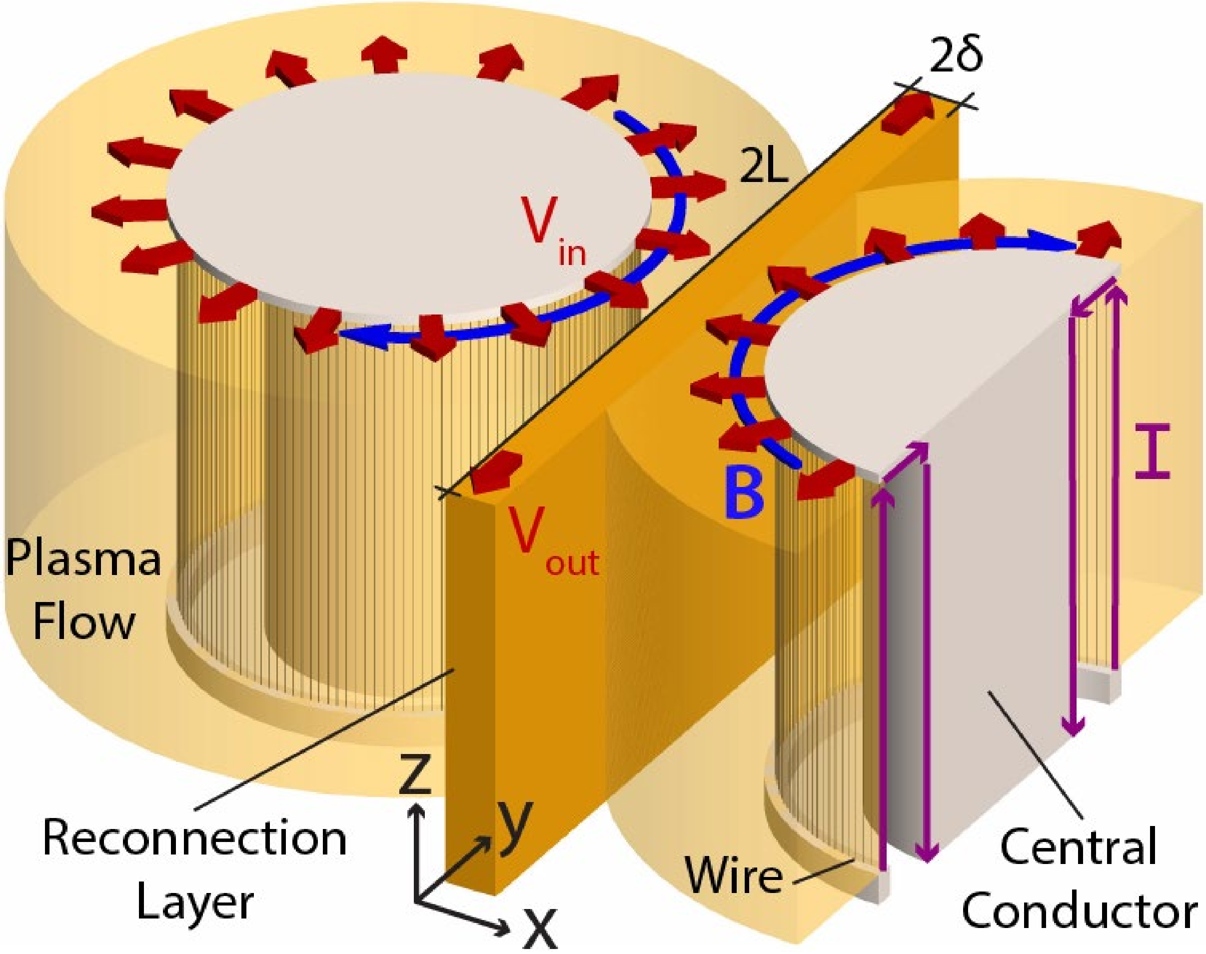
Imperial College London

Cornell University

J. D Hare, *Phys. Rev. Lett.* **118**, 085001 (2017)
J. D Hare, *Phys. Plasmas* 25, 055703 (2018)

Going to higher currents on Z





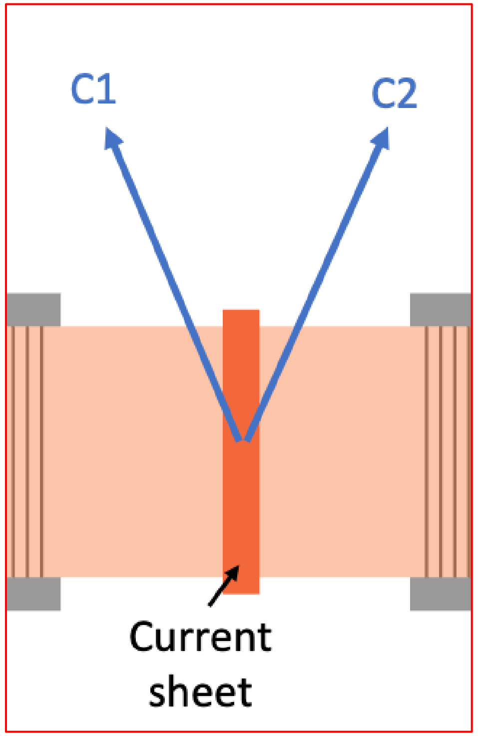
MAGPIE experiments at 1.4 MA:

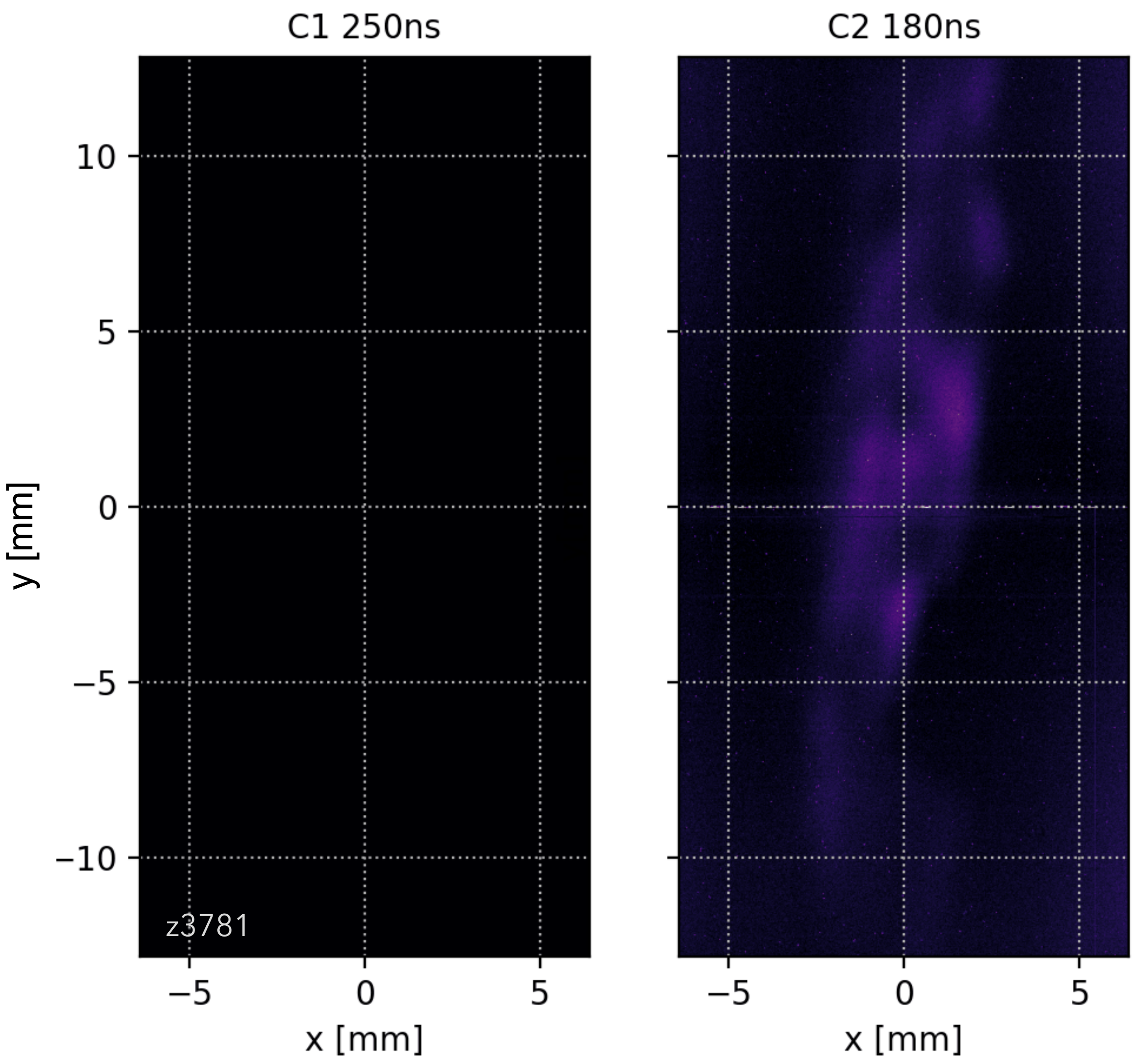
- Plasmoids (higher S_L) **or**
- Cooling ($\tau_{cool} \ll \tau_A$)

Z experiments at 20 MA:

- Denser **and** more energy
- Plasmoids **and** cooling

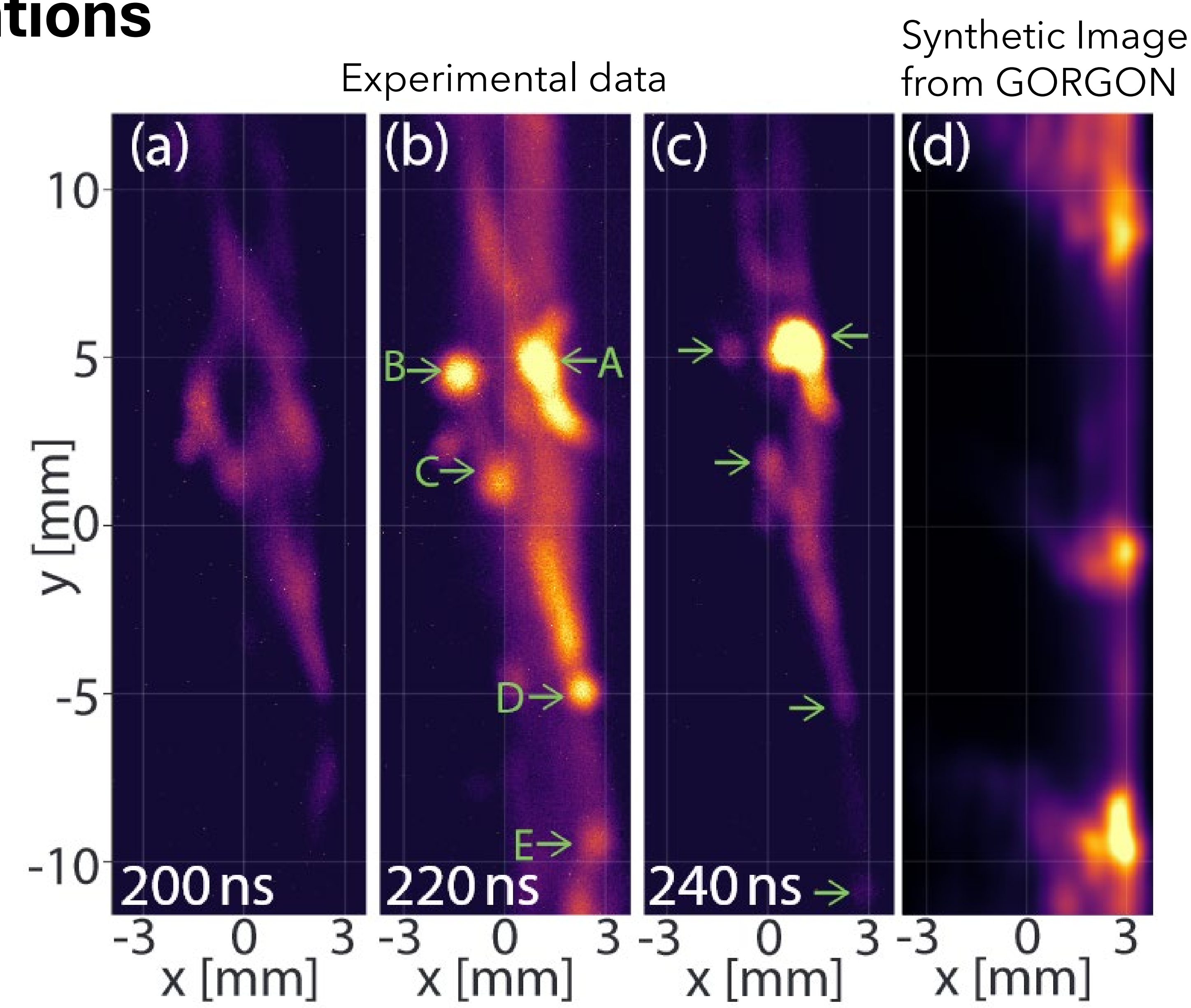
Layer diagnostics: X-Ray Imaging





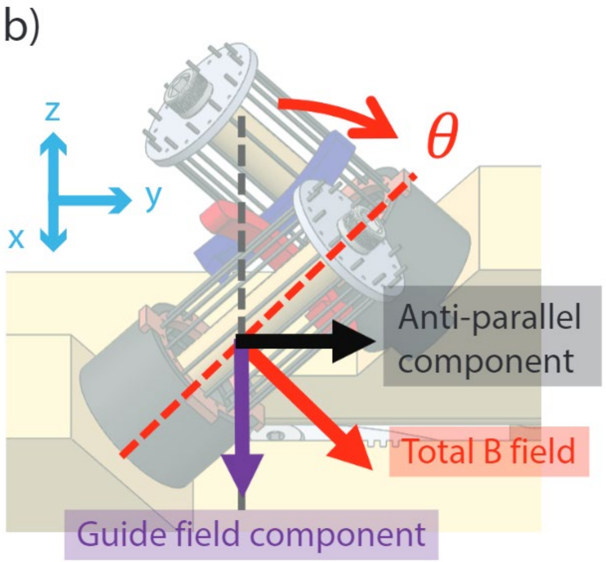
Plasmoids appear as hotspots of X-ray emission

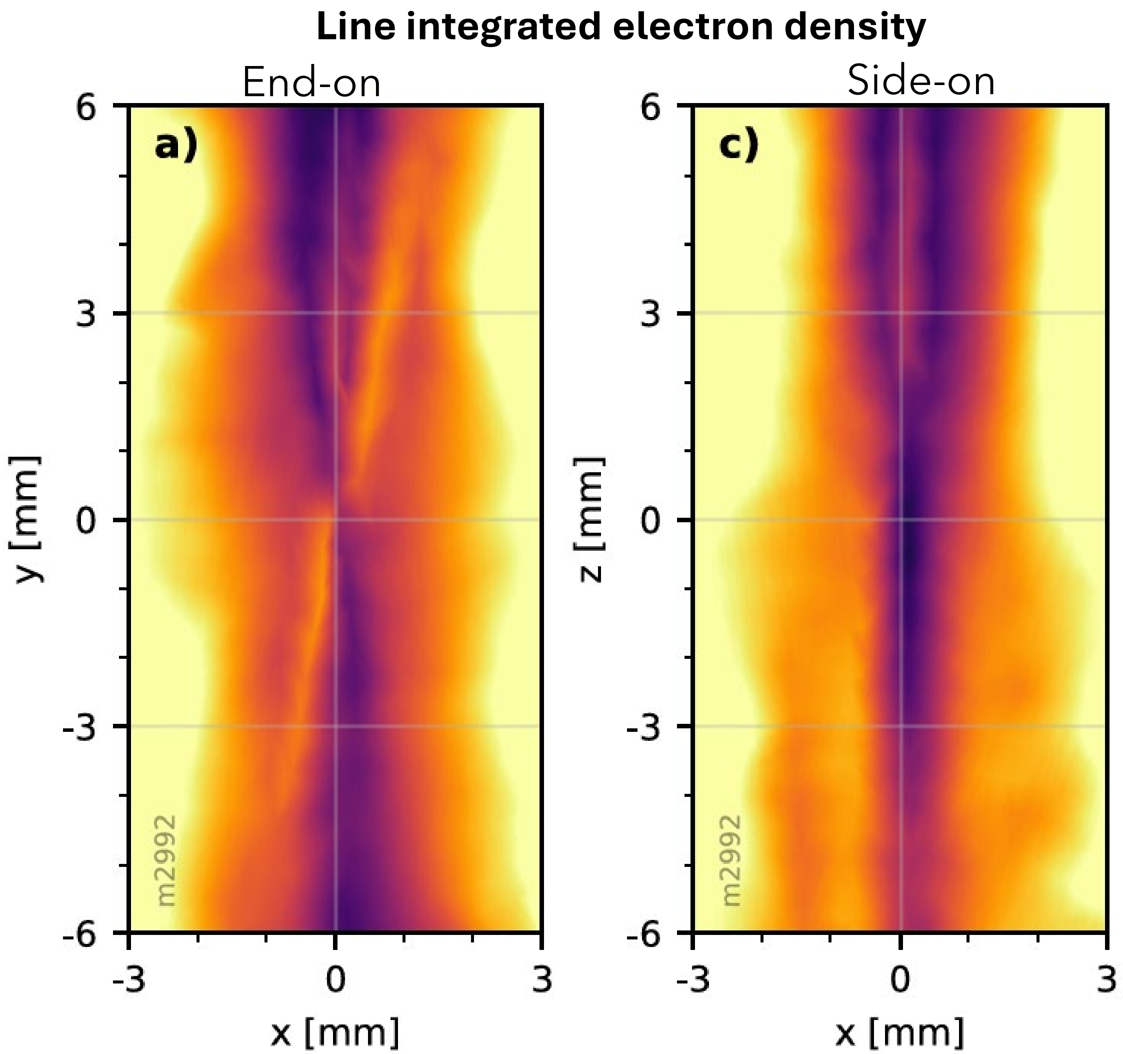
Experimental observations of Hotspots Consistent with 3D Gorgon simulations



Tilting exploding wire arrays embeds an axial field

Led by MIT GS Thomas Varnish



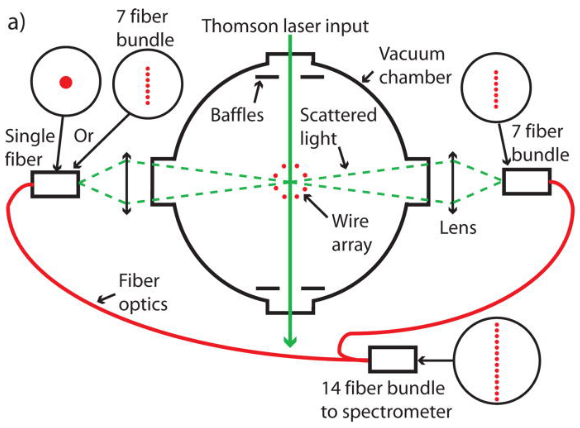


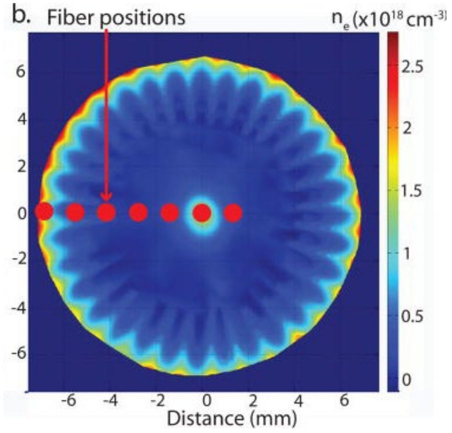
- Axial field interacts with Hall term to produce complex density structures
- Using laser imaging interferometry, we observe quadrupolar structures in the line-integrated electron density

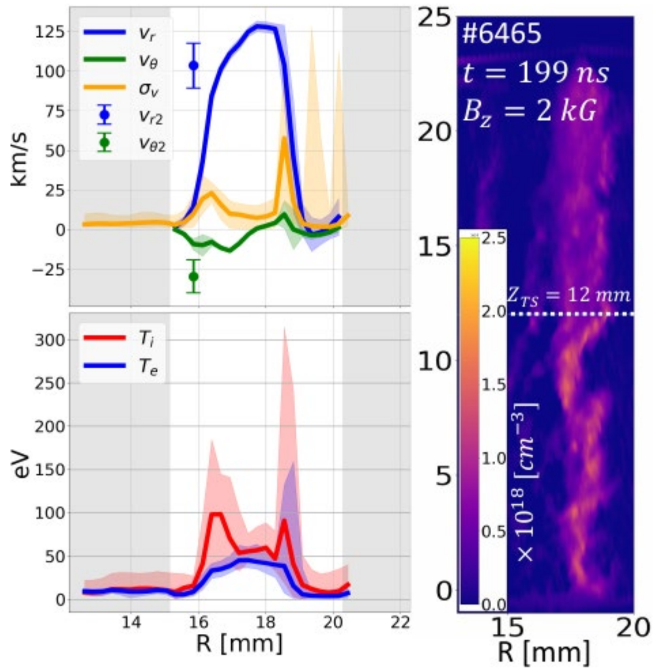
Varnish *et al*, *Phys. Plasmas* 32, 022118 (2025)
+, Editor's Pick Scilight article
+ Best poster at the recent NNSA SSAP

Thomson scattering for Z-pinches

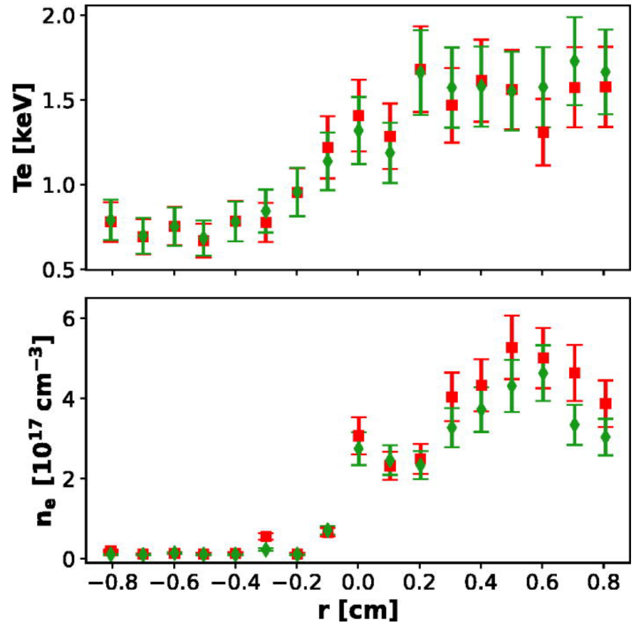
- First complete data from Imperial research in 2011
- Distributed to other MA scale university scale drivers
- Expertise applied in private facilities (Zap Energy)
- Now working toward implementation at Sandia (Jacob Banasek, ex – Center student)



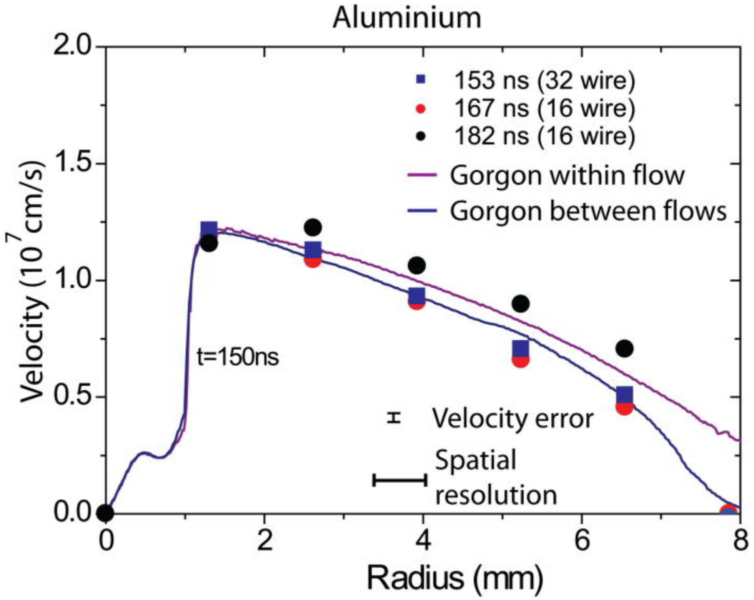




OTS data from gas puff loads on COBRA
Lavine *et al. IEEE Trans. Plasma Sci.* (2024)



OTS Data from deuterium plasma column at Zap Energy
C. Goyon et al, Phys. Plasmas 31, 072503 (2024)
J. T. Banasek Rev. Sci. Instrum. 94, 023508 (2023)



OTS Development on MAGPIE Arrays
A. J. Harvey-Thompson *et al*, Phys. Plasmas 19, 056303 (2012)

Simulation development for Z-pinches

Gorgon MHD - *Jerry Chittenden, Andrea Ciardi, Chris Jennings*

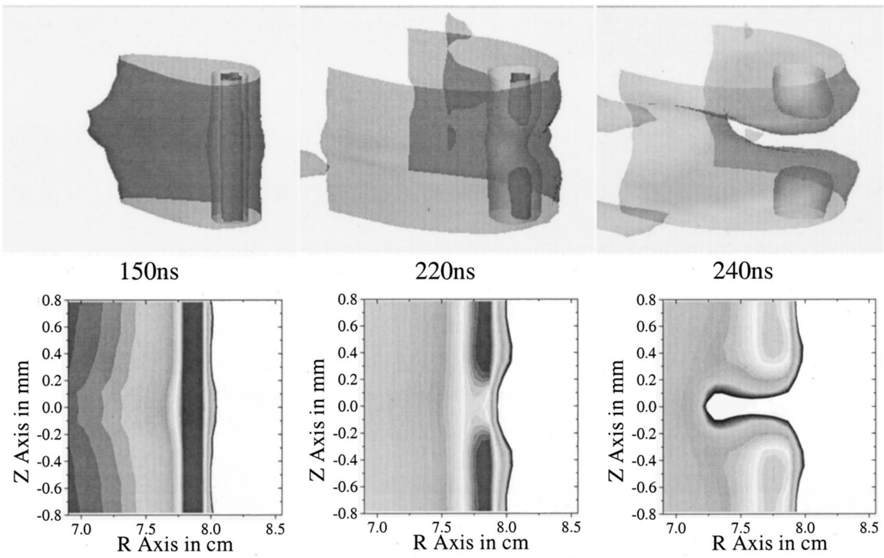
- Extensively benchmarked against a wide range of experiments
- Practical implementation that allows experimental comparisons (e.g. synthetic diagnostics)
- Pushed towards 3D simulations which enable a thorough understanding and matching to x-ray performance

Perseus xMHD - *Charlie Seyler, Matt Martin and Pierre Gourdain*

- Demonstrated the importance of Hall physics in almost all HED z-pinch systems
- Advanced hydro and MHD algorithms

- Both highly parallelizable (vital for time and spatial scales)

- Both continue to be actively developed (e.g. mesh refinement, radiation transport, kinetic effects, applications in laser plasmas, NIF implosions, neutron spectra analysis)



Using a series of 1-D, 2-D, and 3-D models we have built up a composite model of the different phases of wire array Z-pinch implosions. The 1-D and 2-D ''cold-start'' models of wire initiation are useful for illustrating the important processes involved during the plasma formation phase and for model verification, as their results can be readily compared to the wealth of data available for single wire experiments. The absence of three-dimensional effects, however, severely limits the ability of such calculations to predict the behavior of wires in an array.

Chittenden *at al*, Phys. Plasmas 8, 2305–2314 (2001)

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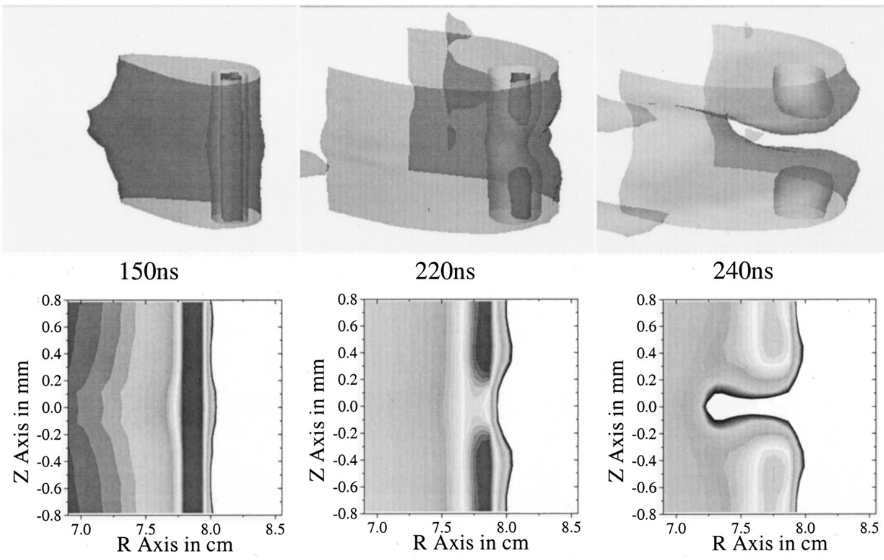
- Demonstrated the importance of Hall physics in almost all HED z-pinch systems
- Advanced hydro and MHD algorithms

- The earlier empirical nature of experimental progress gave way to strong simulation guided innovation and quantitative comparison
- Far easier to train students and allow them to develop routines with non-classified codes



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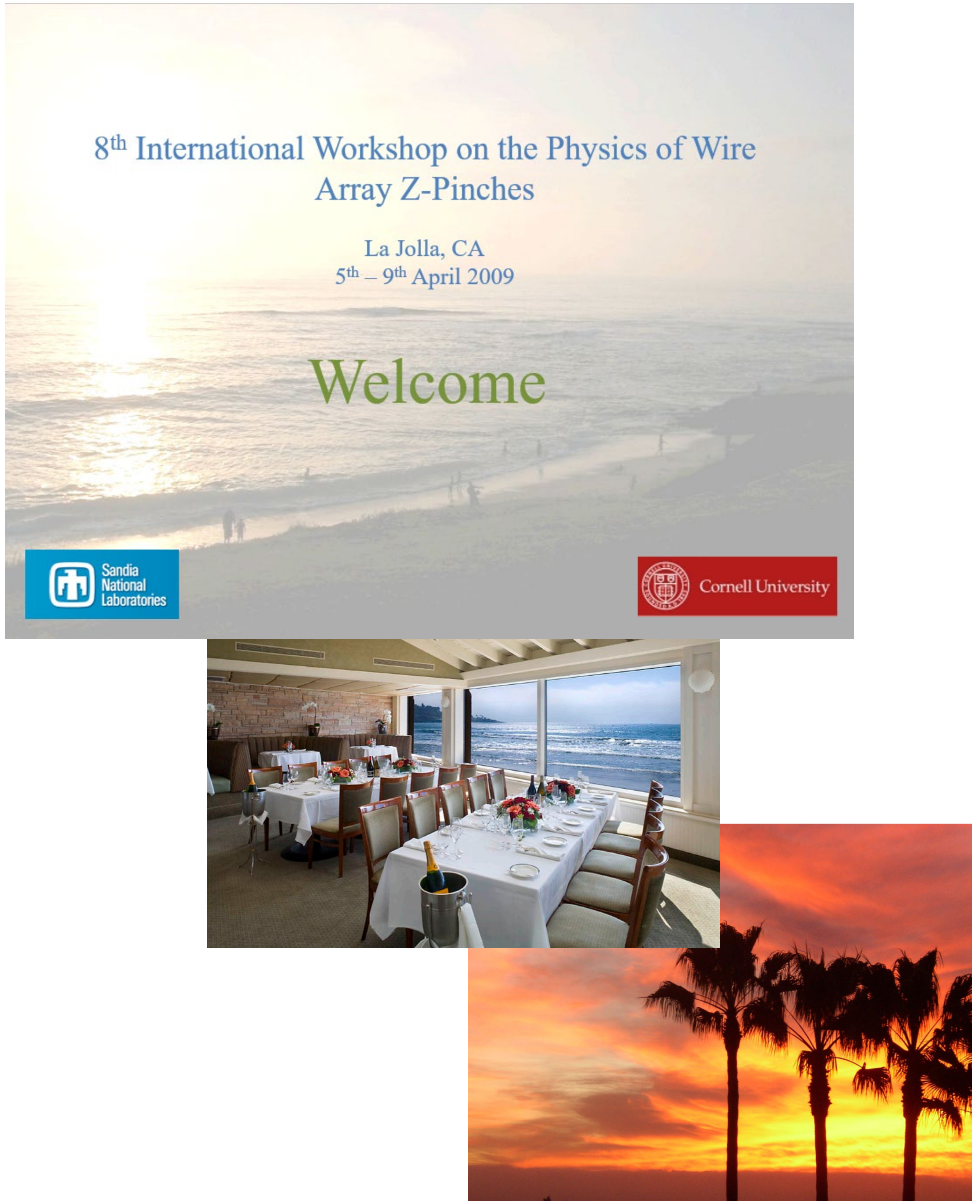
Chittenden *at al*, Phys. Plasmas 8, 2305–2314 (2001)

Both Gorgon and Perseus now regularly used at Sandia by ex-Center researchers

And then the Wire Array Workshop 2009.........

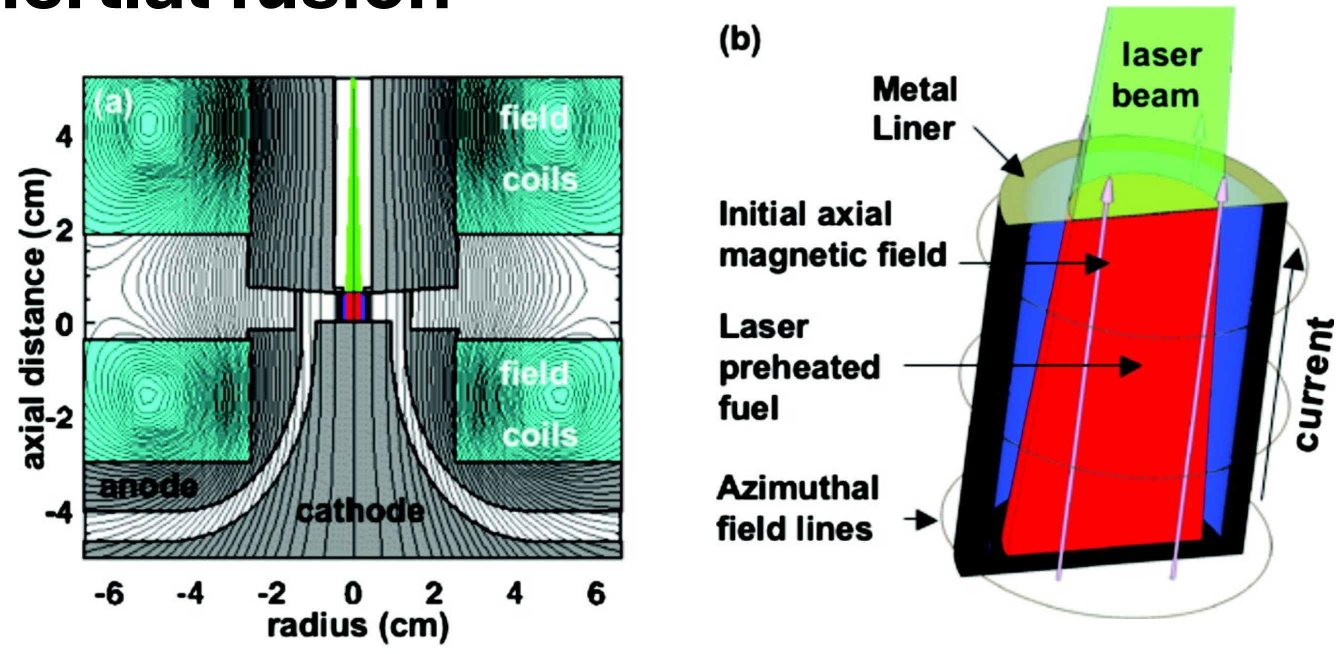


8th International Workshop on the Physics of Wire Array Z-Pinches
5th - 9th April, 2009 *La Jolla, CA*

MONDAY		THEME
	8:15 - 8:30	Welcome & opening comments
ICF PREDICTION CHALLENGES	**Technical Session 1A**	**Wire Array Z-Pinch Program Overview**
	8:30 - 10:00	Cuneo (SNL)
	Technical Session 1B	**GORGON OVERVIEW**
	10:30 - 12:00	Chittenden (IC) - GORGON summary
	Technical Session 2A	**ALEGRA SUMMARY & POWER FEED ISSUES**
	13:30 - 15:00	Jennings (SNL) - Alegra summary & effect of powerfeed losses on array performance
	Technical Session 2B	**NEW DATA RELEVANT TO MODELLING CYLNDRICAL ARRAYS**
	15:30 - 17:00	Greenly (Cornell) - B-field Measurements in ablated plasma flow
		Knapp (Cornell) - Development of the ablation flow periodicity
		Thompson (IC) - Plasma evolution in an inverse wire array
TUESDAY	**Technical Session 3A**	**RADIATION SOURCES**
RADIATION SOURCES & ICF/IFE GENERATORS	8:30 - 10:00	Jones (SNL) - K-shell sources summary
		Calamy (Gramat) - Large diamter arrays on SPHINX
	Technical Session 3B	**RADIATION SCIENCE & OPACITY**
	10:30 - 12:00	Apruzese (NRL) "Opacity issues in Z-pinch plasmas"
	Technical Session 4A	**X-Pinches**
	13:30 - 15:00	Sinars (SNL) - High Current X-Pinches
		Hammer (Cornell) "X-pinches: two directions of progress"
	Technical Session 4B	**ICF/IFE TECHNICAL ISSUES**
	15:30 - 17:00	Herrmann (SNL) - IFE Program Overview
WEDNESDAY	**Technical Session 5A**	**HEDP APPLICATIONS 1**
HEDP APPLICATIONS	8:30 - 10:00	Lebedev (IC) - Laboratory Astrophysics
		Bland (IC) - Kinetic Drive Experiments
	Technical Session 5B	**HEDP APPLICATIONS 2**
	10:30 - 12:00	Rochau (SNL) - Radiative Shockwave Generation
		Mancini (UNR) - Photo-ionization Experiments
	Technical Session 6A	**ALTERNATIVE IMPLOSION GEOMETRIES 1**
	13:30 - 15:00	Bland (IC) - Radials on MAGPIE/Saturn
		Zucchini (Gramat) - Radial Arrays on SPHINX
		Safronova (UNR) - Planar Arrays on ZEBRA/Saturn
	Technical Session 6B	**ALTERNATIVE IMPLOSION GEOMETRIES 2**
	15:30 - 17:00	Oleynik (TRINITI) "Implosion of quasi spherical wire arrays"
		VanDevender, (SNL) "Quasi Spherical Direct Drive"
		Ivanov (UNR) "Control of plasma flows and generated x-ray pulse in star-like wire arrays"
		Hall (IC) -Coiled Wire Arrays
THURSDAY	**Technical Session 7A**	**ALTERNATIVE IMPLOSION / FUSION CONCEPTS**
NOVEL SCHEMES AND SUMMARY	8:30 - 10:00	Slutz (SNL) - title tbc
	Technical Session 7B	**SUMMARY / OTHER COMMENTS**
	10:30 - 12:00	

From Wire arrays to liners for inertial fusion

- Development of Magnetized Liner Inertial Fusion (MagLIF)
- Takes advantage of the efficiency of direct B-field drive for pulsed power
- Clearly differentiated from laser drive approaches



S. A. Slutz *et al*., Phys. Plasmas **17**, 056303 (2010)
S.A.Slutz, Phys. Rev. Lett. 108, 025003 (2012)
Cuneo *et al, IEEE Trans*. Plasma Sci., **40**, 3222 (2012)

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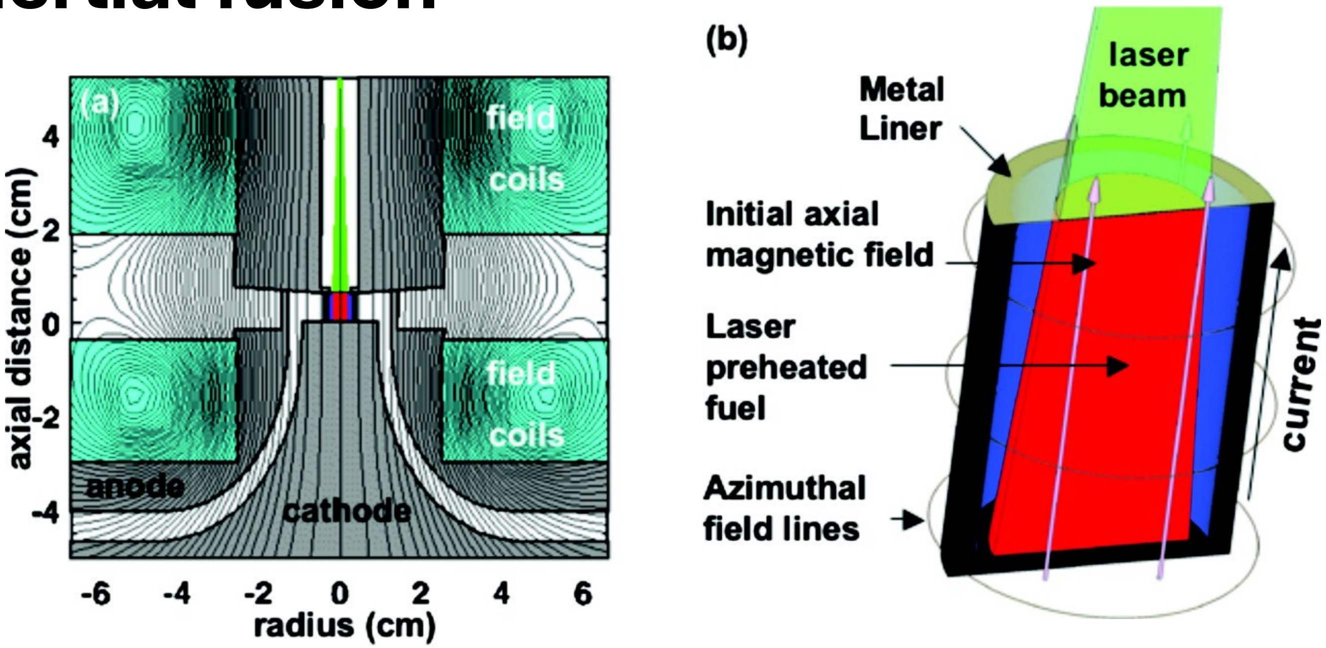
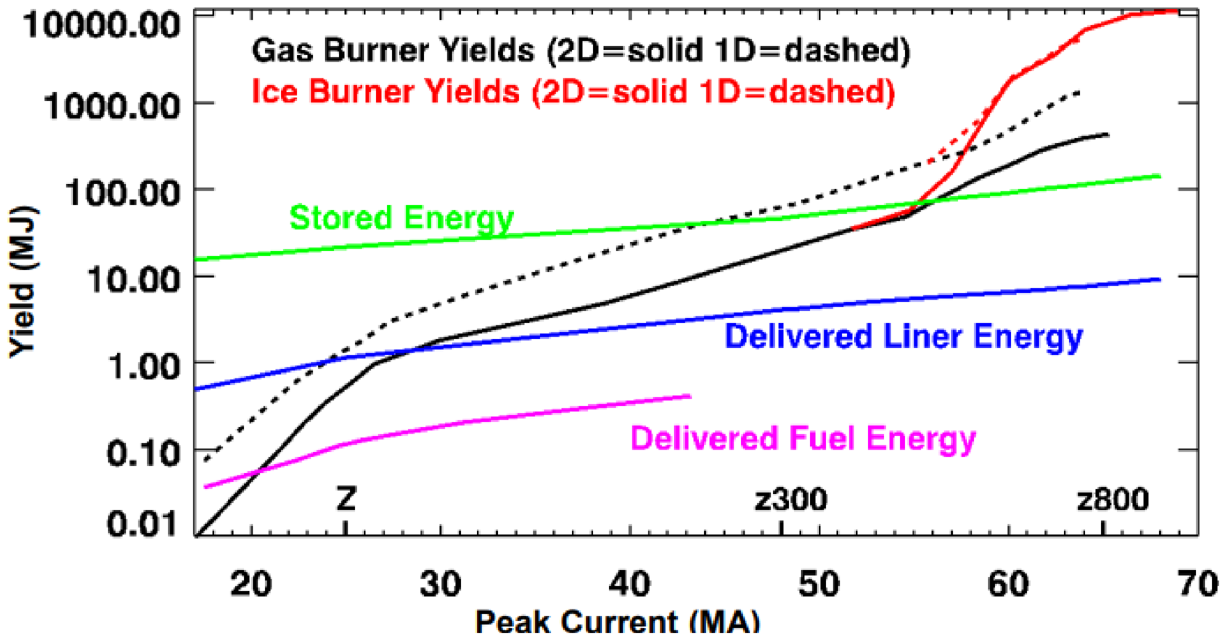
- Takes advantage of the efficiency of direct B-field drive for pulsed power
- Clearly differentiated from laser drive approaches
- **Driver with I > 55 MA could realize an engineering gain > 1**





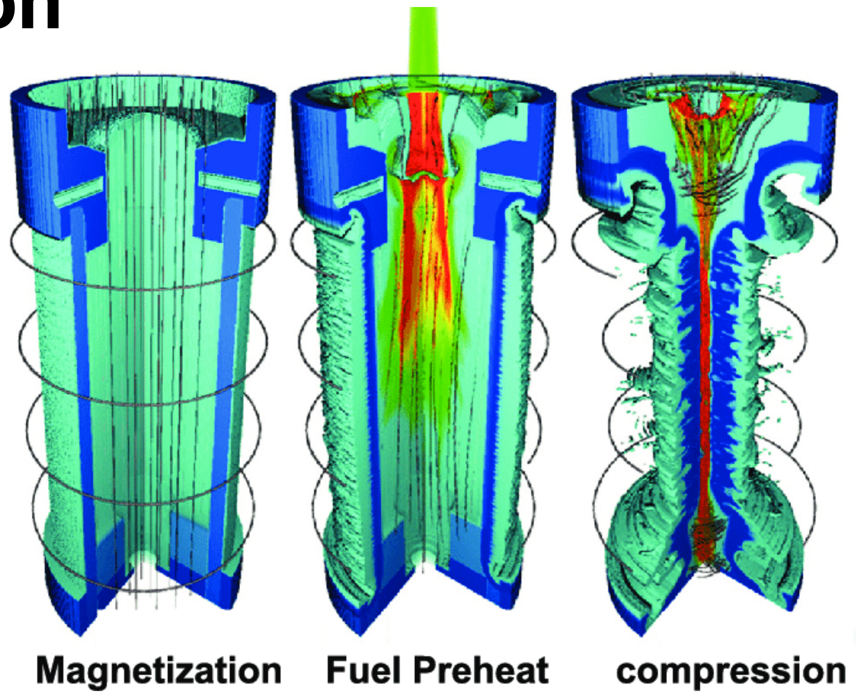
S. A. Slutz *et al.*, Phys. Plasmas **17**, 056303 (2010)
S.A.Slutz, Phys. Rev. Lett. 108, 025003 (2012)
Cuneo *et al, IEEE Trans*. Plasma Sci., **40**, 3222 (2012)

From Wire arrays to liners for inertial fusion

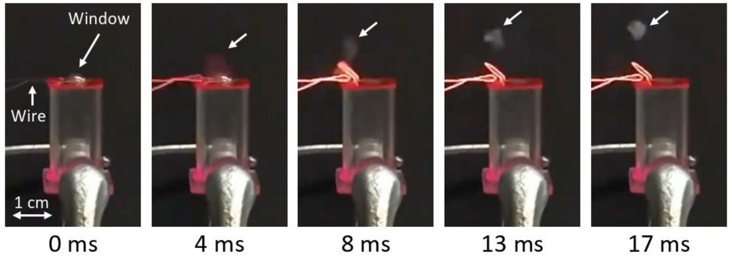
- MagLIF is an integrated system requiring magnetization, fuel preheat to achieve significant neutron yields
- While the system is not separable, many of the unknowns and problem are:

Examples

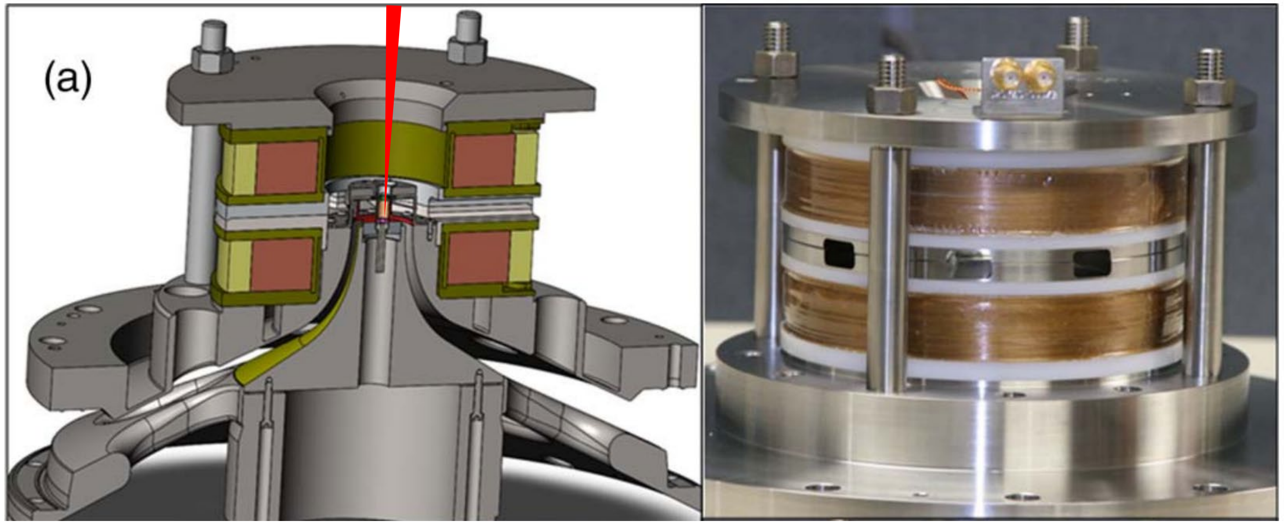
- Can the LEH be removed immediately prior to heating to increase efficiency?



LASER-GATE S. M. Miller, RSI 2020



- How does electrical contact affect liner drive?
- Can fuel preheat be achieved my means other than the present laser system?

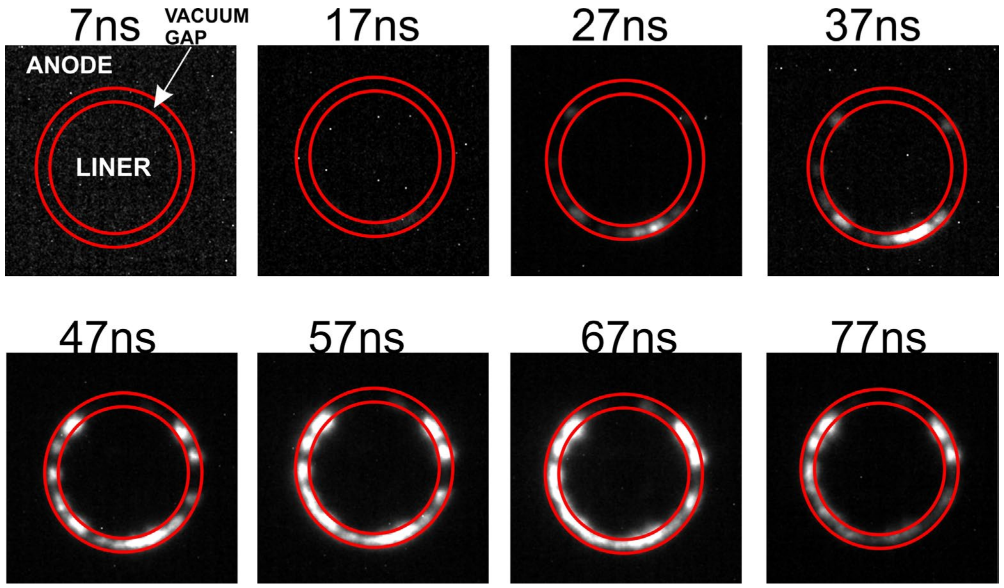


D. C. Rovang et al, Review of Scientific Instruments 85, 124701 (2014)

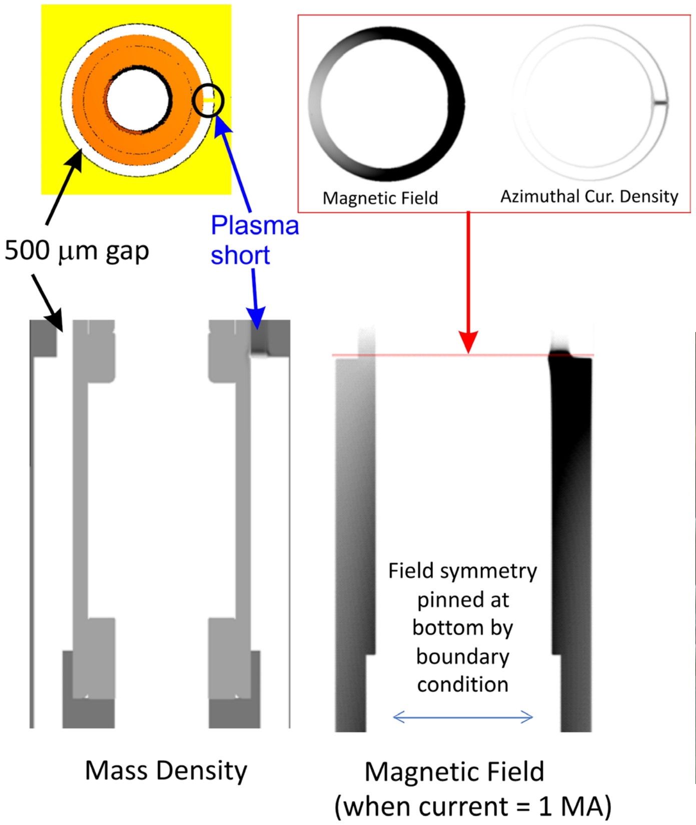
Current uniformity in liners

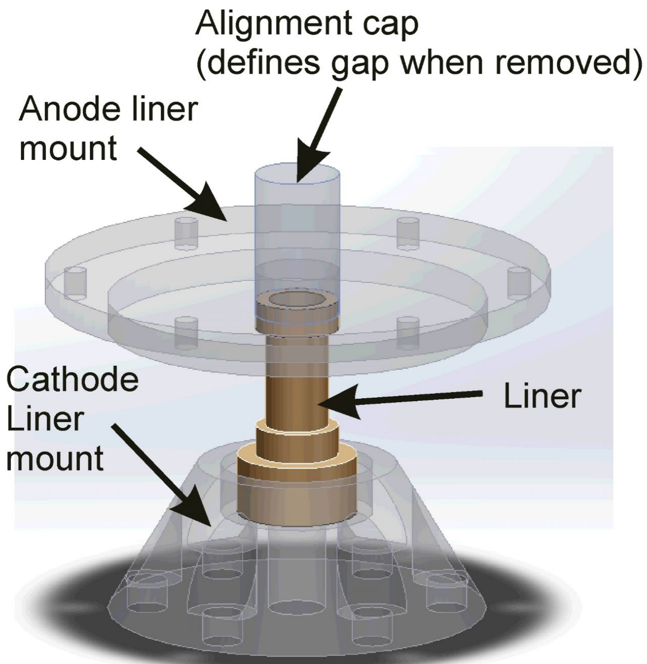
- Experiments demonstrated that if current flow is initially non-uniformly around the azimuth of a liner, this can remain non-uniform for long periods (i.e. >100ns)

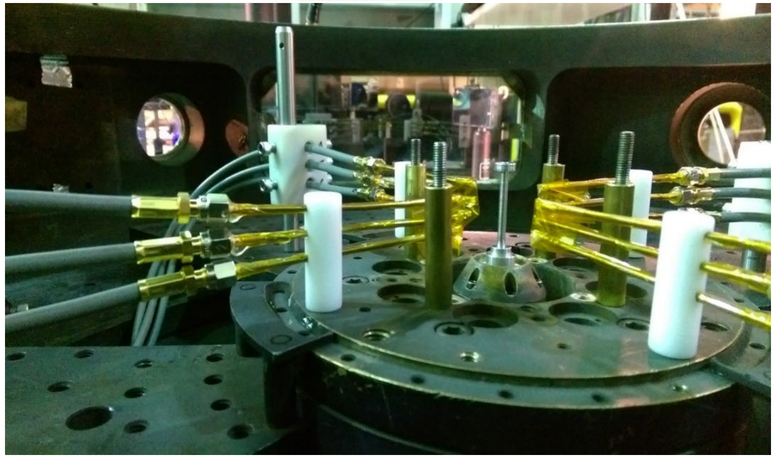
- How can this be resolved?



Gated optical emission frames on COBRA



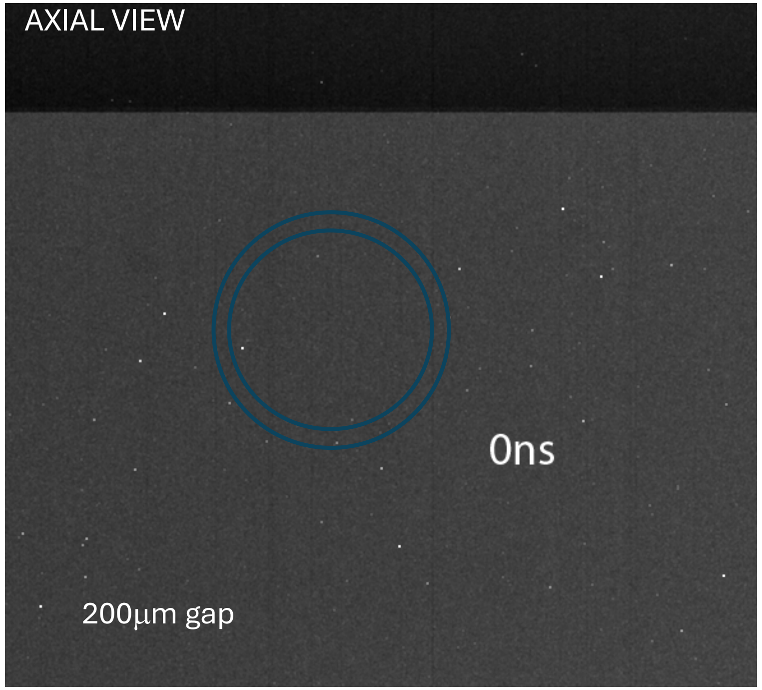




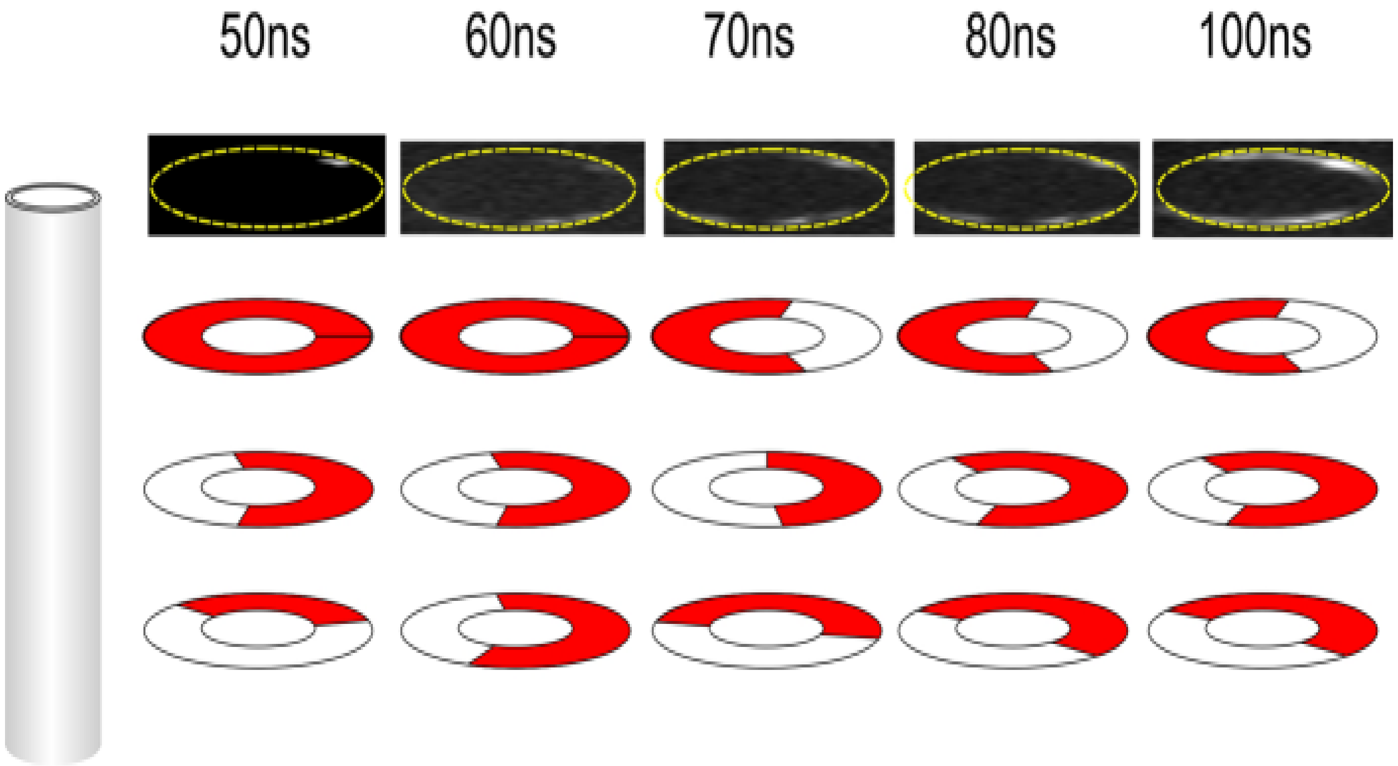
3D B-dot array on COBRA

Multi-frame optical camera and bdot array demonstrate non-uniform current

GATED OPTICAL IMAGING



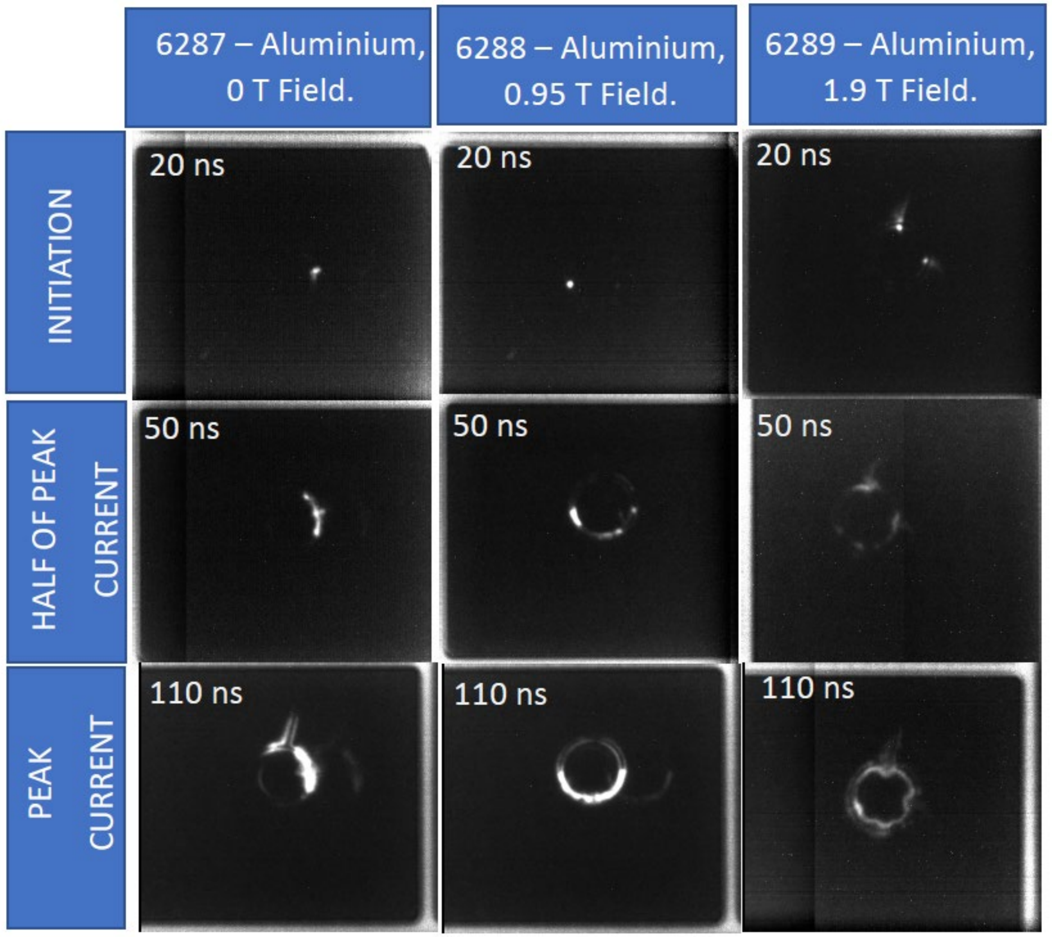
INFERRED LOCATION OF CURRENT CENTROID FROM BDOT ARRAY

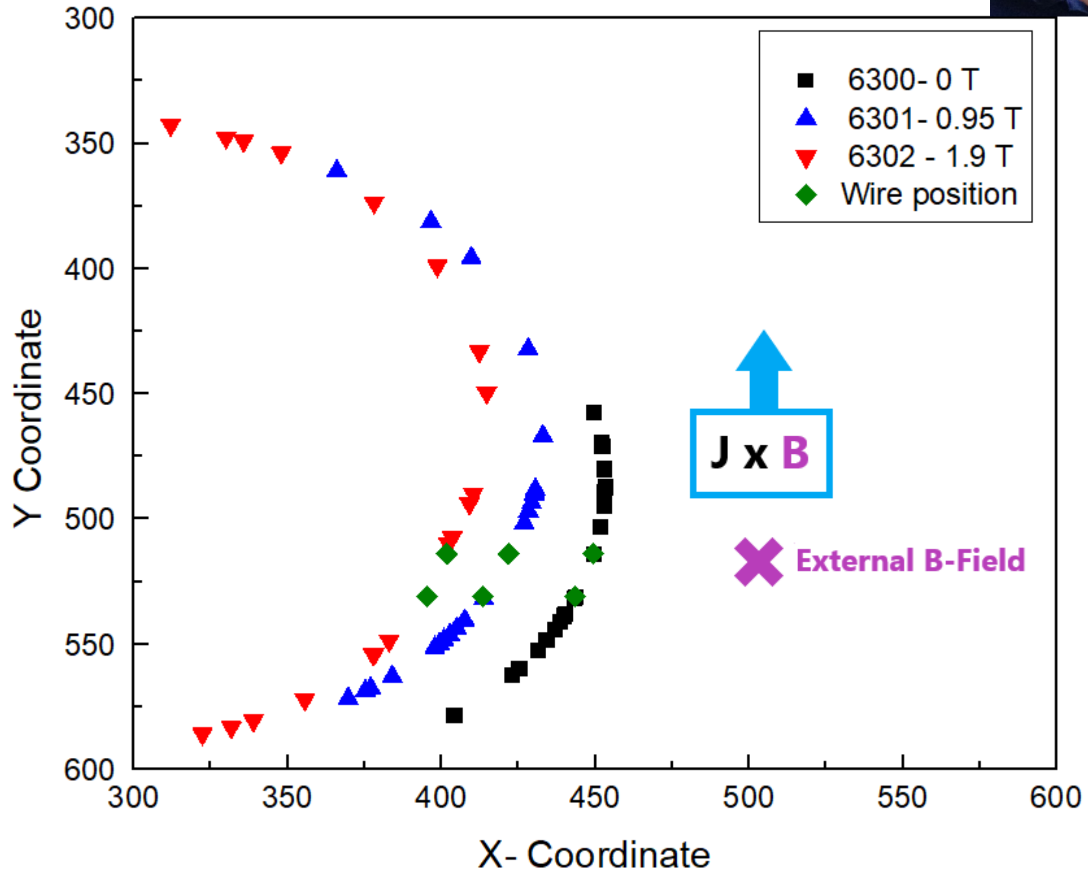


- Initial breakdowns form multiple hotspots which evolve relatively slowly
- Data show axial as well as azimuthal non-uniformity

S.C.Bott-Suzuki et al. Phys. Plasmas, **23**, 092711 (2016)

Effect of an axial B-field on Current uniformity in liners on COBRA

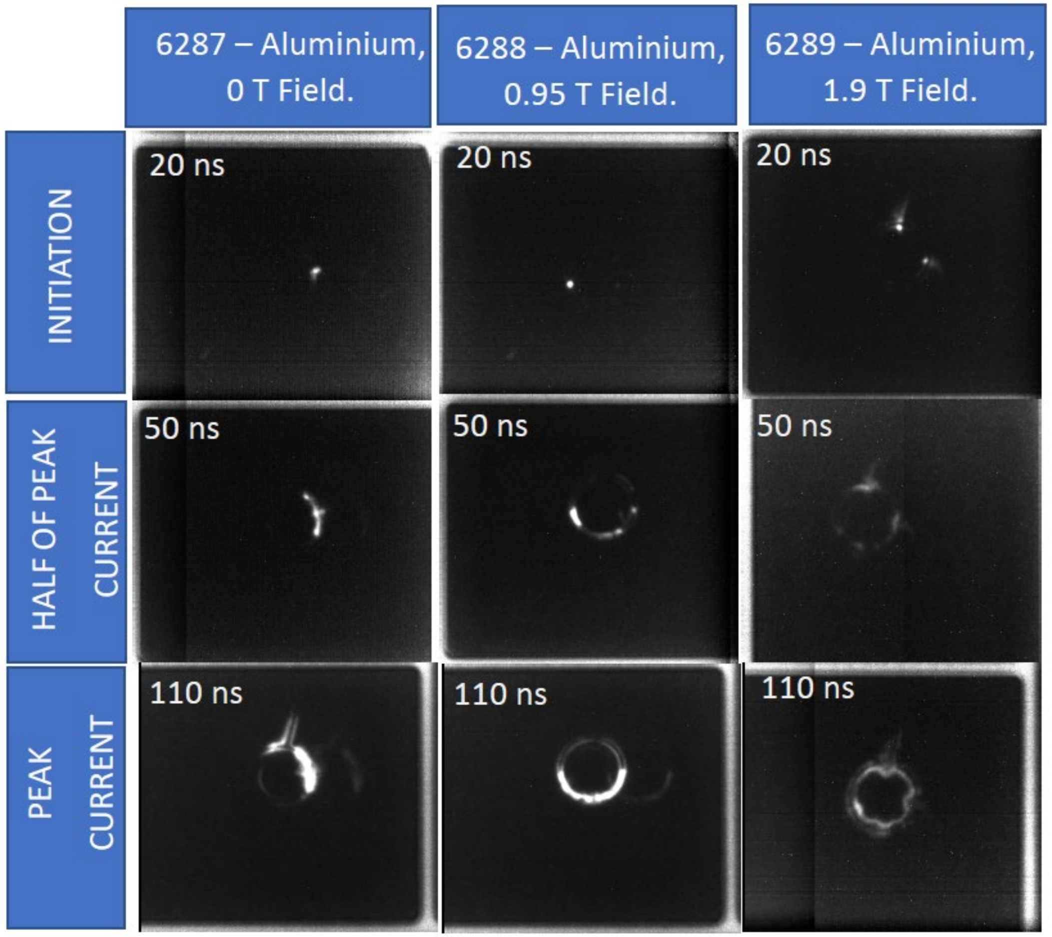




- **The axial B-field generates a JxB around the liner azimuth, driving plasma and improving the current distribution in the liner**

- Paper in preparation, Cordaro *et al* (July 2025 submission)

Effect of an axial B-field on Current uniformity in liners on COBRA



Effectiveness of this mechanism depends on jxB

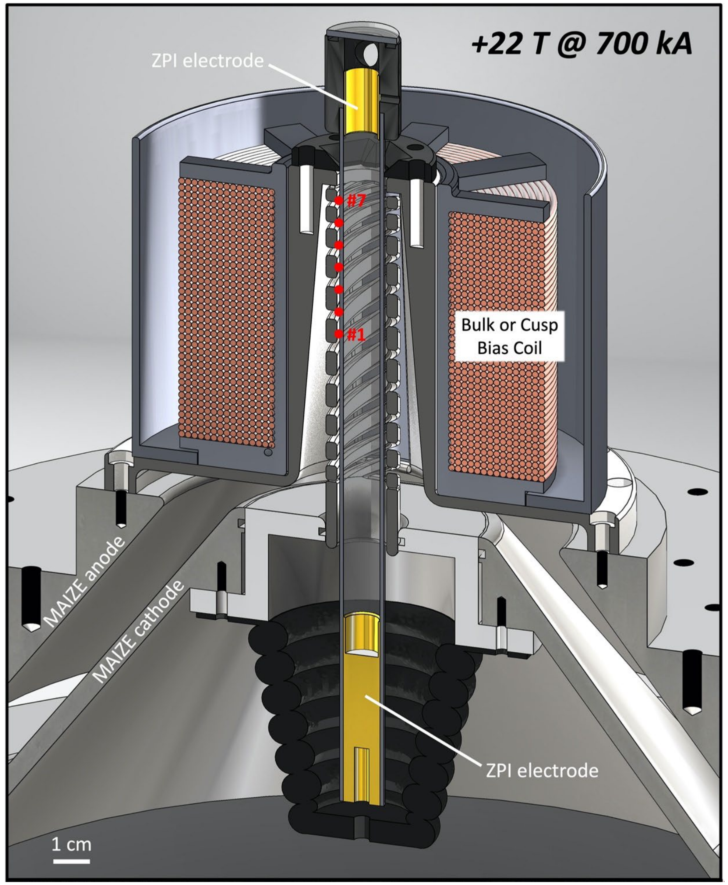
On Z: J increases by x20
B increases by x 15

NO PROBLEM FOR MAGLIF

- **The axial B-field generates a JxB around the liner azimuth, driving plasma and improving the current distribution in the liner**

- Paper in preparation, Cordaro *et al* (July 2025 submission)

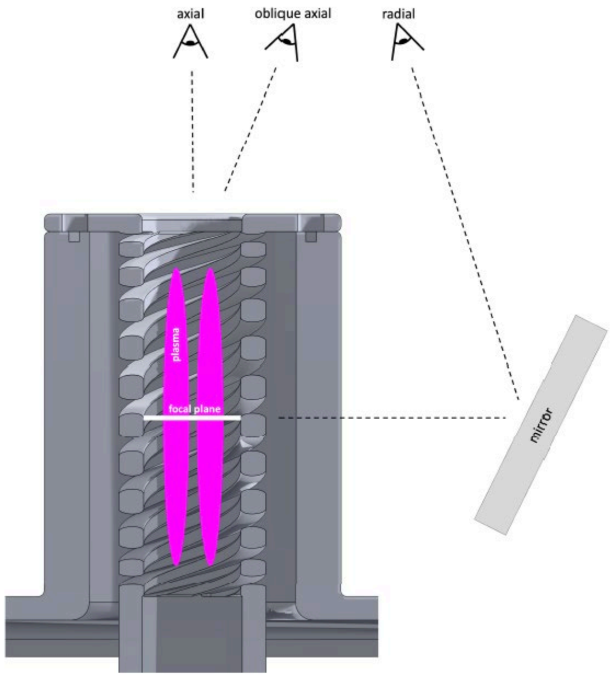
FRC platform on MAIZE (for potentially preheating and pre-magnetizing MagLIF fuel)

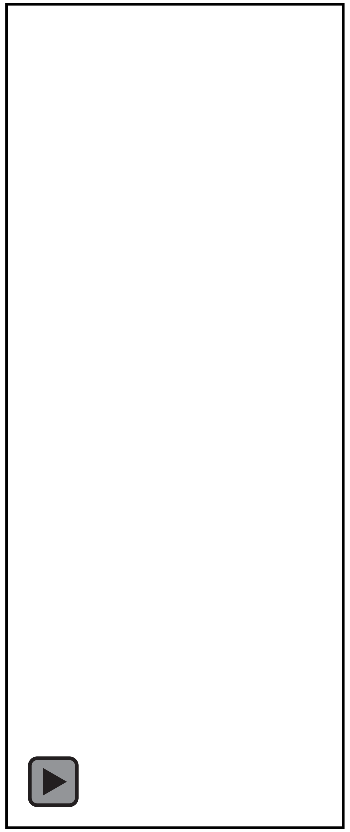


2 separate Coils:

- 3D printed fast reverse coil
- 3D printed housing for slow bias coil (wound in-house)

Simultaneous side-on and top-down self-emission imaging with fast 12-frame visible light camera





Bdot probe data and optical imaging demonstrate FRC formation for a range of parameters

Recent PhD Student
& LRGF Fellow
Dr. Brendan Sporer
(now at TAE)

FRC platform on MAIZE (for potentially preheating and pre-magnetizing MagLIF fuel)

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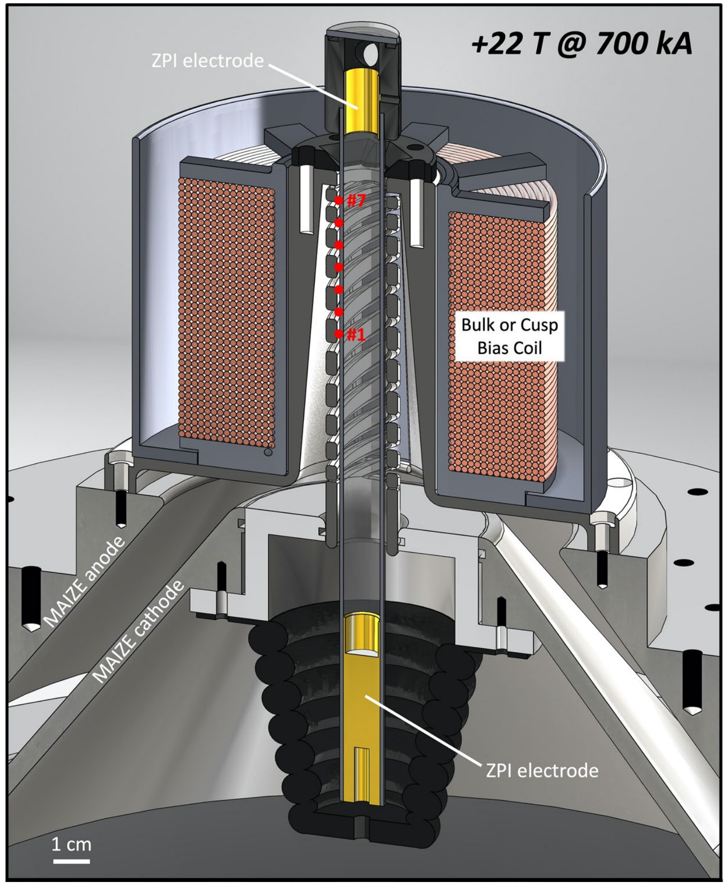
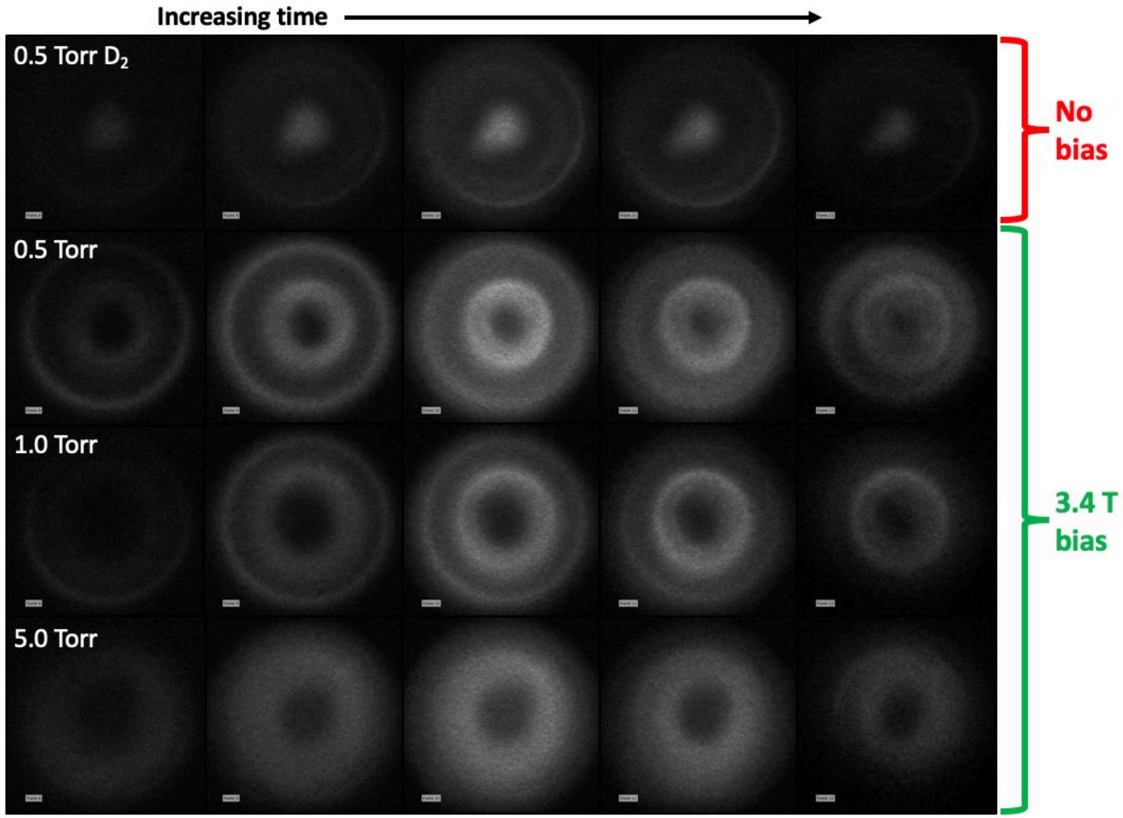


Experimental data collected; now coordinating simulation & theory efforts with Center partners: U. Washington , Princeton, Imperial College, Sandia



Ring-like plasma structures have radius agreeing with data from external B-dots assuming rigid-rotor structure for FRCs

B. J. Sporer, "High-Energy-Density Field-Reversed Configurations for Sub-Microsecond Magnetized Target Fusion", PhD Dissertation, UM (2023); https://dx.doi.org/10.7302/8481;

The NNSA Center of Excellence in pulsed power has been highly successful (and continues to be)

National Nuclear Security Administration

- So, we have presented a number of interesting experiments – what is the outcome of these efforts?

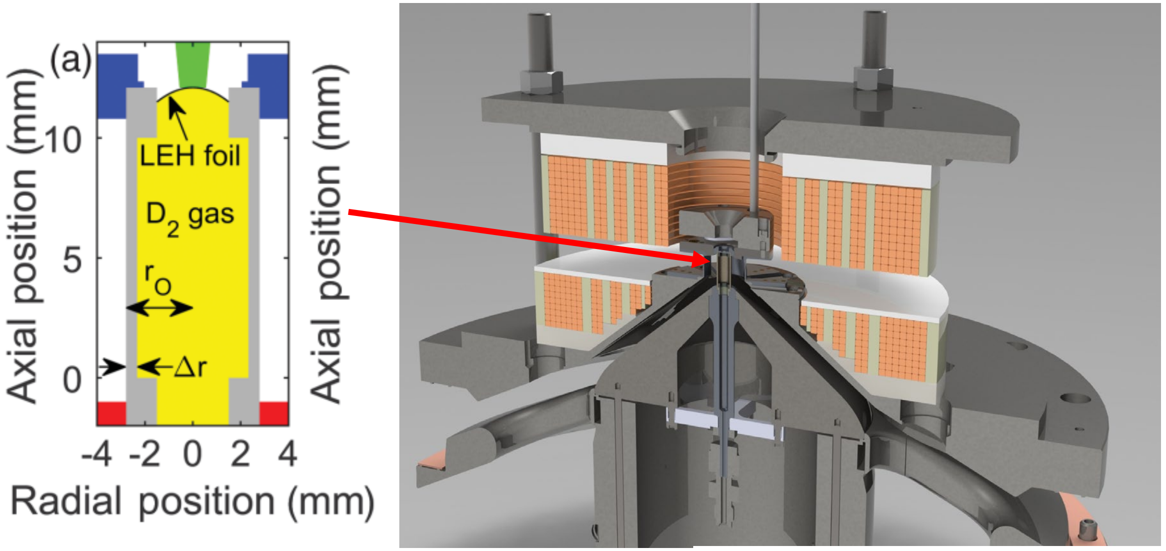
During the recent 5-year Cornell-led Center we:

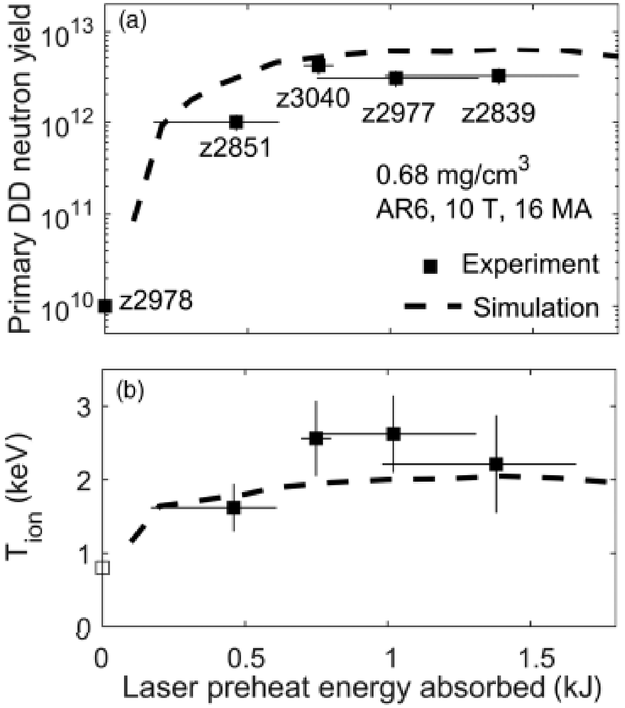
- Published 102 peer-reviewed journal articles (including 5 PRLs) **> 20 per year for 23 years**
- Placed 10 PhD graduates at the NNSA labs **1-2 per year for 23 years**

  (including 3 at SNL, 5 at LLNL, and 2 at LANL).
- Many ex-Center students and researchers occupy national leadership roles

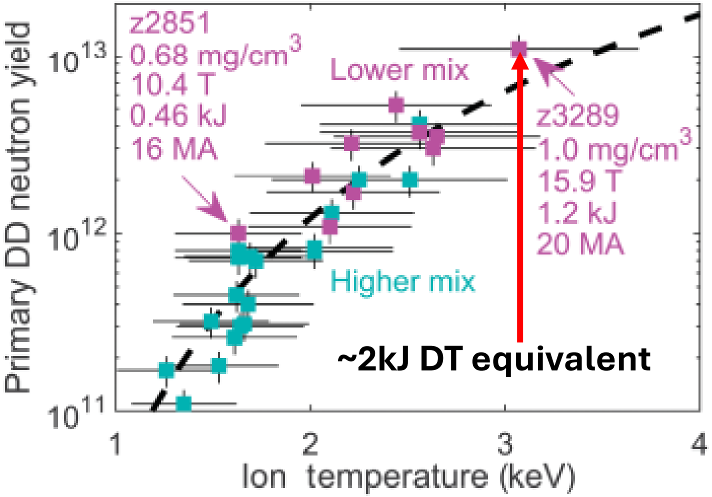
- These collaborations, and specifically the NNSA's support, has provided foundational support for academic pulsed power programs
- We act as stewards of pulsed power driven plasma systems, developing workforce talent, physics programs, pulsed power drivers, simulation codes and diagnostics

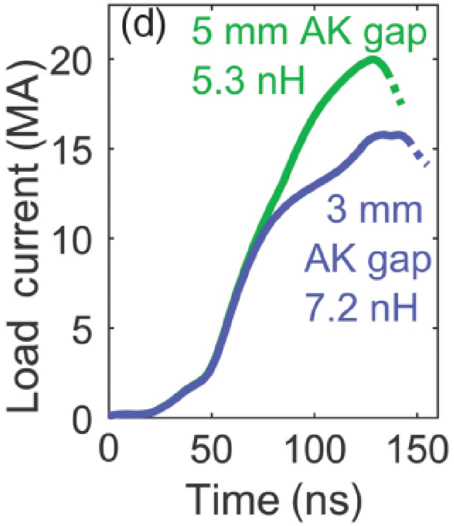
Magnetized Liner Inertial Fusion: Present Status





- Yields and plasma parameters scale roughly as expected from simulations
- Lasnex calculations suggest moderate increases in parameters can achieve significant increase in yield





Peak current (MA)	16.6	19.2	22.3
ρ_{fuel} (mg/cm^3)	0.8	1.1	1.4
Magnetic field (T)	30	30	30
Preheat (kJ)	3.2	4.4	6.0
DD yield	3.9×10^{13}	1.6×10^{14}	4.5×10^{14}
CR	34	34	36
T_{ion} (keV)	4.0	4.9	5.5
P (Gbar)	1.0	1.8	2.8
τ (ns)	4.4	3.7	3.1
BR (MG cm)	0.50	0.55	0.64

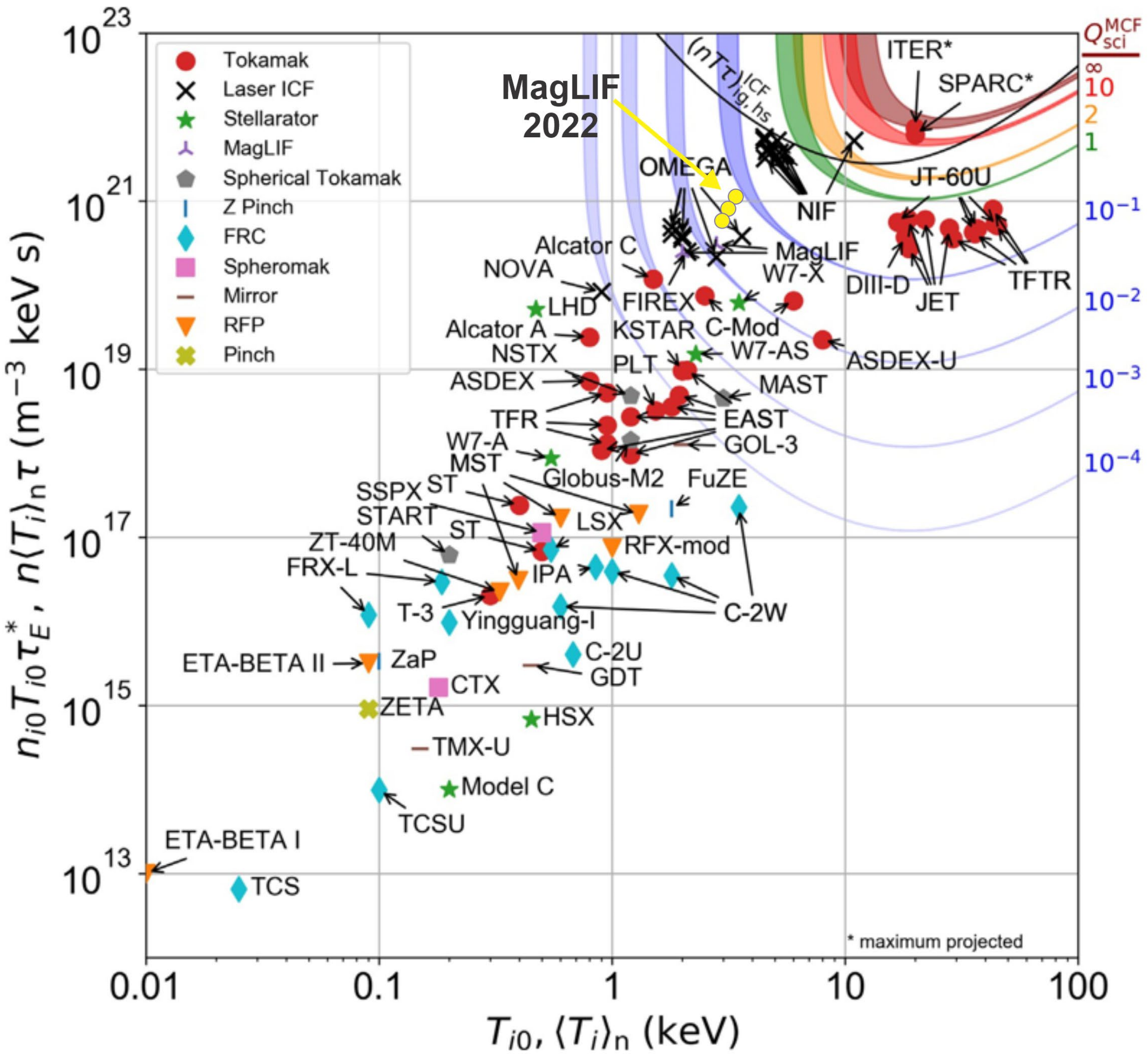
~100kJ DT equivalent on Z

- **Assuming MagLIF continues to scale as predicted, driver needs to be ~60 MA to reach IFE relevant yields**

Gomez, Slutz et al. PRL, 2020

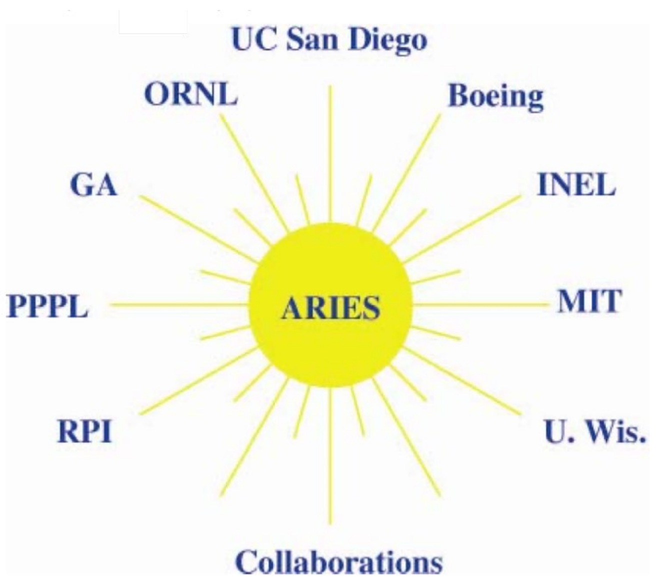
Why is MagLIF and MD-IFE interesting?

- **Progress has been rapid over the last decade**
  - Fully integrated experiments demonstrated the efficacy of the design
  - Performance only below NIF; $n t \tau > 10^{21}$ m^{-3} keV s on a sub-scale driver
  - Innovation still improving performance; self-magnetizing loads may enable $T_i > 7$ keV (Shipley 2025) on present drivers
  - Scalable driver technologies available now
  - For IFE, low repetition rate is a significant advantage
  - Less stringent vacuum needs than many IFE schemes
- Large scale issues needs to be address to go from single shot, moderate yields to high yield, rep-rated operation for all IFE approached
- **How do universities continue to contribute?**



Wurzel & Hsu, Phys. Plasmas 29, 062103 (2022)

ARIES Concept Studies (1982 – 2013)

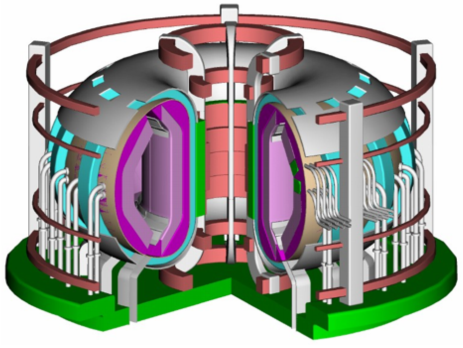


- ARIES program was very successful at UCLA (Bob Conn) then moved to UCSD in 1994 (Farrokh Najmabadi & Mark Tillack)
  - ***- a university led program to design a fusion power plant***
- Included experts across 14 different areas including confinement physics, material science, electric power conversion, tritium systems and, systems integration
  - Supported and trained many researchers in fusion technology
  - Since this was disbanded, those personnel have migrated or retired
  - Importance on continuity of funding to grow workforce (Analogous to the Center in HEDP)
  - New initiatives (Milestone and FIRE Centers) and looking to re-enable this sort of work

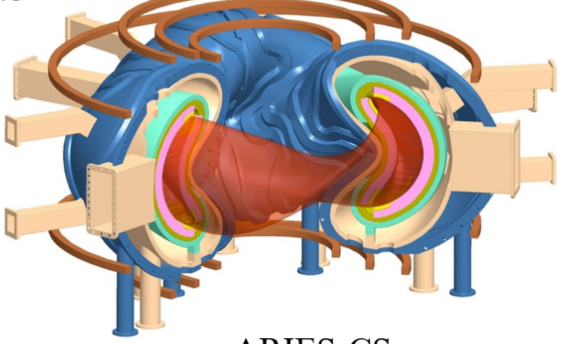
http://qedfusion.org/DOCS/

TITAN (published 1988)	Reversed field pinch
ARIES-I (1990)	"First stability" tokamak: low beta, high field, SiC_f/SiC structures
ARIES-II/IV (1992)	"Second stability" tokamak
ARIES-III (1991)	D-^{3}He tokamak
Pulsar (1993)	Pulsed tokamak
SPPS (1994)	Stellarator
ARIES-RS (1996)	Reversed shear tokamak
ARIES-ST (1999)	Spherical tokamak, DCLL, He/W divertor
ARIES-AT (2000)	Advanced (phys & tech) tokamak, SiC SCLL
ARIES-IFE (2004)	IFE chamber design and comparison study
ARIES-CS (2008)	Compact "advanced" stellarator
ARIES-ACT (2013)	Advanced and conservative tokamaks

"The Early Years"



"The Later Years"



ARIES-CS

Innovation and sub-scale testing is still a major need in the drive to fusion energy for all approaches

- Significant, repeatable yield in single shot is just the first step.

- New ideas to assess both high yield needs and repetition rated needs must be developed and studied

  - *How do we reload a physics target to define what will limit repetition rates – sub-scale testing*
  - *What chamber protection is needed and effective? Can this be demonstrated in combined neutronic, radiation and pulsed environments on some scale?*
  - *What does that mean for structural materials, heat handling and tritium breeding?*

- All these sub-systems need coordinating into a plant design to accurately predict power generation and availability, maintenance needs, and safety/licensing issues

UC San Diego

PACIFIC FUSION

Sandia National Laboratories

Imperial College London

Los Alamos NATIONAL LABORATORY EST. 1943

UNIVERSITY OF MICHIGAN

Lawrence Livermore National Laboratory

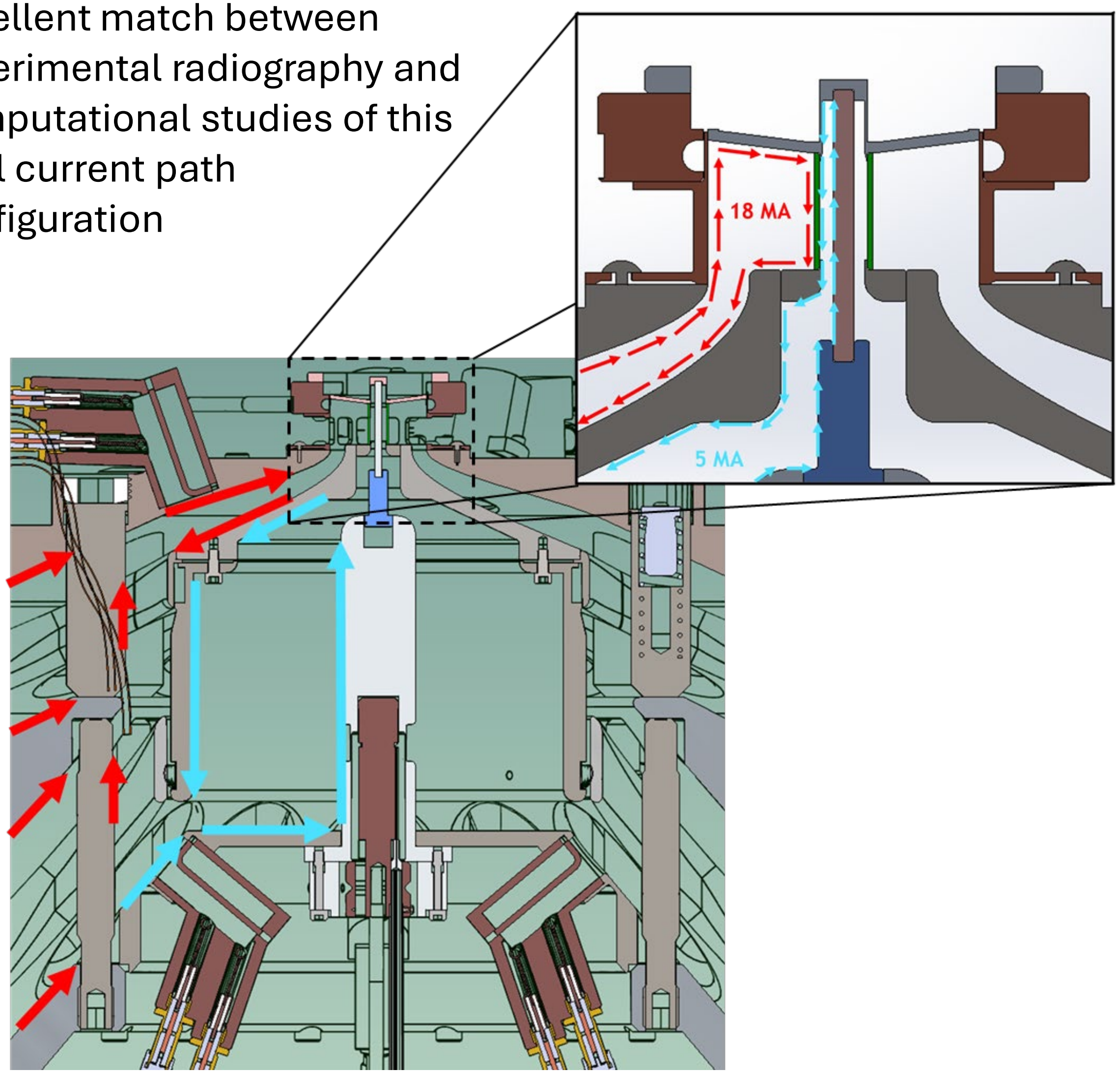
GENERAL ATOMICS

"Affordable, manageable, practical, and scalable (AMPS) high-yield and high-gain inertial fusion"

https://arxiv.org/abs/2504.10680

Sandia have developed a new pulsed power configuration to drive several MA through an ice fiber in parallel with the target enabling higher preheat energies and fuel densities in MagLIF

Excellent match between experimental radiography and computational studies of this dual current path configuration



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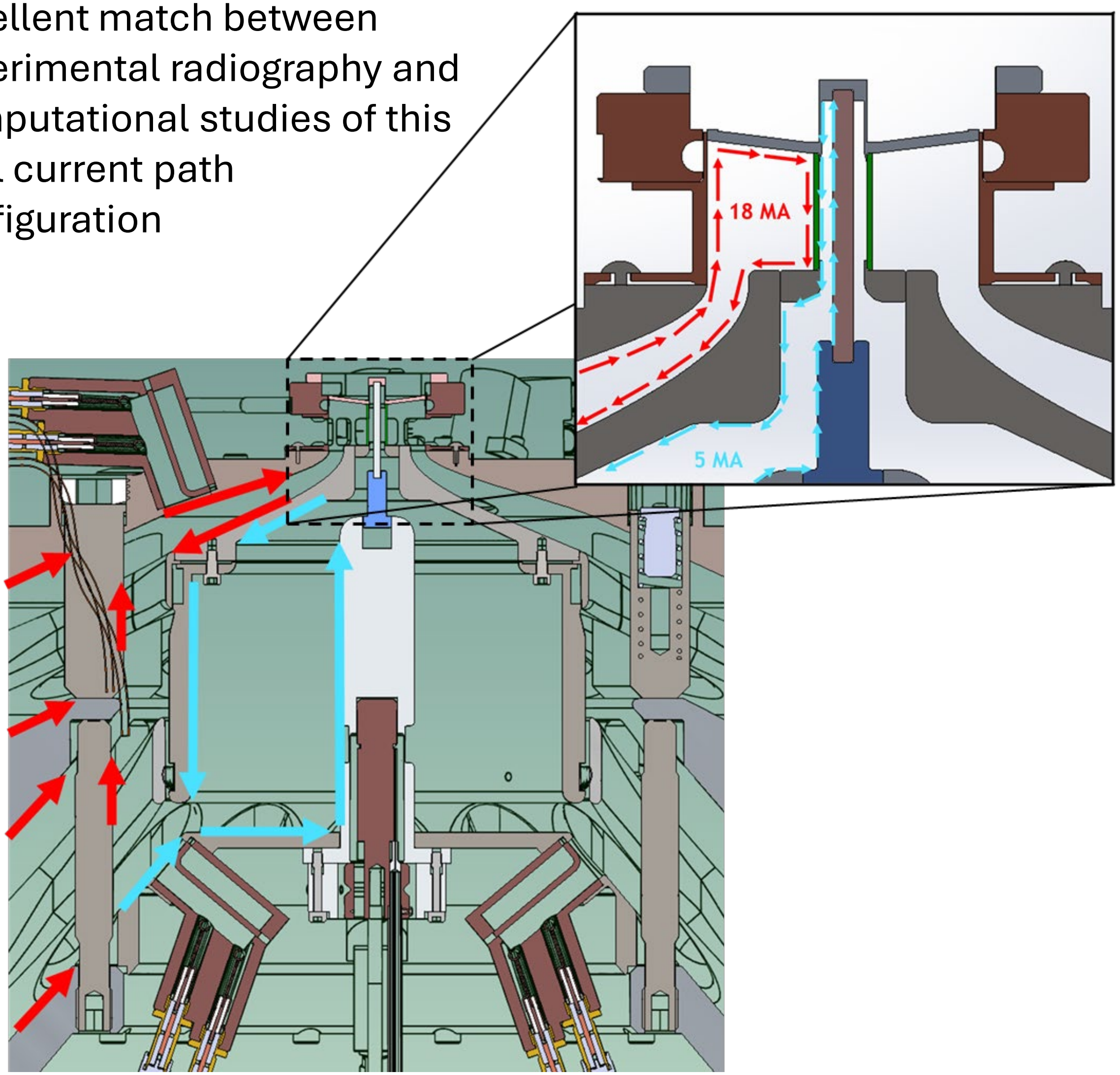
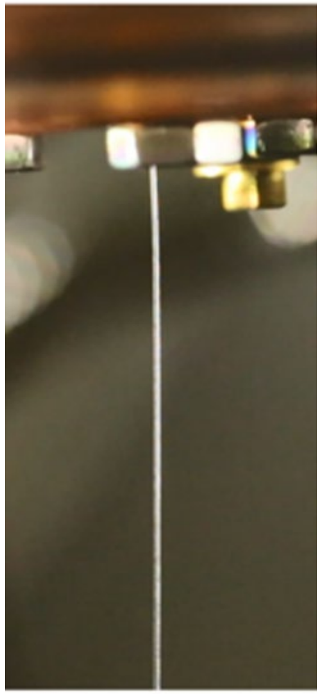


Ice fiber extrusion capability developed in parallel to enable fusion applications
[T.J. Awe++ RSI, 2021]



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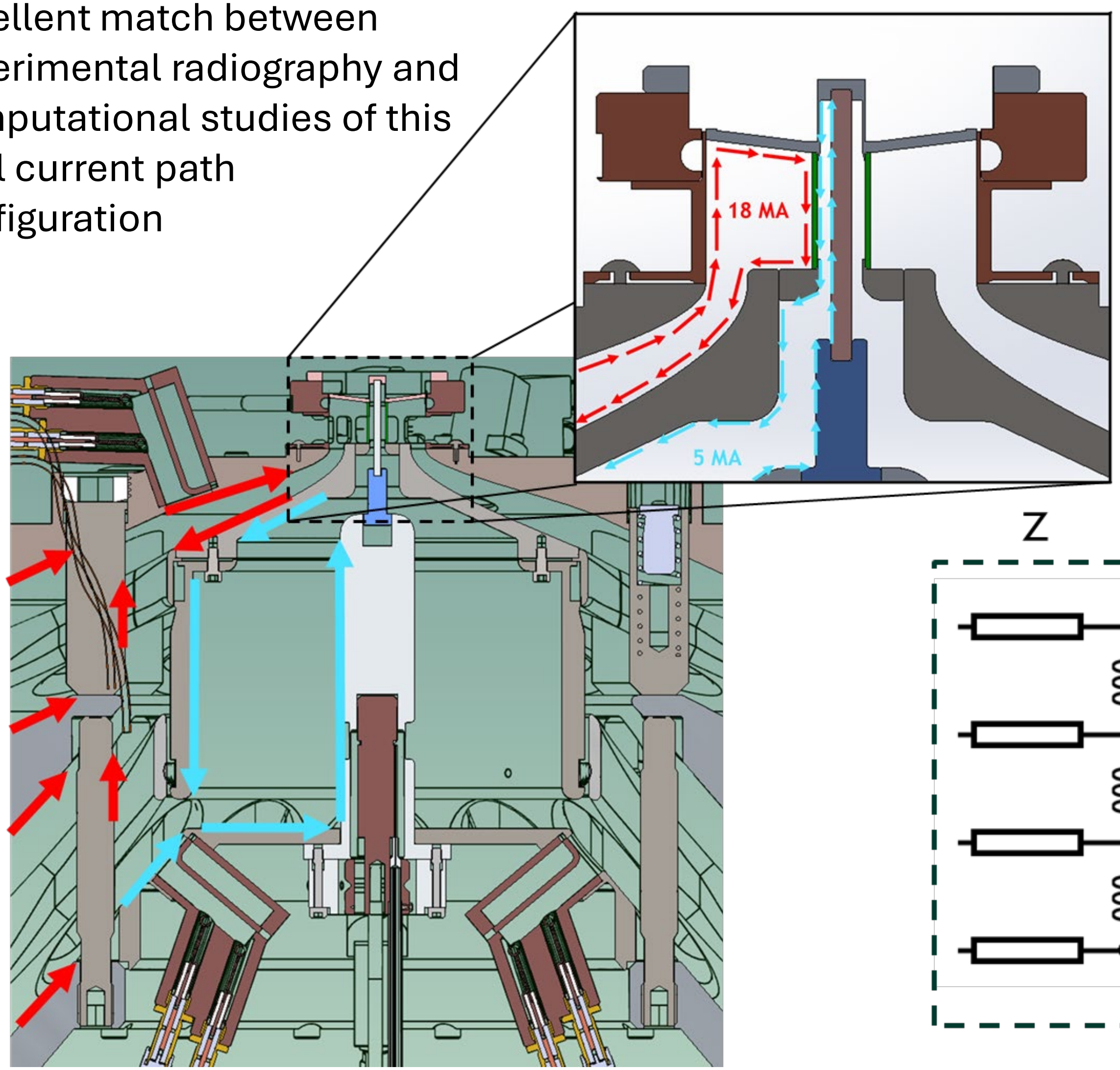
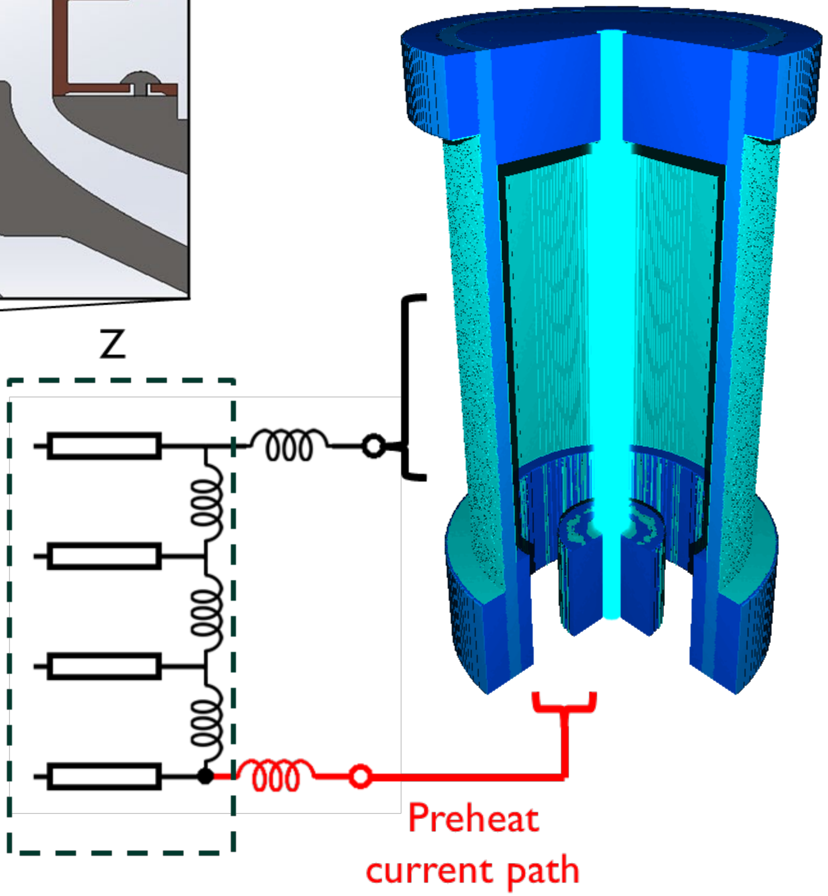


Simulations show higher neutron yields at a more modest target convergence



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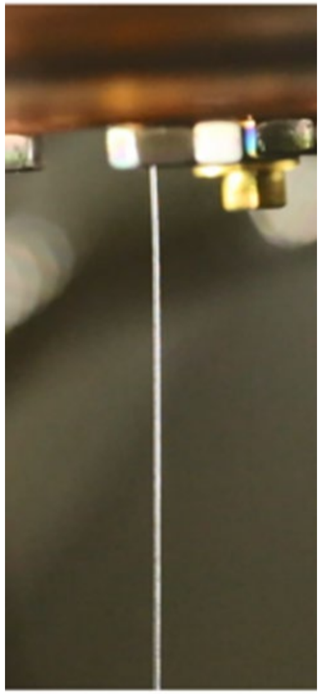
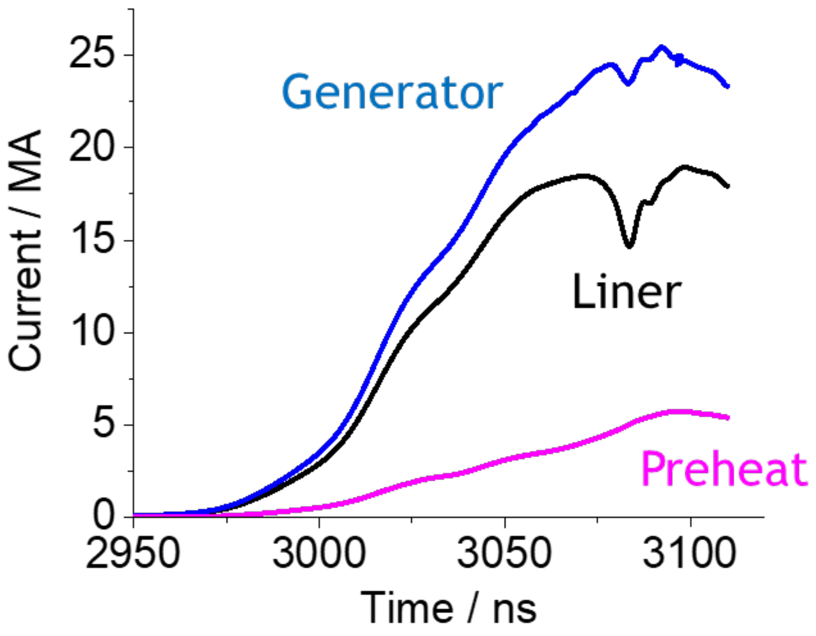
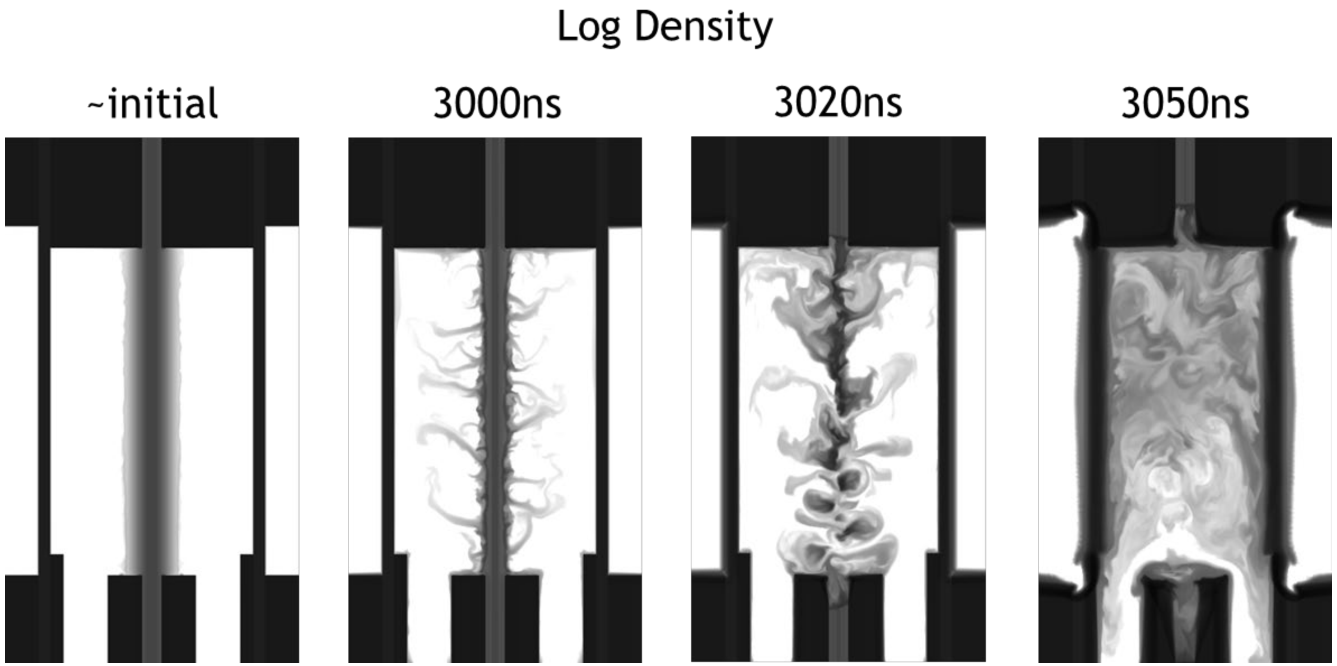


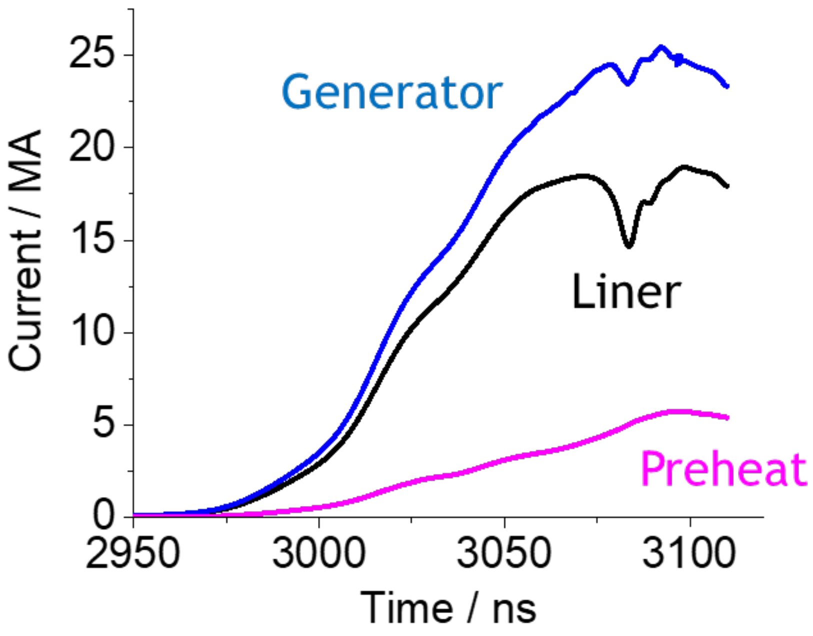
There is an opportunity for universities to lead the effort to understand energy coupling in this preheat mechanism at a scale relevant to Z

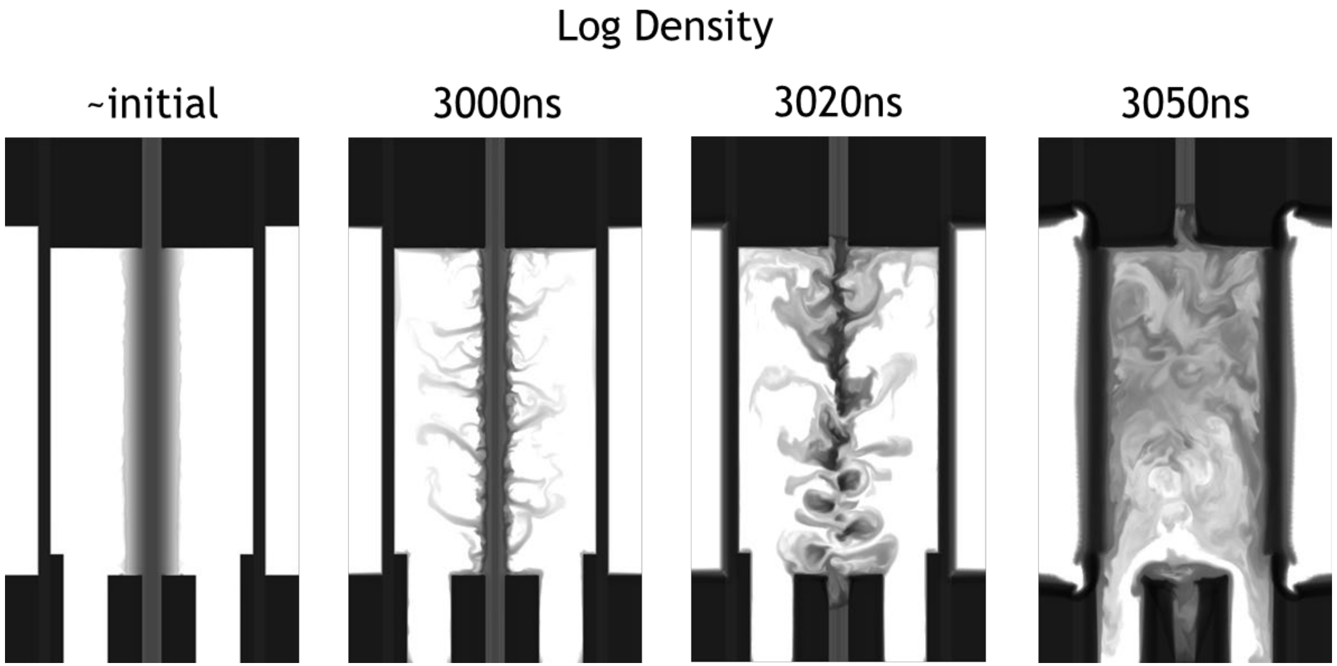




- Early on (3020ns) the fiber implodes and goes unstable, while ~1 MA of current continues to drive energy into the disrupted plasma
- As the liner begins to implode (3050ns), ~3MA of current flows in the interior of the target with a total of ~8 kJ deposited in the fuel

There is an opportunity for universities to lead the effort to understand energy coupling in this preheat mechanism at a scale relevant to Z





- **MA-class generators could drive several kJ of preheat energy into a fiber, comparable to the highest preheat energies achieved with a laser on the Z facility**

- **Understanding the dissipation of energy into a turbulent, spatially confined plasma is critical to making progress in this effort**

Much more information at IFSA

Tours, France, September 14th to 19th, 2025

Friday, 19 September 2025

08:00-13:00 ☑ **Luggage storage**

08:30-10:30 ☑ **Plenary lectures IV** (auditorium Ronsard)

Pulsed power driven preheat using a cryogenic Ice fiber for MagLiF experiments on Z
Chris Jennings, SNL, United States

Progress, challenges, and plans for the MagLIF platform on Z
Adam Harvey-Thompson Adam Harvey-Thompson, SNL, United States

Approaching hydro-equivalent inertial confinement fusion ignition in OMEGA direct-drive cryogenic implosions
Michael Rosenberg, LLE, United States

10:30-11:00 ☑ **Coffee break** (salons Agnès Sorel)

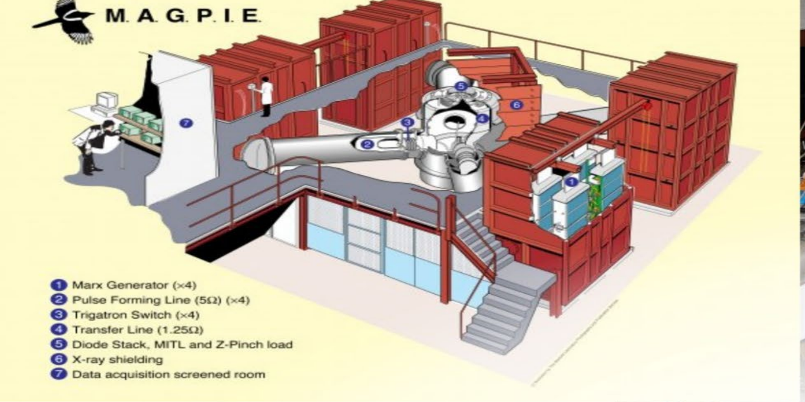
11:00-12:20

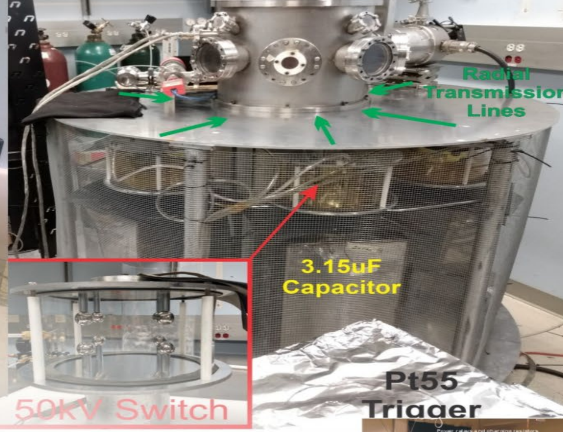
auditorium Ronsard	auditorium Descartes	room George Courteline
☐ **Inertial Fusion Science: Alternative laser-driven approaches II**	☐ **Inertial Fusion Science: Target design II**	☐ **Inertial Fusion Science: Z-pinch physics**
Recent progress of the DCI campaign from R11-R12 experiments Jie Zhang, CAS IoP, China	*Toward Robust High-Gain Designs for Inertial Fusion Energy via Bayesian Optimization* M. Giselle Fernández-Godino, LLNL, United States	*Demonstrating dual current paths as a method to preheat and implode a magneto-inertial fusion target* Matthew Gomez, SNL, United States
Demonstration of Fast Heating Performance in Double-Cone Ignition Scheme via Fusion-neutron Detection Xiao Su, Shanghai Jiao Tong U., China	*Tuning inertial confinement fusion designs using Bayesian optimization* Shailaja Humane, Michigan U., United States	*Electrothermal instability growth in Magnetised Liner Inertial Fusion (MagLIF) liners* Nikita Chaturvedi, Imperial College London, United Kingdom
1D hydrodynamics study on proton-driven fast ignition laser fusion with p11B fuel Igor Morozov, HB11 Energy, Australia	*Laser Indirect Drive Designs at 10 MJ of Incident Energy* Denise Hinkel, LLNL, United States	*Improved Machine-Target Coupling Through Tailored Electrode Coatings* Alex Sarracino, SNL, United States
Development of Liquid Deuterium Filled Solid Sphere for Fast Ignition Inertial Fusion Energy Research Shinsuke Fujioka, ILE, Japan	*High yield design options for a next-generation ICF facility* Chris Weber, LLNL, United States	*Simulations of electrothermal instabilities in wires, foils and liners of relevance to magneto-inertial fusion.* Jeremy Chittenden, Imperial College London, United Kingdom

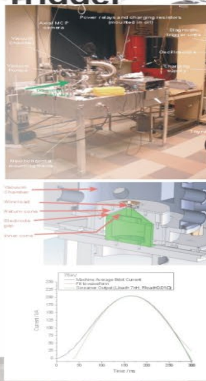
12:30-13:00 ☑ **Closing ceremony** (auditorium Ronsard)

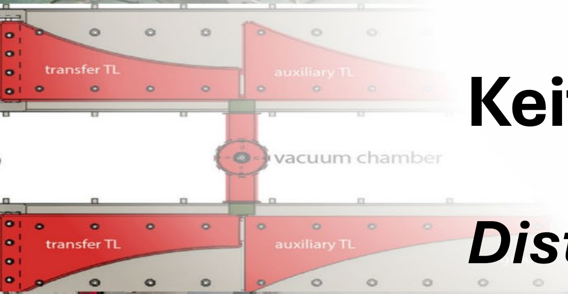
Final thoughts

- HEDP and Fusion energy goals, targets, drivers, system and plant designs have moved many times over the last few decades.
- University collaborations have adapted each to change and continue to provide vital support and innovation for national programs
- University programs are an essential part of a productive ecosystem in fusion and continuous, (reasonably) well-funded programs makes sure they are ready for new challenges.
- Innovation and ‘blue skies’ research keeps students invigorated for any plasma career





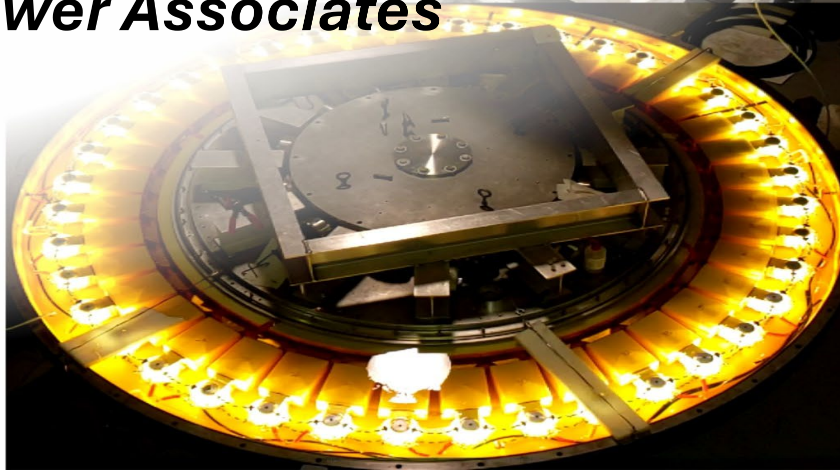


“The scientific learning that can be done on university-scale experimental facilities with creative thinking is phenomenal”

Keith Matzen

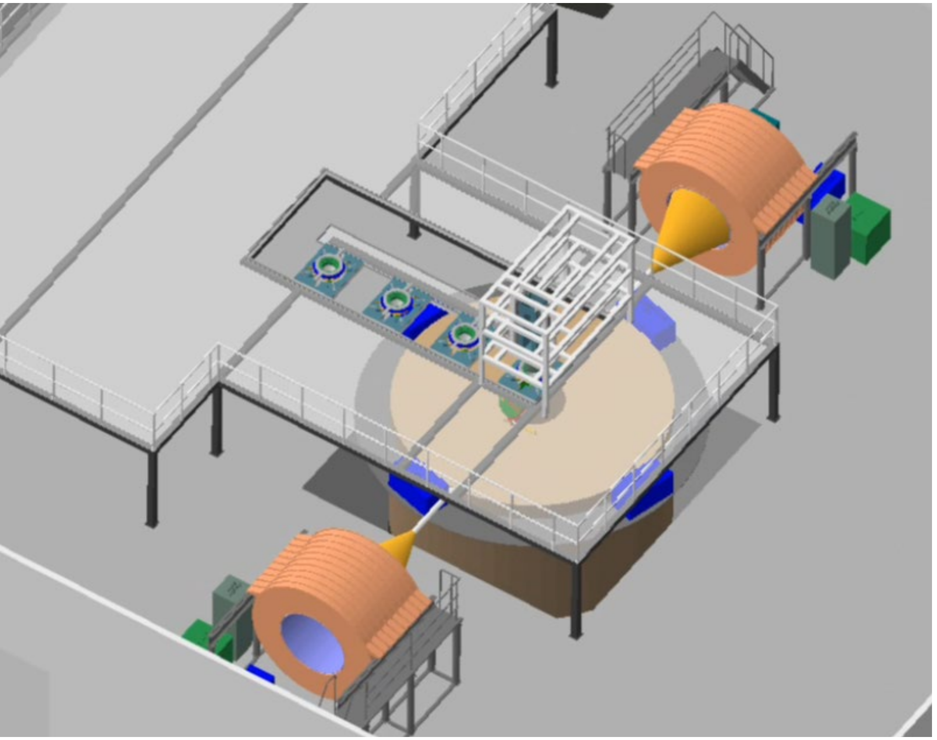
Distinguished Career Award from Fusion Power Associates
American Physical Society Fellow
Sandia National Laboratories Fellow



Back-up Slides

Z RTL Reload Proof-of-Principle



- Standoff requirements will be determined by designed yield
- Envisioned to be 1-10 GJ/pulse at 0.1 Hz

- Coils are not recyclable, so fuel magnetization solutions built into the target are being investigation (Auto-Mag, FRC)
- Mass in RTL will be activated, so handing and recycling vital

FIRE:STORM

Fusion Innovation Research Engine: The Science and Technology of Repetitive Magnetic-Drive

- A collaborative Dept of Energy FIRE Center on liner-based inertial fusion energy was proposed which examines exactly these issues
- Focused on accelerating the TRL of critical elements and addressing concerns of the wider fusion energy community (National Academy, BRN-IFE reports)

UC San Diego · Pacific Fusion · Sandia National Laboratories · Imperial College London · University of Michigan · Lawrence Livermore National Laboratory · Los Alamos National Laboratory EST. 1943 · General Atomics

- Decision pending

U.S. DEPARTMENT OF ENERGY

FIRE:STORM takes advantage of academic collaborations, national labs and private industry

What is the university program role as we move towards full-scale fusion systems?

UC San Diego

Imperial College London

University of Michigan

- Full system design based on present data at large facilities
- Innovation and sub-scale testing (triggers, switches…)
- Dedicated Workforce training

Sandia National Laboratories

- Advanced target design and demonstration
- Simulation benchmarking & performance projection
- High yield needs

Lawrence Livermore National Laboratory

- Materials and chamber protection

Los Alamos National Laboratory EST. 1943

- New Target simulations

Pacific Fusion

- Full scale yield and requirements, including rep-rate operation

"Affordable, manageable, practical, and scalable (AMPS) high-yield and high-gain inertial fusion"

https://arxiv.org/abs/2504.10680